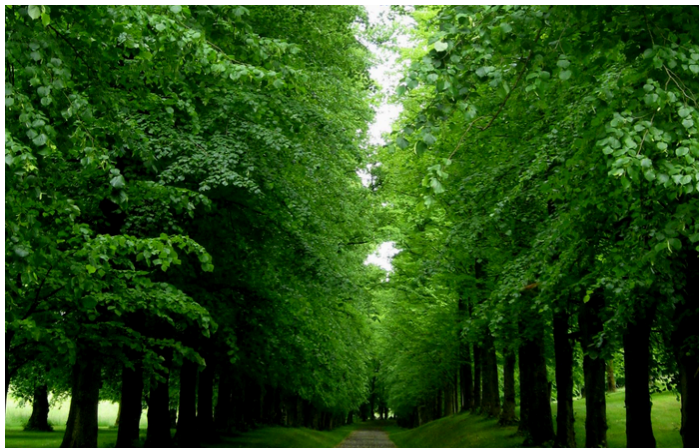




**DEPARTMENT OF BIOLOGICAL AND
ENVIRONMENTAL SCIENCES**

PERMEABLE GROUND, PERSISTENT EFFECTS: A DECADE OF LEGACY GROWTH IN URBAN *TILIA X EUROPAEA* AT LINDHOLMSALLÉN, GOTHENBURG

Permeable ground as a growth variable



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Frontpage figure: Avenue of Tilia x europaea in the UK, source: wikipedia.org

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Abstract

Urban trees deliver critical ecosystem services ranging from transpiratory cooling and stormwater management to carbon sequestration and biodiversity support, however their capacity to provide these services is fundamentally shaped by the conditions of their immediate growing environment. Impervious ground surfaces restrict water infiltration, elevate soil temperatures, and impair root zone aeration, all of which constrain tree growth and long-term vitality. Measurements done between 2015 to 2016 demonstrated that a low fraction of permeable ground surface significantly suppressed both current-year shoot growth and, to a lesser extent, long-term stem growth in *Tilia x europaea* street trees along Lindholmsallén, Gothenburg. The present study revisits the same individual trees a decade later, with the aim of determining whether that permeability signal has persisted, strengthened, or diminished as the trees have aged and their urban context has intensified.

Stem circumference and crown dimensions were re-measured in February 2026, and surface permeability was reassessed to account for both crown expansion and substantial ground surface alterations resulting from a decade of urban development, including the construction of large buildings and a tram line. The results reveal that yearly diameter growth is no longer significantly associated with surface permeability, likely reflecting a combination of age-related growth deceleration, probable exhaustion of confined root volumes, climatic stress including the exceptional 2018 drought, and construction-related disturbance. However, total accumulated basal area in 2026 shows a clear and statistically significant positive relationship with permeable surface fraction, with trees in the highest quartile of permeability access having accumulated 12.3% greater basal area than those in the lowest. These findings demonstrate that the influence of ground surface permeability on urban tree growth does not diminish with time but compounds as a structural legacy with direct consequences for the long-term ecosystem service capacity of street trees and for the planting decisions that determine it.

Keywords: Urban trees, Permeability, Diameter, Basal area, Trunk, Crown.

Abstrakt

Urbana träd levererar kritiska ekosystemtjänster som sträcker sig från kylning och regnvattenhantering till kolbindning och stöd för biologisk mångfald, men deras förmåga att tillhandahålla dessa tjänster formas i grunden av förhållandena i den närmaste växtmiljön. Icke permeabla markytor begränsar vatteninfiltrationen, höjer marktemperaturen och försämrar syresättningen i rotzonen, vilket sammantaget hämmar trädens tillväxt och långsiktiga vitalitet. Mätningar genomförda mellan 2015 och 2016 visade att en låg andel icke permeabel markyta signifikant hämmade både den innevarande säsongens skotttillväxt och, i något mindre utsträckning, den långsiktiga stamtillväxten hos urbana träd *Tilia x europaea* längs Lindholmsallén i Göteborg. Föreliggande studie återbesöker samma individer ett decennium senare, med syftet att undersöka huruvida detta samband har kvarstått, förstärkts eller försvagats i takt med att träden har åldrats och deras urbana kontext har intensifierats.

Stamomkrets och kronmått mättes åter igen i februari 2026, och markytans genomsläpplighet omvärderades för att ta hänsyn till både kron-utbredning och väsentliga förändringar av markytan till följd av ett decennium av konstruktionsarbete i området, innefattande uppförandet av stora byggnader samt en spårvägsutbyggnad. Resultaten visar att den årliga diametertillväxten inte längre uppvisar något signifikant samband med markytans genomsläpplighet, vilket sannolikt återspeglar en kombination av åldersrelaterad tillväxt-avmattning, trolig uttömning av begränsade rotvolym, klimatrelaterad stress inklusive torkan 2018, samt störningar orsakade av byggverksamhet. Däremot uppvisar den totalt ackumulerade grundytan år 2026 ett tydligt och statistiskt signifikant positivt samband med andelen genomsläpplig markyta, där träd i den översta kvartilen av genomsläpplighet hade ackumulerat 12,3 % större grundyta än de i den lägsta. Dessa fynd visar att markytans permeabilitets inverkan på urbana trädets tillväxt inte avtar med tiden, utan ackumuleras som ett strukturellt arv med direkta konsekvenser för gatuträdens långsiktiga kapacitet att leverera ekosystemtjänster och för de planteringsbeslut som avgör denna kapacitet.

Nyckelord: Urbana träd, Permeabilitet, Diameter, Grundyta, Stam, Trädkrona.

Introduction

Urban Trees as Green Infrastructure

Urban trees are a fundamental component of sustainable green infrastructure, providing a wide array of locally generated ecosystem services that are essential for the health and resilience of modern cities. These services include the filtration of air pollutants, the preservation of biodiversity, and the provision of recreational and aesthetic values for urban inhabitants (Alvey, 2006, Bottalico et al., 2016, Nowak et al., 2025). Furthermore, urban trees play a critical role in micro-climate regulation through shading and transpiratory cooling, which significantly mitigates the urban heat island effect (Tan et al., 2016). The presence of healthy urban forests is so impactful that it has been linked to 15 of the 17 United Nations Sustainable Development Goals, highlighting their necessity for creating liveable and sustainable communities (United Nations, 2015).

