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Research article

Exploration of potential ecosystem service trade-offs when establishing trees in different urban substrates

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A B S T R A C T

Urban trees are expected to contribute to increased urban resilience, as part of multifunctional installations, and under a wide range of environmental conditions. Ideally, such installations should be beneficial both for trees and cities. The aim of this experiment was to increase our understanding of the effects of different substrates used in urban tree plantings. Two stone-based structural soils, one pumice-based planting substrate and a traditional horticultural mix were installed in 1 m^3 containers, with one tree of *Tilia x europea* 'Kristina' in each container, in a factorial design with eight replicates per substrate. Half of the trees were treated with a mycorrhizal inoculum. Total height, shoot growth, leaf area and colour, and stem growth were monitored the first two years after planting, and leaf C, N, δ^{13}C and δ^{15} were analysed in the second year. Soil characteristics were determined using measurements of runoff water quality as well as water infiltration capacity and drainable porosity. The study revealed a trade-off between plant performance and multifunctionality, with the horticultural mix resulting in mean shoot growth rates up 2.5 times higher, and a 64 % greater stem base after two growing seasons. It also had the healthiest leaf colours and a significantly higher mean total height (349 cm) than both structural soils (304 and 257 cm, respectively) but slower infiltration rates. The pumice-based substrate had a mean total height of 320 cm and the highest field capacity. Awareness of substrate characteristics and consequences for plant vitality, is important for building sustainable and resilient cities. The results indicate that installations of multifunctional substrates can have stormwater management benefits but might demand more management to maintain tree vitality.

1. Introduction

Urban trees improve climate resilience, sustainability and human wellbeing in urban areas by providing a suite of necessary ecosystem services (Wang and Akbari, 2016; van den Bosch and Sang, 2017; Gotsch et al., 2018). However, their potential to provide these needed ecosystem services is often compromised due to challenging growing conditions, commonly resulting in poor tree establishment and reduced long-term vitality (Koeser et al., 2014; Roman et al., 2014). One of the main causes for this are challenging below-ground conditions (Day and Bassuk, 1994; Jim, 2017). Soil quality is often low, and there is often a lack of rooting space due to high compaction levels (Czaja et al., 2020). Soil compaction and street pavement cause imperviousness, leading to low water infiltration rates and storage capacity (Grey et al., 2018). These conditions commonly result in soils with low water availability and low nutrient levels, which hamper tree establishment and prevent healthy tree growth (Day and Bassuk, 1994; Levinsson et al., 2024).

To improve urban tree planting sites, different types of constructed urban soils, so-called engineered substrates, can be used (Scharenbroch et al., 2018). Historically, engineered substrates have been designed with a primary focus on supporting vegetation vitality, using horticultural or planting substrates. More recently, focus has been placed on multifunctionality, with substrates designed to support heavy overlying infrastructure ("structural soils") and/or short-term water storage (structural soils, pumice-based planting substrates, rain garden substrates). However, the capacities of these more recently pioneered engineered substrates to support tree health and vitality has not yet been well explored (Livesley et al., 2016; Hanley et al., 2024).

Structural soils were developed in the early 1990's with the aim of increasing tree pit size for street trees growing in dense urban areas. These systems consist of a load-bearing structure of coarse stones, and an engineered root-friendly substrate, typically a horticultural substrate mix, in the voids in between the stones (Grabosky and Bassuk, 1995). The purpose of structural soils is to physically support aboveground infrastructure while at the same time enabling root growth in volumes that would otherwise be completely compacted and unavailable for roots. Structural soil can be installed under traffic lanes and pedestrian areas without jeopardising the integrity of the hard surfaces above. Thus, installation of structural soils opens up the possibility for long-term tree growth in tight locations with limited rooting space

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(Bartens et al., 2009; Bühler et al., 2017). When Grabosky and Bassuk (1999) compared tree performance of *Tilia cordata* in structural soils vs. compacted mineral soils during the first years after planting, both shoot and stem growth were higher in the structural soils. It has also been shown that the performance of two oak species in structural soils was similar to those grown in non-compacted tree lawn soil, both in the short-term (Grabosky et al., 2002), and over the longer-term (Grabosky and Bassuk, 2016).

Only a few studies have compared different types of structural soils (Ow and Ghosh, 2017; Scharenbroch et al., 2018). In a comparison between a structural soil and structural cells (a load-bearing plastic structure with almost 95 % of soil volume in the structure's interspace), both including a clay sand mixture substrate, Ow and Ghosh (2017) found that tree performance was better in the structural cells. They suggested that the reason was the higher volume of root-available substrate in the cells as compared to the structural soil. They found similar results in a second study including two structural soils, structural cells and a conventional horticultural substrate, where trees in the structural cells outperformed the other three treatments (Ow et al., 2018). However, all structural varieties showed higher growth rates than the conventional soil in the study In contrast to their findings, Scharenbroch et al. (2018) found that tree health was highest in a horticultural substrate, as compared to both sand- and rock-based structural soils in a long-term study of the development of engineered urban substrates.

Today, the use of structural soils is increasingly prescribed by urban tree managers and cities, and examples of such constructions can be found in several European cities, both where load-bearing capacity is needed and where it is not (Alvem and Embrén, 2017; Murer and Schmidt, 2019). To some extent, structural soils have replaced the use of more traditional horticultural substrates, such as the sand-clay mixture that has traditionally been the standard in Sweden, called AMA A. One major factor behind this shift of paradigm is the recognition that lack of aeration in the rhizosphere is a primary cause of tree failure for urban trees, and the conception that the use of structural soils ensures a better gas exchange in the rooting zone (Bretzel et al., 2020).

Meanwhile, new recipes with different sizes of the structural stones, as well as different mixtures of substrates filling the interstitial voids, are continually being developed by tree managers. There is currently no consensus regarding to which degree the voids should be filled or unfilled to assure sufficient aeration. Over time, there has been a tendency in Europe towards less filled voids, and the original clay loam soil (Grabosky and Bassuk, 1995) is commonly being replaced with various fractions of organic-rich compounds like compost and more recently, biochar (Alvem and Embrén, 2017; Murer and Schmidt, 2019), which is considered a more stable organic amendment (Piccolo et al., 2022). Although several studies have shown increased tree growth when biochar was included in urban soil mixtures (e.g. Ghosh et al., 2015; Somerville et al., 2020) other studies have shown mixed results and, in some cases, biochar may cause negative changes in soil properties and plant health (Mukharjee, 2014).

The goal of the development of new substrate recipes is fundamentally to support tree health by improving aeration and nutrient availability, but also increasingly to aid in climate adaptation by providing below-ground storage for water (Richter et al., 2024) to reduce pluvial flooding and combined sewage overflow following heavy rainfall. Substrates engineered for stormwater performance must allow for rapid infiltration and include sufficient storage volume (Szota et al., 2018). Pumice and similar volcanic porous aggregates that have a long tradition in horticultural production have therefore become increasingly used in urban settings where sustained infiltration combined with high water holding capacity is needed (Boertje, 1995; Gizas and Savvas, 2007). Using these types of aggregates has been seen as a potential avenue to simultaneously maintain rapid infiltration and ensure sufficient water-holding capacity, which is conducive to tree development.