Stressors in the Built Environment

Despite their significant value, urban trees must endure harsh and unique growing conditions that are often absent in natural forest environments. Street trees, in particular, frequently exhibit high mortality rates and shorter average lifespans due to a complex set of interacting stressors, including air and soil pollution, excess radiant heat, and limited soil volumes (Konijnendijk et al., 2005). Climate change further exacerbates these challenges, as rising temperatures and shifting precipitation patterns can drive many species to the limits of their physiological tolerance, resulting in decreased vitality and a reduced capacity to provide the very ecosystem services they were planted for.

Sweden's average annual temperature has risen nearly 2°C since the late 19th century, outpacing the global average, and the country is already grappling with severe impacts of a warming climate, with extreme weather events becoming more frequent and expected to intensify in coming decades (Hwang., 2025). Within this broader trend, the summer of 2018 stands out as a pivotal climate event for the region. Two long-lasting high-pressure systems produced extended heat waves over Scandinavia, and anthropogenic climate change was found to have strongly increased the probability of such a warm summer occurring in Sweden (Wilcke et al., 2020). As cities continue to warm and precipitation becomes less predictable, the conditions under which urban trees must grow will only become more demanding, making an understanding of the factors that support or constrain their long-term health increasingly urgent. Prolonged drought causes soils to shrink and crack, dramatically reducing their permeability and limiting the infiltration of rainfall meaning that even when precipitation does occur, much of it runs off rather than reaching tree roots. This moisture deficit forces trees into sustained physiological stress, impairing nutrient uptake, weakening structural integrity, and leaving them increasingly vulnerable to secondary stressors such as pests and disease (Bréda et al., 2006).

Ground Surface Permeability as a Primary Growth Determinant

A primary stress factor restricting the growth and health of trees in the built environment is the widespread use of impervious surface paving. Paved surfaces create a physical barrier that limits the infiltration of rainwater into the soil, thereby reducing the availability of water and nutrients for root uptake (Gillner et al., 2014). Beyond water restriction, impervious surfaces absorb and re-radiate solar energy, elevating both local air and soil temperatures. Soil temperatures beneath paved areas can exceed root tissue heat tolerance thresholds, inhibiting root development and microbial activity that would otherwise support nutrient cycling (Celestian & Martin, 2004). Compounding these thermal effects, the aeration of soil beneath paving is typically poor, potentially inducing oxygen deficiency in tree roots and further constraining growth (Morgenroth & Buchan, 2009). Together, reduced water infiltration, elevated temperatures, and impaired soil aeration create a below-ground environment that is not conducive to optimal root function, and by extension, to the overall vitality of the tree above.

The consequences of these stressors are not merely physiological. When urban trees are compromised in their growth and function, their capacity to deliver ecosystem services is directly diminished. A tree with suppressed shoot growth and reduced canopy area provides less shade, transpires less water, intercepts less rainfall, and sequesters less carbon than a healthy counterpart (Rahman et al., 2018). Trees at highly paved sites in Gothenburg exhibited significantly reduced gas exchange, leaf area density, and modelled cooling effects compared to trees with greater access to permeable surfaces and the degree of surface paving explained more variance in these parameters than species identity itself. Crucially, these differences were most pronounced during hot, dry periods which is precisely the conditions under which urban cooling is most urgently needed (Konarska et al., 2023).

The structural relationship between crown size and trunk development offers a further dimension through which the consequences of paving can be assessed. Research on resource allocation in plants suggests that well-resourced individuals prioritize investment in permanent structural biomass such as roots relative to more transient biomass as a fundamental physiological mechanism of balanced growth. In trees this manifests as a prioritization of trunk biomass allocation rather than within the crown. (Brouwer, 1983, Grabosky & Gilman 2004). If impervious surfaces suppress below-ground resource availability, this allocation balance may shift, producing trees with proportionally larger crowns relative to their trunk size. Tracking the crown-to-basal area ratio across time therefore provides a morphologically grounded indicator of cumulative resource stress that complements direct growth measurements (Dobbertin 2005). Urban heat island effects intensify by 0.5–1°C during heat waves in Swedish cities, making the cooling capacity of street tree canopies a progressively more critical component of climate adaptation infrastructure (Wang et al., 2025). The canopy-based services most commonly invoked to justify street tree planting are shading, transpiratory cooling, and stormwater interception which are overwhelmingly crown-dependent rather than trunk-dependent (Ziter et al., 2019).

From a city planning perspective, this represents a significant return on investment problem; Trees are expensive to plant, establish, and maintain, yet impervious paving in their immediate surroundings may silently undermine their long-term performance from the moment of planting. Recognising this, many municipalities have increasingly incorporated permeable paving, tree pits, and structured soil systems into urban design guidelines, though implementation remains inconsistent (Mullaney et al., 2015, Konarska et al., 2023). While structural soils have been introduced in many Swedish cities as a partial mitigation measure, evidence suggests they cannot fully compensate for the water limitations imposed by surface paving (Konarska et al., 2023).

Cumulative and Legacy Effects of Surface Impermeability

While the negative impacts of paving are well-documented in shorter-term studies, fewer investigations have tracked how the specific degree of ground surface permeability shapes tree growth trajectories over longer time horizons. Sand et al. (2018) addressed this directly by measuring stem and current-year shoot growth across 95 same age *Tilia europaea* street trees in Gothenburg, finding that trees with only 10% permeable surface cover had stem growth approximately 10% lower and shoot growth reduced by up to 55% compared to trees with fully permeable surroundings. Notably, the effect on shoot growth was observed under both the unusually wet year of 2015 and unusually dry year of 2016, suggesting that the benefits of permeable surfaces are not limited to periods of drought but hold across a range of precipitation regimes. Konarska et al. (2023) demonstrated that the fraction of non-paved area around street trees explained more variance in structural parameters such as tree height, crown radius, and stem diameter than species identity itself, even across species with contrasting drought tolerance strategies. Together, these studies suggest the proportion of permeable surface around an urban tree is not merely a secondary site characteristic but a primary determinant of its long-term growth potential and, by extension, its capacity to deliver ecosystem services at the scale at which cities need them.