Another consideration in determining appropriate urban substrate characteristics, is the potential for trade-offs between tree growth and stormwater quality, since the use of horticultural substrates in the planting pits could result in increased nutrient runoff, increasing the risk of eutrophication further down the stormwater pathway (Hobbie et al., 2017). Such effects have been observed for other urban nature-based solutions such as rain gardens (Guo et al., 2019) and green roofs, which can serve as a source of dissolved nitrogen and especially phosphorus in runoff for many years following construction, if built with nutrient-rich substrates (Buffam and Mitchell, 2015; Mitchell et al., 2017).

There is also an increasing interest in the inclusion of mycorrhiza in urban tree plantings, as a means to improve growing conditions and tree vitality by augmenting nutrient acquisition. Mycorrhizal symbiosis has been observed in urban environments (Van Geel et al., 2019; Tyburska-Wo's et al., 2024; Khalid et al., 2024), although in some studies, not to the same extent as in natural conditions (Nielsen & Rasmusen, 1999; Bainard et al., 2011; Chen et al., 2021) Furthermore, there has been limited *in situ* research of mycorrhiza and their interaction with urban trees (Authier et al., 2022), and with mixed results (Garbaye et al., 1999; Appelton et al., 2003; Rewald et al., 2015).

In summary, engineered substrates have been identified as potentially playing a fundamental role in both the performance of stormwater management systems and vitality improvement of trees in urban planting pits (Smith et al., 2023). However, significant knowledge gaps persist regarding the effects of substrate design on performance (Jones et al., 2021), particularly since previous research has focused on tree development in first-generation structural soils, which differ from the substrates currently being installed in many cities. Furthermore, conditions for optimum tree development might not coincide with those for stormwater management, showing a need to study both perspectives in the same study, as multifunctionality is increasingly expected from tree installations. The objective of this study is thus to enhance our understanding of the functionality of engineered urban substrates, with a focus on those currently employed in tree pits in Swedish cities.

We carried out a two-year controlled experiment using replicated mesocosms to explore the combined effect of two factors; the physical makeup of four different engineered substrates, and the presence/absence of mycorrhizal fungal inoculum. We specifically addressed the following research questions: (a) How is the development and vitality of a common street tree (Linden, *Tilia* x *europea* 'Kristina') affected by the substrate type during the first years of establishment?; (b) How do the different substrates perform with respect to stormwater management, particularly focusing on water infiltration, total drainable porosity and

Table 1
The substrates included in the experiment. AMA A - AMA (Hasselfors, AMA DCL.11/1), Pumice -PU (Baramineral ©), Stone-mix - SM (Hasselfors ©), and Rock-mix - RM (mixed on site).

Substrate	AMA A (AMA)	Pumice (PU)	Stone-mix (SM)	Rock-mix (RM)
Structure	Sand	Pumice	Crushed rock	Crushed rock
(% by volume)	60–65	70	100	100
Size of structure (mm)	0.06–2.0	2.0–8.0	32–90	100–150
Compost (% by volume)	–	30	7.5	7.5
Biochar (% by volume)	–	–	7.5	7.5
Clay content (% by weight)	5.0–15	–	<5	–
Peat content (% by dry weight)	5.0–8.0	–	–	–
Bulk density (kg/m3)	Ca 1250	Ca 400	Ca 1700	–
pH	5.5–7.5	7–7.5	6.0–8.0	–
Conductivity	1.5–4.0		>2.0	–
Fertilizer	Long-acting natural	–	Long-acting natural	–

Fig. 1. The four different substrates, immediately after the planting of the trees and the installation of irrigation bags. Upper left is AMA, upper right is PU, lower left is SM and lower right is RM.

substrate characteristics?; (c) How is the runoff water quality influenced by the chosen substrate?

2. Materials and methods

2.1. Experimental setup

The experiment was set up at the campus facilities at the Swedish University of Agricultural Sciences, Alnarp (55°40′ N & 13°03′ E), in the spring of 2022. 32 one m^3 large, reconditioned IBC plastic (high-density polyethylene) containers with an outer steel construction for stability and a removed top were used in the experiment. The containers were placed on pallets and had an outlet spigot at one of the sides near the bottom. A drain tube (approximately 1.5 m) was placed in the bottom of the containers and perforated plastic pipes were installed to enable water measurements.

Four different types of substrates were installed in the containers by filling them up to the 1000 L indication mark. The substrate mixes included in the study were labelled: AMA A (AMA), pumice (PU), "stone-mix" (SM), and "rock-mix" (RM) (Table 1). The AMA A substrate is a constructed engineered soil as specified in the Swedish reference manual for building products and processes (AMA anläggning 23, 2023). The substrate is designed as a general planting soil for normal conditions (Fig. 1). The pumice substrate (PU) is a substrate aimed at tree plantations in dense urban areas, and it contained 70 vol% pumice (2–8 mm) and 30 vol% compost. PU is used as a more aerated alternative to the traditional horticultural mix (AMA), constructed to be used where rooting space is limited, and stormwater could be detained. The "stone-mix" (SM) substrate contained crushed stone fragments of size 32–90 mm with 7,5 vol% uncharged biochar and 7,5 vol% compost. SM has been developed from a need for onsite direct installation of structural soils, and has been referred to as the Stockholm system (Ow et al., 2018). The Rock-mix (RM) is an adaptation of the traditional structural soil and consists of large angular rocks and rock fragments of size 100–150 mm. The rock matrix is filled with 7,5 vol% uncharged biochar and 7,5 vol% compost. SM and AMA were produced by Hasselfors©, while PU was produced by Bara Mineraler©, as were the unfertilized biochar and the compost used in RM. The rocks in RM were sourced from Ågab Syd. The biochar was EBC-certified (European Biochar Certificate) and produced from wood chips and by-products from the forestry industry from broadleaved trees, pyrolyzed at 750 °C or higher. Since the SM, PU, and AMA substrates were pre-mixed by the suppliers, we filled them directly into the containers upon delivery. The RM substrate was mixed on site, by filling the containers with rock fragments in size 100–150 mm, biochar and compost in five layers. We put in 200 L of rock fragments, then 15 L of biochar and 15 L of compost, which we sprinkled down into the voids in between the rocks, and repeated this five times until there were 1000 L of rock fragments and 75 L of biochar and 75 L of compost in the container. We used a best management approach when installing the substrates, meaning that compaction of the non-structural substrates was avoided, except from what occurs due to gravity and as a result of irrigation.

The selection of substrates was based on different types of structural and aerated soils currently being used in major cities in Sweden. AMA A is the traditional soil that is used when structural soils are not included, and is the Swedish standard prescribed soil for normal conditions (AMA DCL.11/1).