This pattern is not unique to *Tilia* or to Gothenburg. Reduced available soil area produces measurably smaller overall tree dimensions across species with quite different growth strategies, suggesting that the mechanism of cumulative soil-volume constraint on size is broadly general (Sanders & Grabosky, 2014).

Cumulative effects are particularly important to consider. The influence of impervious surfaces on a tree's water budget and root environment does not reset each year, but accumulates across the lifetime of the tree. Trees that have experienced restricted water availability and elevated soil temperatures for many years may develop structural deficits in root architecture, sapwood area, and canopy volume that persist and compound even if surface conditions later improve. This temporal dimension means that short-term measurements of stem or shoot growth may not fully capture the legacy effects that impervious surfaces exert over the life of a tree.

Overarching Study Goal

The aim of this study is to examine whether the relationship between surface permeability and long-term stem growth identified by Sand et al. (2018) has persisted, strengthened, or weakened a decade after the original measurements were taken. A ten year interval is a meaningful unit of analysis for this purpose because it spans physiological processes that shorter follow-ups cannot adequately capture. Chief among these is root system development; Conflicts between trees and their paved surroundings are particularly associated with trees more than 15 to 20 years old, as root networks progressively exploit and ultimately exhaust the finite soil volumes available to them in standard urban planting specifications (Watson et al., 2014). The study trees, planted in 1999 and originally provided with 16 m³ of growing space, were approaching this threshold at the time of the original study and are now well into the phase where below-ground physical constraints are likely to dominate. Root architecture and hydraulic infrastructure also develop on decadal timescales, sapwood which determines the efficiency of the tree's water transport system is maintained for multiple years, meaning the hydraulic capacity of a tree at any given moment reflects growing conditions integrated over many preceding seasons rather than the current year alone (Zweifel & Sterck, 2018). Cumulative stress exposure matters similarly for canopy development as crowns built under chronic water limitation during the establishment phase may carry structural deficits in branching architecture and leaf area that persist and compound regardless of whether surface conditions later improve (Anderegg et al., 2015). In many cities, supplemental irrigation is provided only during the initial establishment phase, leaving mature trees to rely almost exclusively on annual precipitation, meaning any advantage conferred by permeable surfaces during establishment becomes increasingly consequential over time (Dekel et al., 2026).

Aim

By revisiting the trees measured by Sand et al. (2018) ten years later, this study aims to determine whether the correlation between access to permeable surface and yearly radial growth previously observed has continued to be maintained over an additional decade of growth.

Material and method

Study Site and Tree Population

Field measurements were conducted along Lindholmsallén, including the cross-streets Pumpgatan and Götaverksgatan, located on Hisingen, Gothenburg (57°45'N, 11°54'E). The study trees are *Tilia x europaea*, originally planted in 1999 in regular soil planting beds on construction waste. Between the 2015–2016 measurement period of Sand et al. (2018) and the present study, the Lindholmsallén area has undergone substantial urban development. Notable projects include the construction of the skyscraper Karlatornet (2019–2023) and a new tram line, which completed construction on 14 December 2025. As a direct result of these interventions, two trees from the original study population of 95 trees were excluded from the present analysis having been removed to accommodate the tram line infrastructure.

Tree locations from the original study were georeferenced by overlaying the original positional data onto a current satellite image in ArcGIS (ESRI 2025. ArcGIS Pro 3.7), producing a spatial reference map used to identify and cross-reference individual trees in the field (Fig. 1). To aid with this and ensure all trees measured were the same as previously measured by Sand et al. (2018) static references which had not been moved or altered such as the edges of buildings and parking lots were used to determine the exact tree to be measured. Maps of the area during previous years were acquired from Lantmäteriet (minkarta.lantmateriet.se - February 14 2026). Field measurements were conducted over two weeks in mid-to-late February 2026.



Fig. 1. An overview of the area the studied trees were located in covering Lindholmsallén, Pumpgatan and Götaverksgatan, with each tree's individual ID being shown. Note that trees 94 and 95 were not included in the study due to having been cut down since the original study. Additionally tree ID 01 is slightly cropped in the used map, however as the ID represented the tree at the central point this did not impact measurement accuracy for this specific tree.

Stem Circumference Measurements

Stem circumference was recorded at 1.30 m above ground using a measuring tape and converted to diameter by dividing by π . However, to support the trees during the significant construction activity of the preceding decade, wooden bracing supports had been installed around the trunks of many individuals, particularly in the central section of the avenue. Where these supports were present, direct measurement at 1.30 m was not possible, and circumference was instead recorded at 1.80 m, where the supports terminated. To ensure consistency across all individuals, a correction equation was derived to estimate circumference at 1.30 m from the 1.80 m measurement. This was achieved by performing a linear regression of directly measured 1.30 m and 1.80 m circumferences for trees where both measurements were accessible, with the 1.30 m value as the dependent variable and 1.80 m as the predictor. The regression yielded a coefficient of determination of $R^2 = 0.948$, $P < 0.001$, confirming that the 1.80 m measurement is a strong predictor of the 1.30 m circumference. The resulting Ordinary Least Squares equation was:

$$C_{1.3m} = 0.9949 \times C_{1.8m} + 1.9902$$

This indicates that for each centimetre of circumference measured at 1.80 m, the estimated circumference at 1.30 m is approximately 0.995 cm greater, plus a constant offset of 1.99 cm, consistent with the observed tendency for *Tilia x europaea* trunks to taper slightly with height. All circumference values in the final dataset are reported at 1.30 m, whether measured directly or estimated via this equation.

Crown Area Measurements

The vertically projected crown area was estimated by measuring crown width in two perpendicular directions using a measuring tape and a measuring stick, the crown being assumed as perfectly spherical and thus the projected crown being assumed as perfectly circular. Possible irregularities in crown shape were not accounted for. Due to the time of measuring in February measurements were made from the furthest branches and not the furthest leaves. As in Sand et al. (2018), surface permeability was assessed both within the vertically projected crown area and within an area 1.5 times its size, the latter included to capture the hydrological influence of precipitation falling just outside the crown, a portion of which would otherwise be intercepted and evaporated before reaching the ground. Surfaces such as concrete and asphalt were classified as impermeable, while grass, gravel, and mulch were classified as permeable.