On April 22nd, 2022, one 2-year-old *Tilia* x *europea* 'Kristina' E was planted in each of the 32 containers. The plants were micro-propagated and then field grown at a local nursery (average height 194 cm, SD 10) and were delivered bare-rooted, to reduce influence from the nursery's soil on the results. This variety was selected for the experiment to ensure minimal intraspecific variation while still growing on its own roots (i.e. not grafted onto another rootstock). The trees were taken from cold storage at the nursery the morning of planting, and the roots were kept protected under moist cloths to avoid dehydration during the planting day.

The experiment had a full factorial block design, with eight replicates for each substrate; two in each of the four blocks. One of the two substrate replicates within each block was inoculated with ectomycorrhiza at planting (MycorDip Pt, Plant Health Cure B.V.), so that half of the pots in each block included mycorrhiza. *Tilia* x *europea* is both an ectomycorrhizal and arbuscular forming tree species, where ectomycorrhizal symbiosis is more studied (Dudka et al., 2023). The treatments were randomised within each block.

We measured total height and diameter at stem base, and estimated root weight by dipping the root system in a bucket of water placed on a scale, after which they were immediately planted, either directly into the substrate, or following a submerging in the mycorrhiza solution that had been prepared beforehand. To prepare the inoculation, mycorrhiza-powder (MycorDip Pt, Plant Health Cure B.V.) was stirred in a bucket of water with the proportion of 10.6 g/l until it was completely dissolved and had a smooth, firm consistency. The ingredients in MycorDip Pt are: Ectomycorrhiza (*Pisolithus tinctorius* 400,000 spores/gram *Sleroderma citrinum* 41,888 spores/gram) 0.3 %, Rhizobacteria 3 %, Polyacrylate gel 53 %, Seaweed extract 4.5 %, Humic acid 23 %, Maltodextrin 2.3 %, Citric acid 1.4 %, Yeast extract 0.6 % and Inert ingredients 11.9 %. The trees were then secured upright to stakes and one 75 l irrigation bag was installed in each container. The irrigation bags were filled twice a week from the start of the planting until September. Thereafter, they were filled once a week until leaf fall. The following year, the irrigation bags were filled once a week throughout the growing season.

2.2. Measurements

2.2.1. Tree development

In early September 2022 and 2023, we measured the length of the top shoot and the three longest shoots on each plant, together with stem base diameter. We also measured midday stomatal conductance (g_s) on one leaf per plant on a day following an irrigation day, to investigate if there were differences in water uptake capacity.

Average individual leaf area was determined by collecting five representative leaves from each plant, which were immediately stored in plastic bags in cooler bags, then in the refrigerator for one day before further analyses. The leaves were scanned individually together with a ruler as a reference and saved as PDF files with 1200 dpi. The images were then imported into ImageJ (ImageJ 1.53t), and a macro was written to set scale and run for every image. Thereafter, leaf colour was determined by adapting a protocol macro from Strock (2021). We set a threshold to determine the area to be measured, i.e. the leaf, separated the image depending on colour channel, and measured each colour channel. We used the colour coding CIE LAB, which stands for: L = lightness, A = red-green and B = yellow-blue. We used CIE LAB, as it has been shown that it correlates with leaf nitrogen content and leaf chlorophyll content, where high nitrogen content is negatively correlated with yellow colour (Wang et al., 2014).

The leaves collected for leaf area in 2023 were also used for nutrient analysis. After the leaves were scanned for leaf area, they were dried in a drying cabinet (Thermo Scientific Heratherm Advanced Protocol Oven, Heratherm OGS400) at 70 °C for 72 h. All five leaves from each tree were pooled and pulverised using a grinding mill (Foss Cyclotec 1093) and analysed for % Carbon, % Nitrogen, $\delta^{13}C$ and $\delta^{15}N$ at SLU's Stable Isotope Laboratory (Department of Forest Ecology and Management, SLU Umeå) using a Flash EA 2000 elemental analyser coupled to a DeltaV isotope ratio mass spectrometer (Thermo Fisher Scientific, Bremen Germany). The leaf N content and C:N ratio can be used as an indicator of plant stress including the relative supply of plant-available nitrogen in the root environment (Aerts and Chapin 1999; Wright et al., 2001). Leaf $\delta^{13}C$ commonly varies with water use efficiency and can give an indication of environmental stress or soil organic matter properties (Dawson et al., 2002), while leaf $\delta^{15}N$ can give an indication of the source of N (Craine et al., 2015), in particular discriminating between organic and inorganic sources (Bateman et al., 2007).

2.2.2. Water infiltration, total drainable porosity and substrate characteristics

A subset of containers was used to estimate the physical characteristics of the installed substrates. We randomly selected one container for each substrate, excluding the ones with mycorrhiza. We focused on the water flow through the substrates and drainable porosity, as it was impossible to dry the entire containers to access dry weight. We filled the containers from the bottom outlet to avoid problems with trapped air in the substrate. The water volume was measured using a digital water meter (Gardena Water Meter AquaCount). The containers were filled to the 1000 L mark and the water volume was noted. Since the substrate had settled and sunk a bit, we released water out until it was level with the substrate surface and noted the water volume again. This gave us the total substrate volume of the different substrates, as well as the realised substrate compaction for each container. We let the rest of the water out with the water meter still installed as long as there was a continuous flow. The water meter was disconnected when the flow became too low to measure accurately, and we collected the remainder of the draining water with buckets, and measured the volume. This entire process was repeated three times per container. Concurrently, the water level was measured in perforated pipes descending to the bottom of the containers, with a duplicated system using (1) a ZL6 Meter logger with a CTD-10 pressure transducer and (2) an Odyssey Xtreem Capacitance Water Level Logger. The ZL6 logger recorded data at a 5-min interval and the Odyssey integrated logger at a 1-min interval. Finally, the Odyssey water level data was used to calculate the time for release of 90 % of the drainable water from the system, with drainable water being equal to total water content minus field capacity. The total drainable porosity was calculated as the amount of water that was released from saturation to field capacity, expressed as a fraction of total substrate volume.

Mean gravimetric water content was determined through surface soil samples in triplicate when the soil was at field capacity. Soil samples were oven dried until constant weight at 105 °C in a drying cabinet (Thermo Scientific Heratherm Advanced Protocol Oven, Heratherm OGS400).