Data analysis

All statistical analyses were performed with packages tidyverse and ggplot2 in R (R core team., 2025).

To assess how ground surface permeability relates to the growth of the study trees over time, three measures of trunk development were examined across two periods; 1999 to 2016 and 2016 to 2026 alongside a novel analysis of crown-to-basal area ratio. In each case, both the vertically projected crown area (Normal) and the 1.5x expanded crown area (1.5x) measurements were

used as permeability indices. P-values, slope and R² were documented, which can be found at the end of the document under “Appendix” (Table A1).

Results

Yearly diameter growth

Fig. 2 illustrates the relationship between permeable ground surface and yearly diameter growth across the two periods. During the first period (1999–2016), the 1.5x measurement showed a weak but statistically significant positive relationship with yearly diameter growth (slope = 0.0013, R² = 0.061, P = 0.017). The unaltered crown measurement showed a positive but non-significant trend (slope = 0.0011, R² = 0.029, P = 0.104). In contrast, for the more recent period (2016–2026), this relationship has become almost entirely absent. Both the Normal and 1.5x measurements produced near-zero slopes (0.0001 and 0.0005 respectively), negligible R² values (0 and 0.002), and P-values of 0.954 and 0.668, indicating no meaningful association between permeable surface fraction and yearly diameter growth during this decade. Notably, the scatter around the regression line is visibly greater in the 2016–2026 panel, suggesting increased inter-individual variation in growth rates that is not explained by surface permeability.

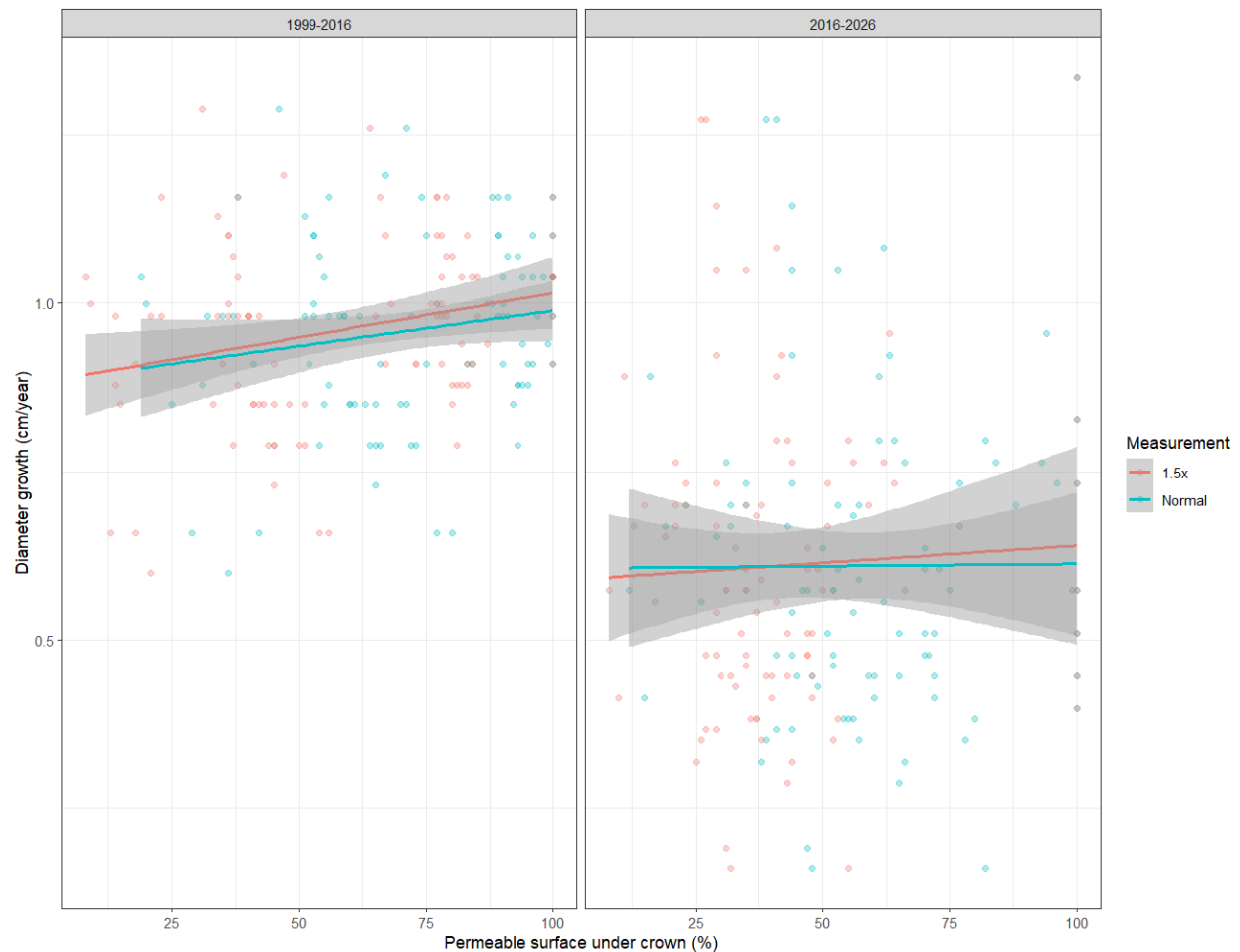


Fig. 2. Mean yearly diameter growth (cm/year) from the year of planting 1999 to 2016 and the following ten years from 2016 to 2026 as a function of percent of permeable surface area surrounding the tree. Blue points and lines relate to the permeable area below projected crown area, red points and lines relate to an area with size of 1.5 x projected crown area. 95% confidence intervals are highlighted in gray.