2.2.3. Runoff water quality

During each of the first two growing seasons, on July 12th, 2022, and again on July 27th, 2023, we measured the concentration of dissolved nutrients in runoff from the plots. The rationale for making these measurements was three-fold: first, as a rough indicator of nutrient availability, where very low concentrations of nutrients in runoff may indicate nutrient limitation for the tree; second, to determine if the addition of mycorrhizal inoculum had any measurable impact on nutrient retention; and third, as an indicator of potential nutrient leaching, which could negatively impact downstream water bodies when implemented at scale. The target parameters included dissolved organic carbon (DOC), total nitrogen (TN), dissolved organic nitrogen (DON), and the dissolved inorganic nutrients ammonium (NH_4^+), nitrate (NO_3^-), and orthophosphate (PO_4^{3-}). Water was collected from the downspout of each of the plots between 2 and 5 h after the initiation of irrigation with the 75 L irrigation bags, at which point 50 % or more of the irrigation water had already been applied to most plots, and the runoff was still actively flowing. This approach was designed to collect representative runoff water quality, avoiding the first flush immediately after runoff starts. Water samples were collected in pre-cleaned polypropylene containers, then transferred to pre-cleaned high-density polyethylene (HDPE) bottles and refrigerated. Subsamples were preserved within 24 h by filtration (0.45 μm PES filter, Agilent Captiva) and frozen until analysis, together with samples of the irrigation water as a control. Samples were analysed at SLU's Biogeochemical Analysis Laboratory (BAL) in Umeå, Sweden. DOC and Total Nitrogen (TN) were analysed using a Shimadzu TOC-V_{CPH} analyser coupled to a Shimadzu TNM-1 nitrogen detector, while NH_4^+, NO_3^- and PO_4^{3-} were analysed using standard spectrophotometric techniques using a SEAL analytical AutoAnalyzer 3 (SEAL Analytical, Wisconsin, USA).

2.3. Statistical analyses

2.3.1. Univariate analysis

All univariate analyses were performed using R with the following libraries: lme4 (Bates et al., 2015), lmerTest (Kuznetsova et al., 2017) and emmeans (Lenth, 2021) with ggplot2 for graphics (Wickham, 2016). Response variables were grouped into three main categories: Tree development (Stem diameter, Height, Shoot length, Leaf area, g_s after watering); Nutrient runoff (DOC, TN, PO_4^{3-}, NH_4^+, NO_3^-); and Leaf nutrients (N, $\delta^{15}N$, C, $\delta^{13}C$, C/N) each containing five response variables. Each response was modelled using linear mixed-effects model with the function lmer. For Nutrient runoff and Tree development, the fixed factors were Substrate (4 levels), Myko (2 levels) and Year (2 levels) including their interactions. The random part of the model was Block with PlotID nested within the block i.e (1|Block/PlotID). For the Leaf nutrients, which were only measured in 2023, the fixed factors were Substrate (4 levels) and Myko (2 levels) including their interactions, with Block as random effect. The significance of the effects was tested with Type II ANOVA using Kenward-Roger's approximation of the degrees of freedom, within package lmerTest. The alpha value for each ANOVA of the five models within each main category was set to a target p-value at 0.01 ($p = 0.05/5 = 0.01$) due to the multiple models tested within each category. To test the effect of the random part of each model the ranova function was used, which drops each random-effect term from the model and tests its influence using likelihood ratio tests. When necessary to fulfil the model assumptions, the response variable was log-transformed. Model assumptions were verified by plotting the residuals from the model. Due to strong effects of Year as well as interaction effects between Substrate and Year, post hoc testing was done as pairwise comparisons within each Year using Tukey's correction for multiple testing with a significance level of 0.05. Running the models as individual linear effects models for each year did not change the main results of the analysis.

The soil and drainage related variables were analysed with a One-way analysis of variance (ANOVA) comparing treatment means across the four substrate types (AMA PU, SM, and RM). Data was tested for normality and homogeneity of variance using Shapiro-Wilk and Levene tests. The data on drainable porosity was log-transformed when needed. All other variables met model assumptions without need for transformation. Tukey's HSD test was used for pairwise comparisons among materials for each variable, with the significance level set to $p < 0.05$.

2.3.2. Multivariate analysis

All multivariate analyses were performed using R with the library vegan (Oksanen et al., 2019). Exploring the relationship between the LAB values of L = lightness, A = red-green and B = yellow-blue revealed very strong correlations between LAB L and LAB B, with coefficients above 0.9 for both rank (Kendall) and linear (Pearson) based methods. Therefore, LAB L was excluded and only LAB A and LAB B were used in the following analyses. The correlation between leaf N and LAB reported by Wang et al. (2014) was evaluated using a Pearson correlation test. To explore the relationship between all the different variables measured, we then for each year performed a correlation-based Principal Component Analysis (PCA) on the Tree development variables of Stem diameter, Height, Shoot length, Leaf area and g_s, as well as the indicator variables LAB A and LAB B. We then applied the 'envfit' (environmental fit) function in vegan to each PCA using the Nutrient Runoff and Leaf Nutrients (in 2023) as explanatory environmental variables. This post hoc function of the ordination reveals possible environmental correlations without constraining the ordination, where correlation significances are based on permutations test of the goodness of fit statistic from the squared correlation coefficient. To visualise significant treatment variables in each year, we plotted them with 95 % confidence areas on the unconstrained PCA plots.

3. Results

3.1. Tree development

The univariate analysis showed significant differences between the substrates in all the measured tree development parameters (Table 2). There were also significant differences between the years for every parameter, except leaf area.

In 2022, the trees in the AMA substrate had greater stem diameter-, height-, shoot- and leaf area growth than in the RM substrate (Fig. 2). Mean shoot length was approximately 2.5 times longer in AMA (64.0 cm) than in RM (25.4 cm), and significantly longer than in SM (41.8 cm). The trees in the AMA treatment also had on average a 47 % larger stem diameter, were 18 % higher and had a 28 % larger leaf area than RM. The other treatments were intermediate and did not differ significantly from either AMA or RM in stem diameter or height. AMA and SM had significantly higher mean leaf area (111.6 and 106.3 cm^2 respectively) compared to RM (71.6 cm^2). In 2023, the differences in tree development between the substrates showed similar patterns as in 2022 but were somewhat more pronounced. RM had significantly lower mean values in all growth parameters than all the other treatments, except in leaf area, where RM (66 cm^2) was only significantly smaller than AMA (99 cm^2). Mean shoot length was again almost 2.5 times longer in AMA (80.5 cm) than in RM (33.3 cm) but not significantly longer than either PU or SM at 77.3 and 63.1 cm, respectively. Mean stem diameter was 64 % greater in the AMA treatment than in RM, and significantly greater than in PU and SM by 11 % and 18 %, respectively. However, PU and SM were also significantly greater than RM. In mean total height, AMA and PU were comparable (349 and 320 cm, respectively), and significantly higher than both SM (304 cm) and RM (257 cm).

Stomatal conductance (g_s) measurements showed slightly different results compared to the other tree development parameters, with SM having the lowest values both years, indicating that transpiration rates were lowest in that treatment. However, in 2022 it was only significantly lower than AMA, and in 2023, not significantly separated from PU.

There were no effects of mycorrhiza, or any interaction effects between mycorrhiza and substrate. As can be seen in Table 2, there was a tendency ($P = 0.029$) in the analyses of stomatal conductance where the non-inoculated plants showed a higher conductance than the inoculated ones. However, when studying the data, a few measurements with extreme values for one of the years exerted large leverage on the analysis.