Yearly basal area growth

Moving from diameter to basal area (total trunk cross-sectional area) as the response variable reveals a moderately stronger pattern during the first growth period, though results remain mixed (Fig. 3). For 1999–2016, the 1.5x measurement yielded a statistically significant positive relationship (slope = 0.037, $R^2 = 0.045$, $P = 0.041$), while the Normal measurement did not reach significance (slope = 0.028, $R^2 = 0.019$, $P = 0.191$). For the 2016–2026 period, both measurements remained non-significant (Normal: slope = 0.045, $R^2 = 0.008$, $P = 0.397$; 1.5x: slope = 0.063, $R^2 = 0.014$, $P = 0.256$).

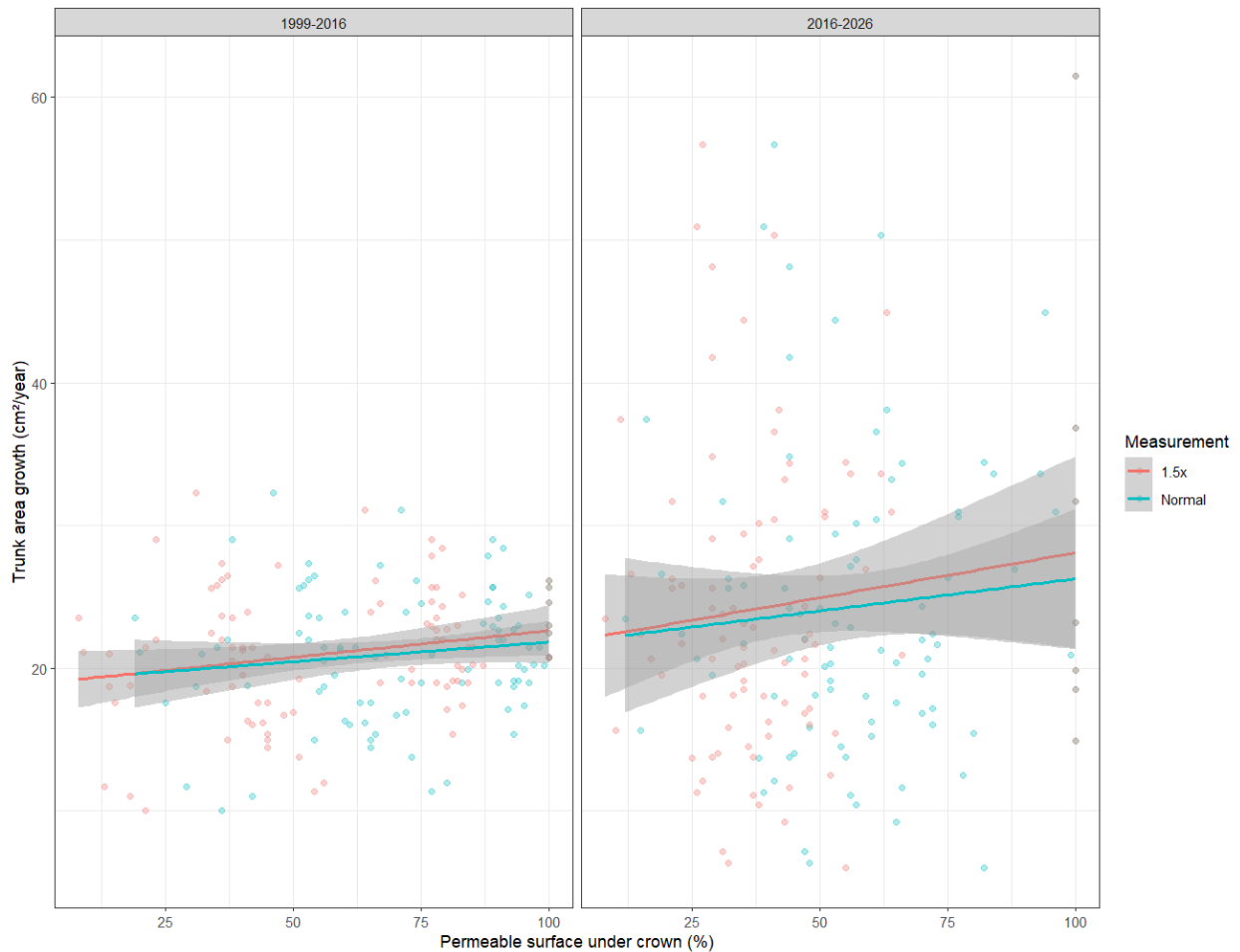


Fig. 3. Yearly basal area growth from 1999 to 2016 and from 2016 to 2026 as a function of the percent of permeable surface under the crown (cm/year). Blue points and lines relate to the permeable area below projected crown area, red points and lines relate to an area with size of 1.5 x projected crown area. 95% confidence intervals are highlighted in gray.

Total basal area

The strongest and most consistent relationships emerge when examining total accumulated basal area rather than yearly growth increments (Fig. 4). In 2016, the positive association between permeable surface and total basal area was modest and only approached significance for the 1.5x measurement (Normal: slope = 0.425, $R^2 = 0.015$, $P = 0.248$; 1.5x: slope = 0.584, $R^2 = 0.037$, $P = 0.064$). By 2026, however, both measurements show statistically significant positive relationships (Normal: slope = 1.62, $R^2 = 0.059$, $P = 0.019$; 1.5x: slope = 1.70, $R^2 = 0.060$, $P = 0.018$).

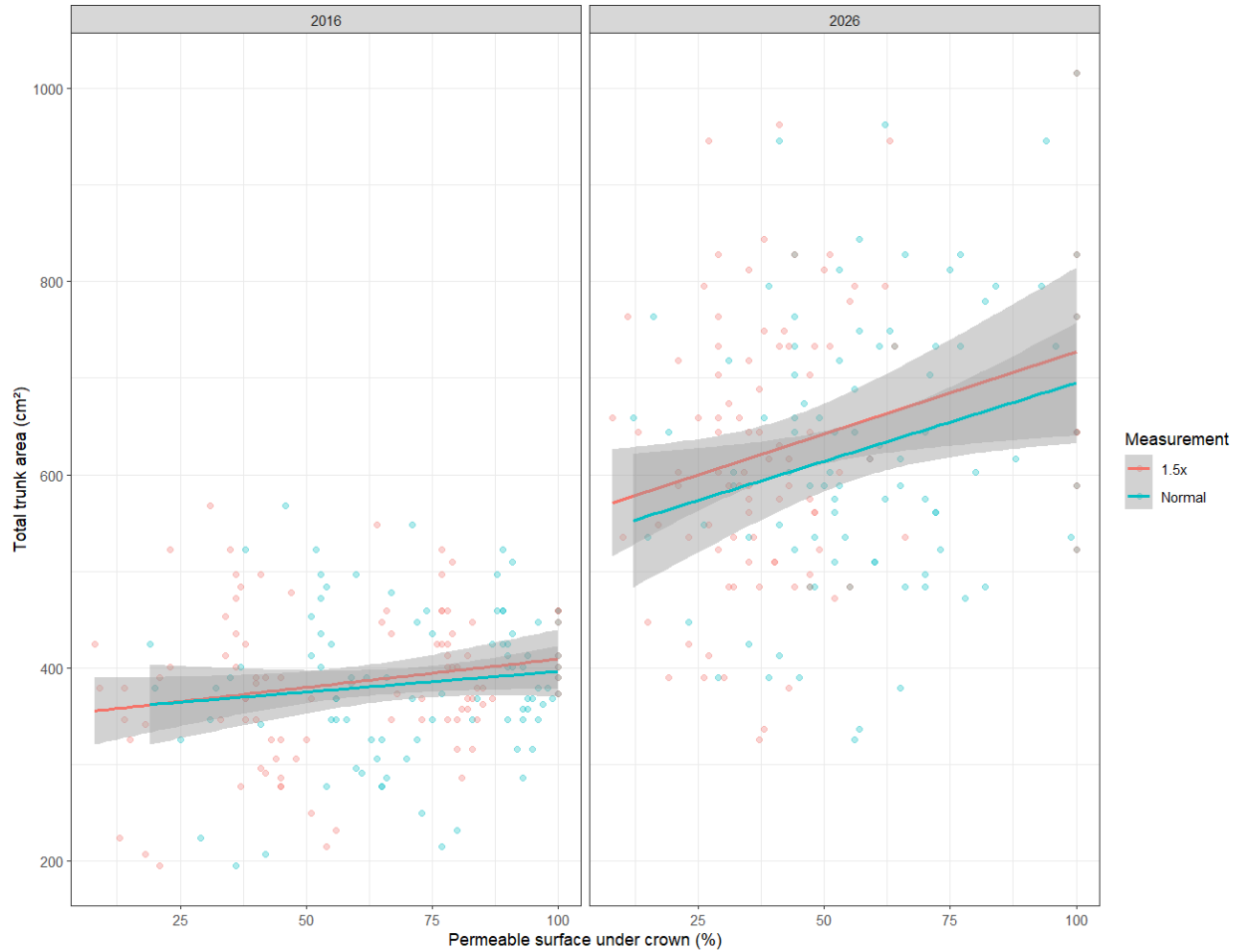


Fig. 4. Total basal area in 2016 and 2026 as a function of percent of permeable surface under the crown. (cm²). Blue points and lines relate to the permeable area below projected crown area, red points and lines relate to an area with size of 1.5 x projected crown area. 95% confidence intervals are highlighted in gray.

Crown-to-basal area ratio

A consistent negative trend in the ratio of projected crown surface area to total basal area as a function of permeable ground surface is observed across both time points (Fig. 5), indicating that trees with greater access to permeable ground have proportionally smaller crowns relative to

their trunk size. This structural pattern somewhat held across both periods, with P-values of 0.070 and 0.032 (Normal and 1.5x) in 2016 and 0.014 and 0.046 in 2026, with the relationship strengthening slightly over time. The R^2 values, while modest (ranging from 0.036 to 0.064), are comparable in magnitude to those seen in the basal area analyses.