3.1.1. Leaf nutrients

The measurement of leaf nutrient levels in 2023 showed significant differences in all tested elements as a function of substrate type (Table 3). Among substrate types, average leaf C content ranged from 48.2 to 49.4 %, N content from 2.0 to 3.0 %, $\delta^{13}C$ from −27.3–29.3 ‰, $\delta^{15}N$ from +1.8 to +5.0 ‰, and C/N from 16.4 to 24.1 g/g. Mycorrhiza-treatment did not affect the nutrient levels, and there was no interaction when testing substrate and mycorrhiza. Overall, RM had the lowest leaf nutrient concentrations and stable isotope ($\delta^{13}C$, $\delta^{15}N$) values. The trees in the PU-treatment showed the highest levels of leaf N, significantly separated from both AMA and RM (Fig. 3). SM did not differ from either AMA or PU, but had significantly higher values than RM. AMA had significantly higher leaf $\delta^{15}N$ levels than the other treatments, and PU and SM did not differ from each other, but were higher than RM. PU also

Table 2
ANOVA table for Tree Development variables stem diameter, height, shoot length, g_s (stomatal conductance) and leaf area. Bold font indicates significance at the set level of 0.01.

ANOVA	Tree Development		Stem D.		Height		Shot length		g(s)after		Leaf area	
Variable	Df_{num}	Df_{den}	F_{value}	p_{value}	F_{value}	p_{value}	F_{value}	p_{value}	F_{value}	p_{value}	F_{value}	p_{value}
Substrate	3	21	20.69	**<0.001**	11.68	**<0.001**	21.17	**<0.001**	7.126	**0.002**	6.95	**0.002**
Myko	1	21	0.53	0.474	0.79	0.383	0.01	0.998	5.484	0.029	0.04	0.847
Year	1	24	1244.7	**<0.001**	322.77	**<0.001**	25.49	**<0.001**	11.37	**0.003**	2.20	0.151
Substrate*Myko	3	21	0.50	0.684	1.01	0.408	0.79	0.514	0.07	0.974	0.95	0.433
Substrate*Year	3	24	51.08	**<0.001**	10.01	**<0.001**	1.96	0.147	1.45	0.253	0.28	0.837
Myko*Year	1	24	1.37	0.254	1.39	0.250	1.61	0.217	4.48	0.045	0.58	0.455
Substrate*Myko*Year	3	24	0.70	0.561	1.39	0.270	1.00	0.409	1.38	0.274	0.98	0.417
$ID*Block_{random}$				<0.001		0.001		1.000		1.000		1.000
$Block_{random}$				1.000		0.943		1.000		0.384		1.000

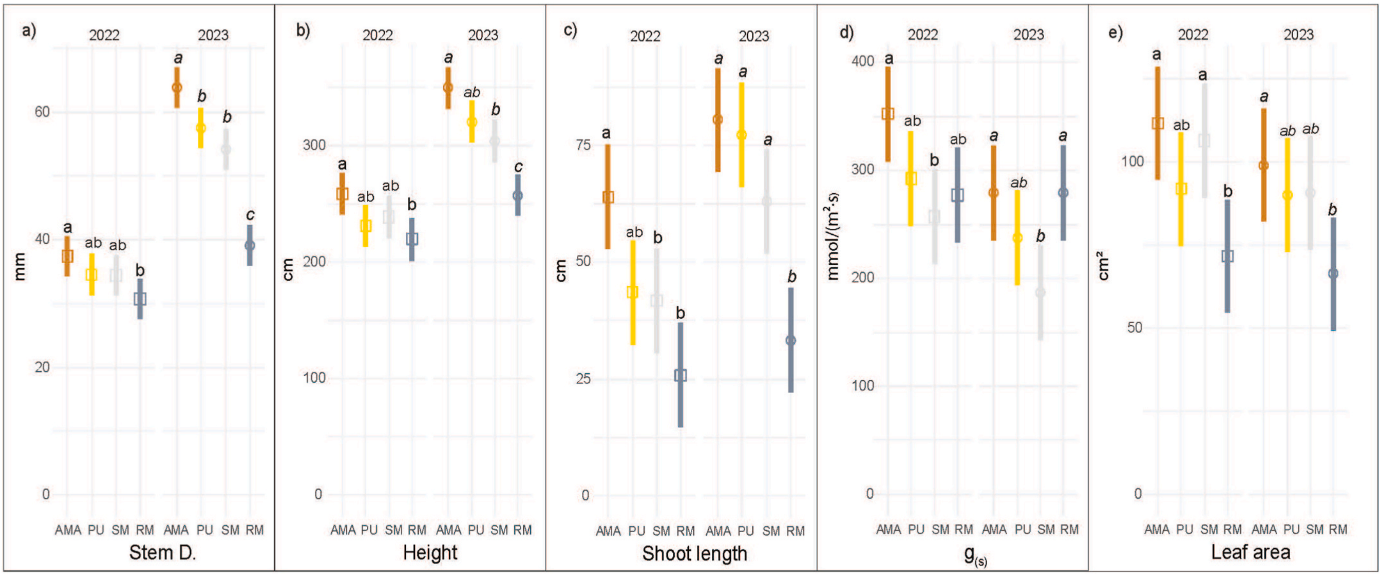

Fig. 2. Estimated marginal means per year with 95 % confidence interval for each Tree Development response and Substrate. Different lower-case letters indicate significant differences within the specific year. Note that there are different unit scales for each panel.

Table 3
ANOVA table for Leaf Nutrients. Bold font indicates significance at the set alpha level of 0.01

ANOVA	Leaf nutrients		N		$\delta^{15}N$		C		$\delta^{13}C$		C/N	
Variable	Df_{num}	Df_{den}	F_{value}	p_{value}	F_{value}	p_{value}	F_{value}	p_{value}	F_{value}	p_{value}	F_{value}	p_{value}
Substrate	3	21	13.55	**<0.001**	24.05	**<0.001**	4.90	**0.010**	8.22	**0.004**	19.30	**<0.001**
Myko	1	21	2.38	0.138	0.37	0.549	0.01	0.963	0.23	0.488	3.21	0.088
Substrate*Myko	3	21	0.16	0.950	1.42	0.265	0.59	0.626	1.82	0.300	0.11	0.954
$Block_{random}$				0.936		0.044		0.500		0.235		1.000

had the highest levels of leaf C, although only statistically separated from RM. RM had significantly more depleted leaf $\delta^{13}C$, and higher C/N, compared to the other three substrate types.

3.2. Water infiltration, total drainable porosity and substrate characteristics

The AMA substrate differed from all other substrates for all investigated variables (Table 4), except in water content at field capacity, where PU had a 55 % higher capacity than AMA, which had the second highest. In particular, AMA had significantly higher settling levels as compared to the other substrates. AMA had compacted more than 20 % on average, followed by PU and SM substrates. The RM substrate was most resistant to settling. A similar pattern was found in drainable porosity where AMA had the lowest values followed by PU and SM substrates. AMA also had the slowest flow of water through the substrate, with more than 2 h passing before 90 % of the total water volume had drained from the system.

3.3. Runoff water quality

There was a significant effect of substrate type and year on the runoff concentrations of all water quality parameters (Table 5, Fig. 4).