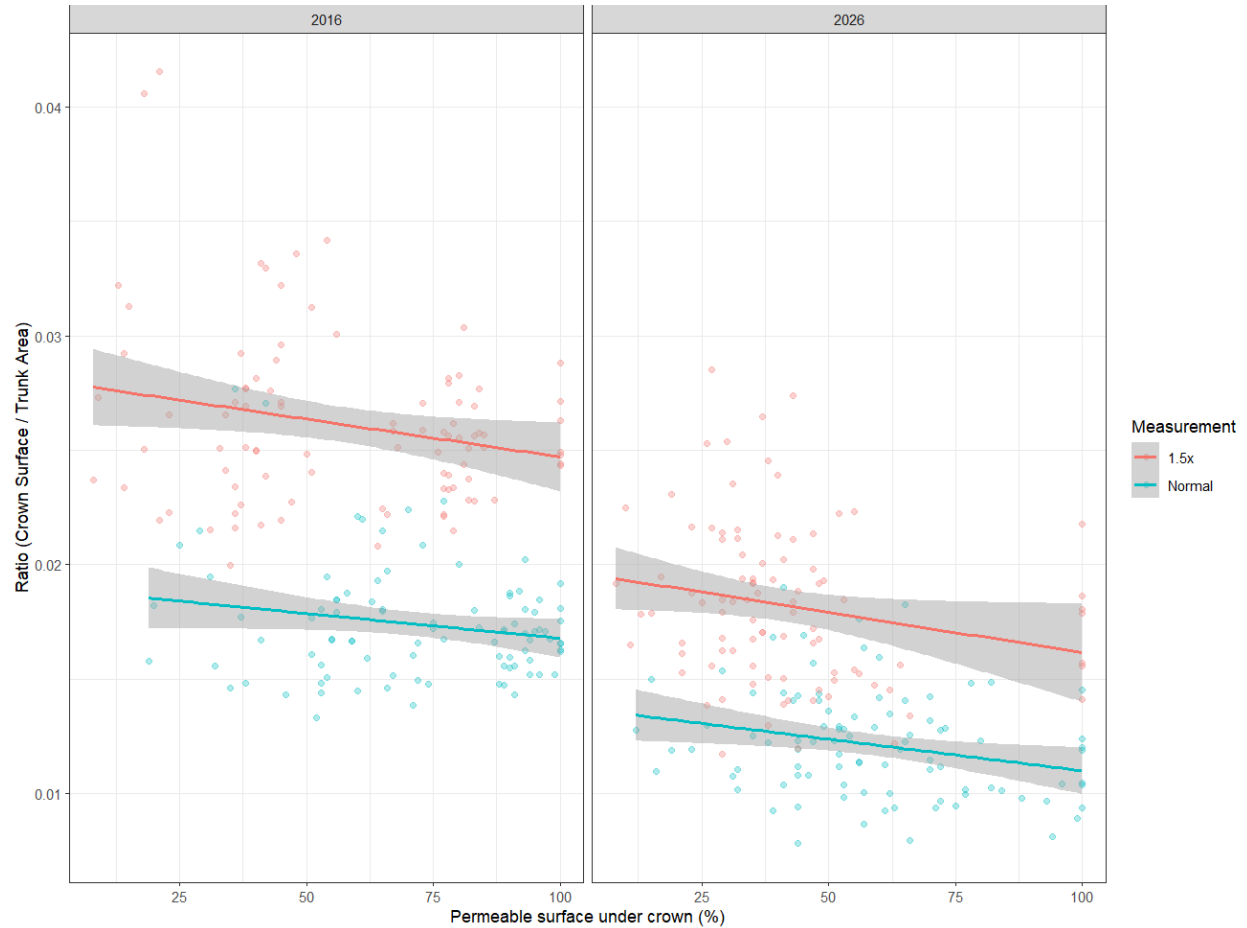


Fig. 5. Crown Surface / Basal area vs permeable surface in 2016 and 2026 (Unitless). Blue points and lines relate to the permeable area below projected crown area, red points and lines relate to an area with size of 1.5 x projected crown area. 95% confidence intervals are highlighted in gray.

Discussion

The Decoupling of Recent Yearly Growth from Ground Permeability

The initial findings by Sand et al. (2018) demonstrated that between 1999 and 2016, the fraction of permeable ground surface had a weak but statistically significant positive effect on the yearly diameter growth of *Tilia x europaea* street trees. However, the follow-up data from 2016 to 2026 reveals a distinct shift; Yearly diameter growth is no longer significantly tied to the presence of

permeable ground. This decoupling must be understood in the context of the trees' ontogeny and the shifting environmental dynamics of the site.

Foremost is the natural age-related decline in diameter increment. The average yearly diameter growth dropped from approximately 1.0 cm per year in the first period to 0.66 cm per year between 2016 and 2026. As trees mature and their absolute circumference increases, the same volume of annual wood production is distributed over a vastly larger surface area, naturally resulting in narrower radial increments. Furthermore, it is highly likely that the root systems of these trees, planted in 1999, are beginning to encounter the physical limitations of their 16 m³ growing boxes (a pit of 4 × 4 m, 1 m deep as described by Sand et al 2018). Two and a half decades later, the root networks have likely fully exploited these confined volumes (Watson et al., 2014). Analyzing yearly basal area growth, a two-dimensional cross-section and therefore a more accurate proxy for actual biomass addition and carbon sequestration, produced no statistically significant correlation with permeability during this period, even though the P-values were lower than for diameter growth.

Additionally, the period from 2016 to 2026 was characterized by intense urban development in the immediate vicinity, including the construction of a skyscraper and a new tram line. The installation of wooden bracing supports on many trunks, alterations to the surrounding surface substrates, and generalized construction stress likely introduced significant environmental noise/scattering into the growth data. This increased inter-individual variation in growth, visible in the wider scatter of the recent data, may have further diluted the localized signal of surface permeability on short-term diameter growth. This subtler connection suggests that the physiological benefits of permeable ground, including better soil aeration, cooler below-ground temperatures, and increased moisture retention, may still be influencing absolute productivity in ways that the cruder diameter metric does not capture (Moser-Reischl et al., 2019). However, while there might be a relationship, the findings of this thesis were non-significant.

The 2016–2026 Climatic Context

The period between measurements was climatically exceptional in ways that would have independently compressed growth rates and introduced high inter-individual variability. Sweden faced its third consecutive year of drought in 2018, driven by low precipitation compounded by high summer temperatures severely straining water availability (Moravec et al., 2021). Sand et al. (2018) demonstrated that the contrast between the wet year 2015 and the dry year 2016 was sufficient to roughly halve current-year shoot growth across all permeability classes, and the 2018 growing season likely represented a more extreme point along this same spectrum. Research on Nordic forest ecosystems confirmed that the 2018 drought drove a 40–60% reduction in mean surface conductance, with soil water deficits particularly severe across southern Sweden including the Gothenburg region (Lindroth et al., 2020). Under such conditions, the signal of surface permeability on short-term diameter growth may not disappear because permeability has become irrelevant, but because all trees regardless of permeability class

were driven toward a shared physiological ceiling imposed by water deficit. A convergence at low growth rates that is ecologically distinct from decoupling driven by root space exhaustion, and the two mechanisms are not mutually exclusive. Similarly applying dendrochronological analysis to street trees at highly sealed urban sites in Dresden found that water availability during the preceding growing season was among the strongest determinants of radial growth, with the carry-over effect of prior-year conditions compounding across rings in a manner structurally analogous to the legacy effects observed during this study (Gillner et al., 2014).

Soil Volume Exhaustion as a Mechanistic Ceiling on Permeability Effects

Over the 27 years since planting, root networks have had ample time to fully exploit and likely surpass the boundaries of these confined volumes. Conflicts between urban trees and their surrounding infrastructure are particularly associated with trees older than 15 to 20 years, due to their roots reaching the edges of their planting pit and beginning to interact with surrounding compacted subgrade and sealed surfaces (Watson et al., 2014; Shi et al., 2023). Roots grow preferentially toward areas of higher oxygen and moisture concentration, and the permeability of the soil volume under surrounding pavement directly affects the extent to which roots can expand laterally beyond the original pit. When root systems are largely confined to a fixed volume, the mechanism by which surface permeability benefits trees' ability to access the rooting zone becomes progressively less relevant. A tree whose fine roots cannot extend further into the surrounding soil matrix cannot take advantage of the greater moisture that permeable surfaces allow to infiltrate beyond the crown projection area. Differences in soil oxygen and moisture between pervious and impervious pavements are often inconsistent when the surrounding soil is heavily compacted or the available rooting volume is restricted, suggesting that structural confinement can effectively neutralise the hydrological benefits of permeability (Johnson et al., 2019). This represents a distinct phase in the relationship between a tree and its planting environment where during establishment and early growth, permeability shapes root exploration and water uptake directly but once the root system has fully mapped the available soil volume, the functional constraint shifts from permeability to spatial availability of soil itself. The significant legacy effects visible in total accumulated basal area are thus best understood as the record of differential root establishment during the earlier, permeability-sensitive phase.

Legacy Effects and Total Cumulative Growth

The substantially steeper slopes in 2026 compared to 2016, despite wider confidence intervals, when looking at total basal area reflect the growing divergence in cumulative basal area between trees with low and high permeable surface access, a pattern consistent with compounding legacy effects of ground surface conditions over time.

The influence of an impervious surface on a tree's water budget and root environment does not reset annually but rather compounds over the lifespan of the tree (Sand et al., 2018; Konarska et al., 2023). Trees that benefited from high surface permeability during their critical establishment phase (1999–2016) were able to maximize root expansion, establish robust hydraulic

architecture, and capitalize on favorable early growing conditions. Consequently, even when yearly growth rates universally slowed down in the second decade due to spatial limitations or other stressors, the trees with highly permeable immediate environments retained their accumulated size advantage.

From a city planning perspective, this emphasizes that maximizing permeable surface area at the time of planting is a critical determinant of a tree's ultimate, long-term ecosystem service capacity, as early structural deficits cannot easily be compensated for later in the tree's life. Among the trees studied here, the ones in the top quartile of permeable surface access (mean 68% permeable within $1.5\times$ crown area) had accumulated 12.3% greater total basal area by 2026 than those in the bottom quartile (mean 22% permeable), corresponding to a mean trunk circumference of 92.5 cm versus 87.1 cm. A structural size advantage accrued entirely through differential growing conditions over 27 years of shared urban planting.

Biomass Allocation: The Crown-to-Trunk Ratio

The analysis of the crown-to-basal area ratio provides novel insights into how urban street trees allocate resources under varying environmental constraints. Across both measurement periods, a consistent negative trend was observed, namely that trees with greater access to permeable ground possess proportionally narrower crowns relative to their trunk size. This structural pattern strengthened slightly over time, suggesting a stable morphological response to the below-ground environment (Grabosky & Gilman 2004).

This ratio could indicate that trees with more abundant below-ground resources prioritize carbon allocation into permanent structural biomass, namely the trunk. However, it is crucial to interpret this morphological finding with a significant caveat; The dynamic nature of urban tree crowns. Unlike the trunk, which is a permanent and cumulative record of growth, the crown is highly transient. It is subject to environmental damage, branch shedding, and, most notably, human intervention. The data indicates that several tree crowns were actually smaller in absolute terms in 2026 than in 2016. This reduction is almost certainly an artifact of pruning necessary to maintain vehicular clearance, especially given the introduction of the new tram infrastructure. Because of this additional scattering in the data it's difficult to make definitive statements on the relationship, even if the trend appears mostly linear.

The Crown-to-Trunk Ratio as a Policy-Relevant Ecosystem Service Indicator

Beyond its physiological interpretation, the crown-to-trunk ratio carries direct implications for urban ecosystem service delivery. The finding that trees with greater access to permeable ground allocate proportionally more biomass to their trunks relative to their crowns suggests a morphological trade-off. A larger trunk represents a more significant carbon store and long-term structural investment, but it does not shade a pedestrian, intercept a rain event, or cool a street surface on a summer afternoon. Trees growing over predominantly impervious surfaces may appear to deliver greater canopy-based services in the short term, but the legacy effects analysis

demonstrates that their cumulative growth is suppressed, meaning they reach the canopy sizes needed for meaningful shade and transpiration more slowly and at a smaller ultimate scale. The crown-to-trunk ratio therefore reframes a morphological observation as a planning imperative where maximising permeable surface area around street trees is a measurable determinant of the canopy-based ecosystem services that cities are increasingly relying upon as heat wave frequency increases (Day & Amateis 2011).

Conclusion

This follow-up study set out to determine whether the positive relationship between ground surface permeability and stem growth identified by Sand et al. (2018) had persisted a decade on. The signal has not disappeared, but it has migrated from yearly growth increments, where it is no longer statistically detectable, to total accumulated basal area, where it has strengthened and reached clear significance by 2026. Trees in the top quartile of permeable surface access had accumulated 12.3% greater total basal area compared to those in the bottom quartile, a divergence arising entirely from differential growing conditions over 27 shared years of urban planting. These findings reinforce the conclusion that maximising permeable surface area at planting is a foundational determinant of a street tree's long-term structural development, whose consequences are still accumulating decades after the paving decisions that set them in motion

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Appendix.

Table A1 Summary of the correlations shown in the figures

Model	N	Slope	R2	P-value
Diam growth 1999-2016 normal	93	0.00106	0.0288	0.104
Diam growth 1999-2016 1.5x	93	0.00132	0.061	0.017
Diam growth 2016-2026 normal	93	0.00067	0	0.954
Diam growth 2016-2016 1.5x	93	0.000515	0.002	0.668
Area growth 1999-2016 normal	93	0.0276	0.0187	0.191
Area growth 1999-2016 1.5x	93	0.0370	0.0451	0.041
Area growth 2016-2026 normal	93	0.0450	0.0079	0.397
Area growth 2016-2016 1.5x	93	0.0629	0.0142	0.256
Total area 2016 normal	93	0.425	0.0146	0.248
Total area 2016 1.5x	93	0.584	0.0372	0.0642
Total area 2026 normal	93	1.62	0.0592	0.0188
Total area 2026 1.5x	93	1.70	0.0597	0.0182
Crown/Basal area ratio 2016 normal	93	-0.00022	0.0356	0.07
Crown/Basal area ratio 2016 1.5x	93	-0.00033	0.0498	0.0316
Crown/Basal area	93	-0.00028	0.0644	0.0141

ratio 2026 normal				
Crown/Basal area ratio 2016 1.5x	93	-0.00035	0.0429	0.0464