During the first year (2022), average runoff concentrations for the different substrate types ranged from 21 to 62 mg/L DOC, from 1.6 to 27.0 mg TN, from 1.4 to 3.2 mg/L P-PO_4^{3-}, from 0.0 to 1.8 mg/L N-NH_4^+, and from 0.3 to 23.9 mg/L N-NO_3^- (Fig. 4). Concentrations of DOC, TN, NH_4^+ and NO_3^- were substantially higher for AMA than for all the other substrate types except with DOC, where SM did not differ from AMA (Table 5). Furthermore, RM had consistently low concentrations of runoff nutrients, particularly for TN and NO_3^- which were significantly lower in RM than for all other substrate types. PU was characterised by intermediate concentrations of dissolved nutrients in runoff, while SM gave rise to the highest PO_4^{3-} in runoff, and intermediate concentrations of TN, NO_3^-, and NH_4^+.

All water quality parameters had significantly lower concentrations in the second year, except for NH_4^+ and NO_3^- for RM, which had already been very low in year 1. Between the two sampling years, DOC dropped on average by 12–43 %, TN by 18–92 %, PO_4^{3-} by 34–94 %, NH_4^+ by 17–65 % (except in the RM treatment), and NO_3^- by 28–99 % (except in the RM treatment).The effect of substrate type varied by sampling year (year * substrate interaction) for all water quality parameters (Table 4, Fig. 5). Specifically, TN, NH_4^+, and NO_3^- dropped substantially in the AMA substrate between 2022 and 2023 samplings, but only dropped moderately (SM) or stayed at already low values (RM) for the other substrate types. The drop in PO_4^{3-} was also much greater, in terms of percent change, for AMA relative to the other substrate types.

The effects of mycorrhiza ("myco") and associated interactions were not significant for NH4, PO_4^{3-}, TN, DOC or NO_3^-.

By year 2, water quality parameters in runoff from all four substrate types were similar in terms of the average concentration of dissolved organic carbon (DOC), which was high (19–36 mg/L) but likely not a particular water quality concern. Mean concentrations of dissolved inorganic N (DIN = NH_4^+ + NO_3^-) in runoff had dropped considerably, especially for AMA, and DIN losses were fairly low from all substrate types; though, there was still some appreciable leaching of NH_4^+ from AMA (0.6 mg/L), and NO_3^- from SM and PU (2.5 mg/L). Average PO_4^{3-} concentrations decreased over time for all substrate types, but remained high (0.9–1.8 mg/L P-PO_4^{3-}) from all substrate types except for AMA in 2023, which was very low (0.1 mg/L). In terms of avoiding nutrient

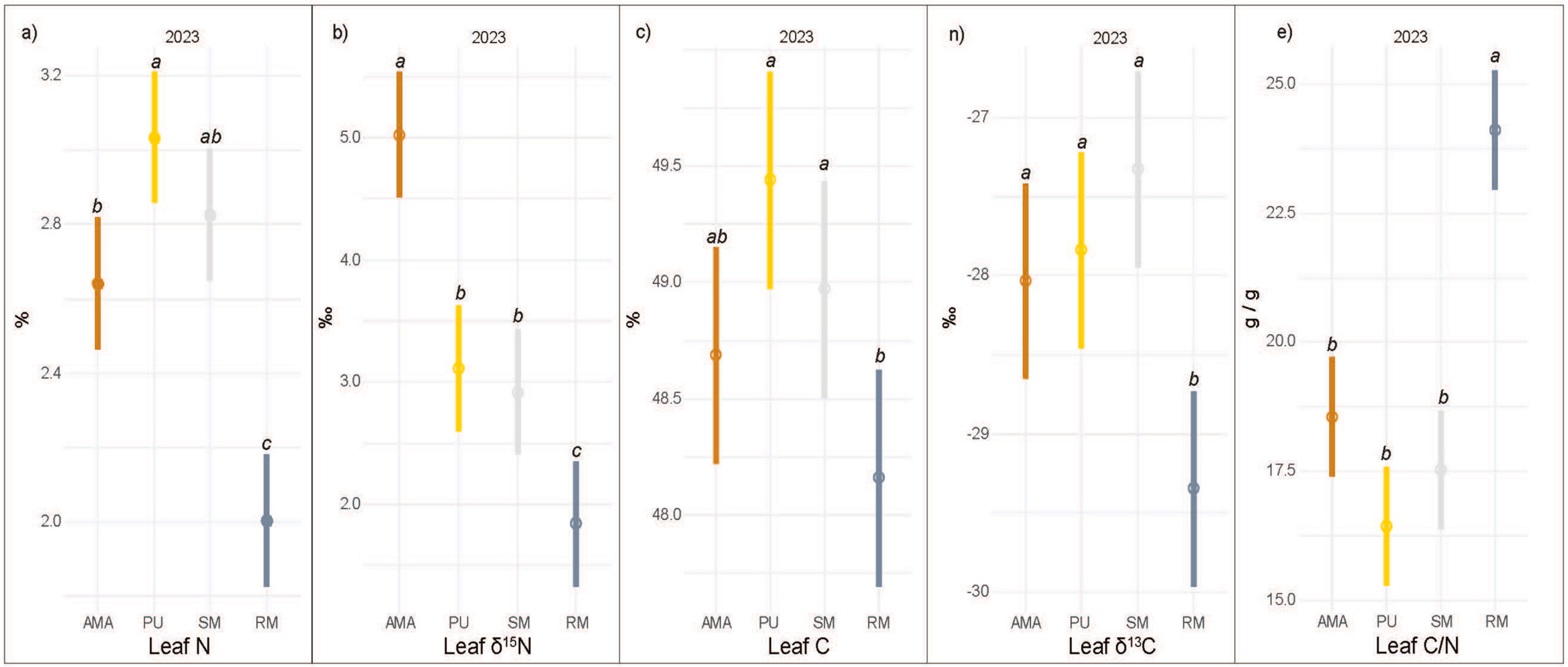

Fig. 3. Estimated marginal means for year 2023 with 95 % confidence interval for each Leaf Nutrient variable and Substrate. Different lower-case letters indicate significant differences within the specific year. Note that there are different unit scales for each panel.

Table 4
Basic physical characteristics for AMA, PU, SM and RM substrates. Table shows mean values and 95 % CI. (Mean water content: df 3, F 38.893, $p < 0.05$; Substrate compaction: df 3, F 36.688, $p < 0.05$; Drainable porosity: df 3, F 48.692, $p < 0.05$; Drainage time: df 3, F 7.822, $p < 0.05$).

Substrate	Water content at field capacity(g water/g soil)		Substrate compaction(%)		Drainable porosity(%)		Drainage time 90 %(min)	
	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI	Mean	95 % CI
AMA	36.60	(21–52.2)^{b}	22.28	(11.39–33.18)^{c}	12.98	(3.91–22.05)^{a}	154.00	(-46.40–354.40)^{b}
PU	56.76	(32.71–80.82)^{c}	9.44	(7.22–11.65)^{b}	29.39	(25.27–33.51)^{b}	41.00	(-32.82–114.82)^{a}
SM	12.55	(-2.37-27.47)^{a}	7.11	(4.02–10.20)^{ab}	27.01	(22.05–31.98)^{b}	8.30	(1.16–15.50)^{a}
RM	5.05	(1.45–8.64)^{a}	3.00	(0.43–5.57)^{a}	37.52	(31.64–43.40)^{c}	6.67	(-0.50-13.84)^{a}

Table 5
ANOVA table for Nutrient Runoff concentrations. "log" indicates that the response was log-transformed, and bold font indicates significance at the set level of 0.01.

$ANOVA_{Nutrient\ Runoff}$			DOC_{log}		Tn_{log}		PO4		$NH4_{log}$		$NO3_{log}$	
Variable	Df_{num}	Df_{den}	F_{value}	p_{value}	F_{value}	p_{value}	F_{value}	p_{value}	F_{value}	p_{value}	F_{value}	p_{value}
Substrate	3	21	14.32	**<0.001**	21.14	**<0.001**	28.25	**<0.001**	146.21	**<0.001**	30.42	**<0.001**
Myko	1	21	0.01	0.977	0.91	0.350	0.51	0.482	0.05	0.823	1.94	0.178
Year	1	24	39.21	**<0.001**	149.82	**<0.001**	100.82	**<0.001**	17.97	**<0.001**	98.8	**<0.001**
Substrate*Myko	3	21	0.7	0.544	0.95	0.430	2.38	0.099	0.42	0.742	2.71	0.071
Substrate*Year	3	24	0.27	0.107	27.86	**<0.001**	4.01	0.019	9.41	**<0.001**	39.05	**<0.001**
Myko*Year	1	24	0.24	0.623	0.01	0.982	0.54	0.468	0.91	0.351	0.20	0.658
Substrate*Myko*Year	3	24	3.23	0.040	2.70	0.068	1.92	0.123	1.07	0.381	1.17	0.340
$ID*Block_{random}$				0.017		0.013		0.065		0.006		0.362
$Block_{random}$				0.103		0.250		0.111		0.815		0.086

losses, AMA was a clear winner in year 2 with both low mean DIN (0.9 mg/L) and PO_4^{3-} (0.1 mg/L) concentrations in runoff. RM also had very low DIN losses (0.4–5 mg/L) and the second lowest PO_4^{3-} losses (0.9 mg/L) in year 2, but was still serving as an appreciable source of P in runoff. In year 2, SM had the highest runoff nutrient concentrations, averaging 2.5 mg/L DIN and 1.8 mg/L P-PO_4^{3-}.

3.4. Multivariate analysis

The multivariate analyses of all the measured tree development parameters showed a separation among the four substrate types (Fig. 5), which was particularly distinct for RM vs. the other three substrate types; and this distinction grew sharper in year 2.

In summary, by year 2, AMA substrate was associated with the most positive values for tree development variables, PU second and SM third, with RM being strongly negatively associated with tree development variables. There was also a clear association of specific leaf and runoff water quality variables with the tree development parameters, and thus between the different substrate treatments. Specifically, the RM treatment was associated with poor growth, yellow leaf colour (LAB B), high leaf C/N ratio, and low values for leaf nutrient content (C and N) and leaf stable isotope values ($\delta^{13}C$ and $\delta^{15}N$). In contrast, the other three substrate treatments (particularly AMA) were associated with relatively vigorous growth, green leaf colour, elevated leaf nutrient content (C and N) and leaf stable isotope values ($\delta^{13}C$ and $\delta^{15}N$), low leaf C/N ratio, and elevated NH_4^+ concentrations in runoff. The study found a negative relationship between yellow leaf colour and leaf area, height, and shoot growth, in both years. In 2023, when leaf nutrient levels were analysed, there was a clear negative association between yellow leaf colour and leaf N. A further analysis of the correlation between leaf colour and leaf N content showed that there was a strong negative correlation with $r = -0.94$, $p < 0.001$. There were no associations between the tree development parameters and g_s.

4. Discussion

In densely-built urban areas, multifunctionality is a critical principle for sustainable urban planning as more functions and qualities have to be combined to ensure resilience in constrained spaces. However, constructing multifunctional urban spaces often comes with trade-offs (Roman et al., 2021). Historically, green spaces and associated ecosystem functions have been losing space to grey infrastructure and housing, resulting in less vegetated surface area, reduced quality of vegetation, and restrictions on the underground space available for planting (Gregory, 2006; Czaja et al., 2020). Structural soil has become an important solution to provide for more underground resources to trees, while maintaining infrastructure functions and road safety (Grabosky and Bassuk, 1995). However, results from this experiment show clear trade-offs when exchanging a traditional engineered soil with either of the tested structural soils, both in tree growth and vitality.

Urban climate adaptability is also heavily dependent on multifunctionality, and in particular on promoting surfaces that allow temporary water storage or infiltration. Here, optimised tree planting beds can be a part of an overarching urban stormwater handling system. Including planting beds in the stormwater infrastructure can, together with other solutions, help reduce the risk of flooding and stormwater runoff in urban areas, while it can also be a way to increase tree water availability and enhance tree vitality (Grey et al., 2018). In this experiment, the pumice-based substrate (PU) had the highest field capacity (55 % higher than AMA, which had the second highest), and although AMA showed the highest values in the tree development measurements, it was only significantly higher than PU in stem basal increment in the second year. However, PU also had a shorter time until being completely drained, indicating that when establishment irrigation ends, the risk of drought is higher in PU as compared to AMA. This indication is supported by the findings of Nielsen et al. (1999), who showed that the faster the water loss rate, the slower the growth rate. High infiltration rate in tree substrates typically comes at the expense of water-holding capacity, meaning that there is a potential trade-off between water detention-efficiency and plant vitality, which was clearly seen in the results where the substrates with the highest porosity and shortest drainage time (SM and RM) also showed the lowest vitality in terms of growth, leaf colour and leaf nutrient levels. Finding a balance between these two needs, or making an informed decision about the consequences of selected technical installations, requires a deepened understanding of the characteristics and function of a given engineered urban substrate. Furthermore, regardless of substrate type, leading stormwater into planting pits also comes with the risk that the temporary waterlogging will reduce tree vitality (Wiström et al., 2023; Levinsson et al., 2024) or that the planting pits in periods between rain events will be

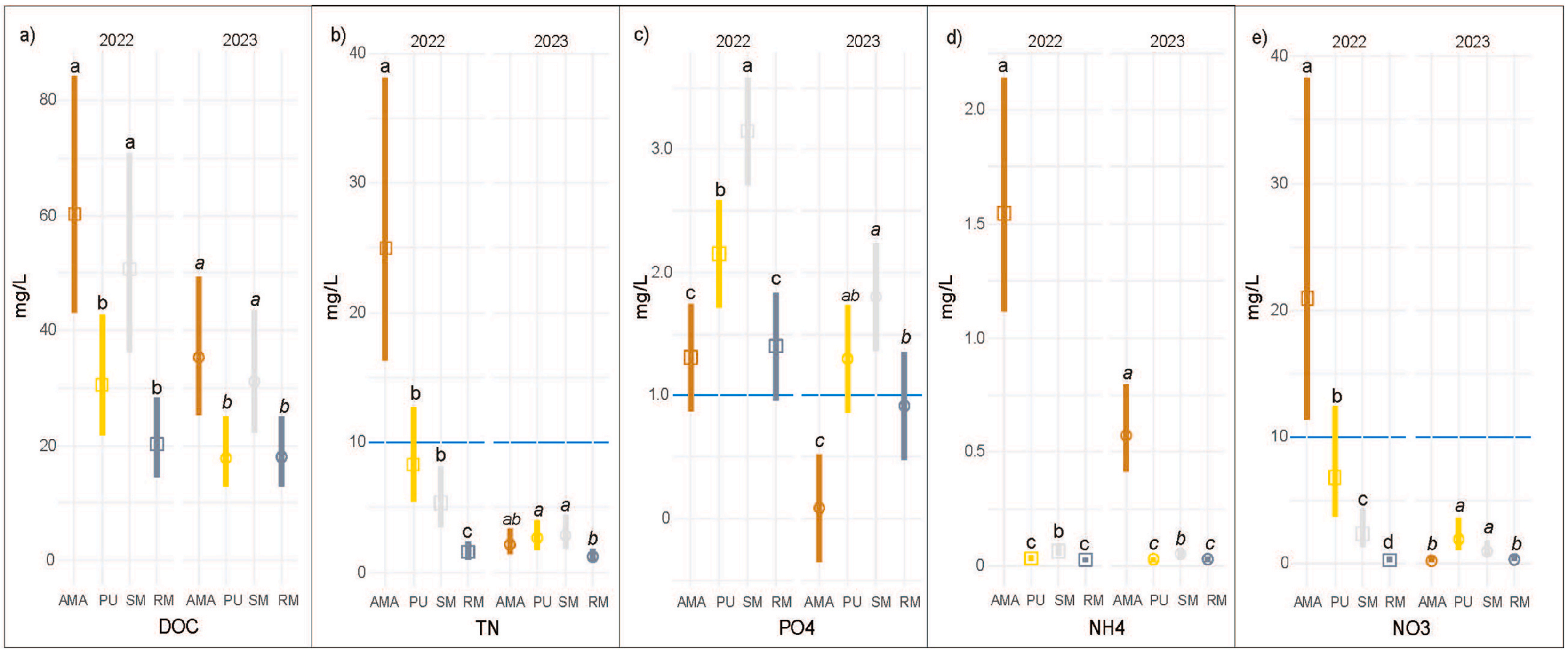

Fig. 4. Estimated marginal means per year with 95 % confidence interval for the concentrations of each Nutrient runoff variable as a function of Substrate treatment and year. Different lower-case letters indicate significant differences within the specific year. Blue horizontal lines indicate levels of potential environmental concern for the pollutants according to USEPA 2024; EC 2024 (note, the EU threshold for tertiary wastewater of 1 mg/L is for TP, not PO4). Note that there are different y-axis scales for each panel.

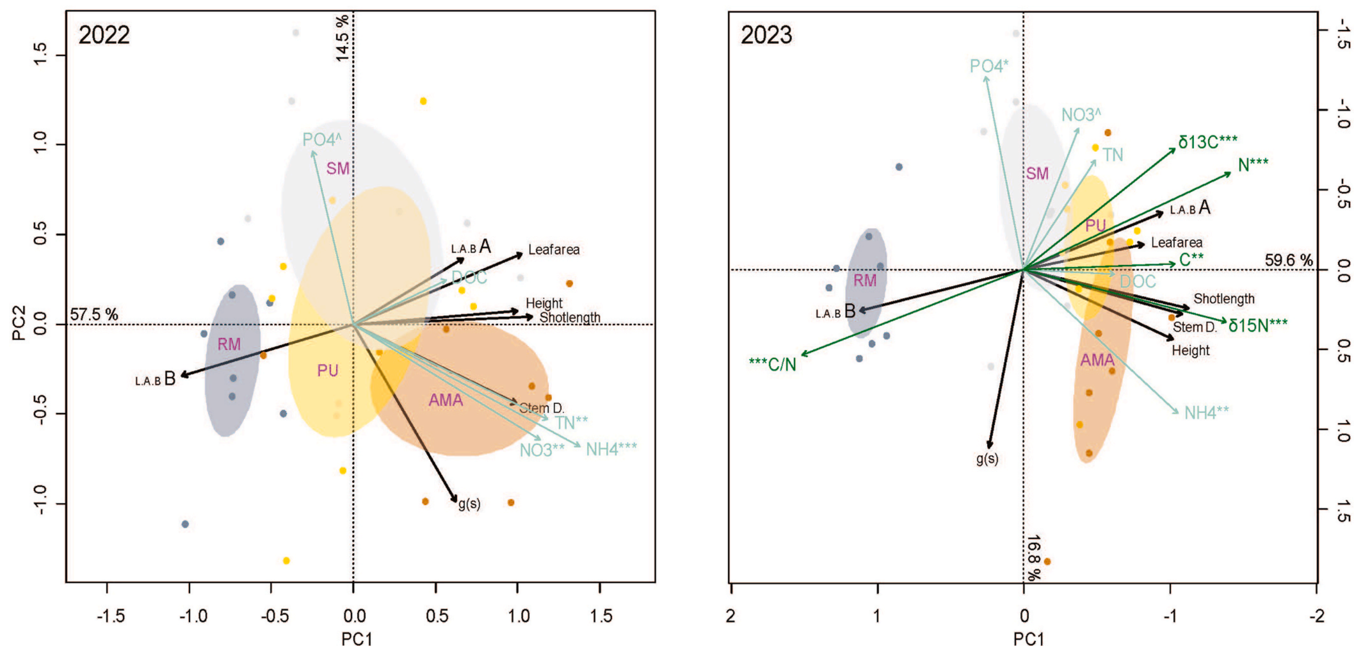

Fig. 5. PCA for 2022 and 2023 of the tree development variables and LAB (LAB A = red-green, LAB B = yellow-blue) values with post hoc fitting using the envfit function of Nutrient Runoff and Leaf Nutrient variables. Significances of post hoc fitted variables are indicated with ***p < 0.001, **p < 0.01, *p < 0.05 without any corrections for multiple testing. Substrates are illustrated with 95 % confidence areas on the unconstrained PCA plots. Explained variation in % of each component is noted on each axis. Axes in 2023 have been rotated to aid readability.

very dry, something that we could see in all substrates apart from AMA in this experiment.

4.1. Tree development and vitality

Although aeration is a key factor for successful establishment and long-term vitality for urban trees (Weltecke et al., 2025), the results from this two-year study indicated that AMA provided enough gas exchange for a healthy tree development during this early post-transplant phase, something that has been debated among tree practitioners. Using structural soils, or reducing the volumes of substrates in the voids of a structural soil for the sake of aeration, might be unnecessarily cautious, considering the higher growth rates in the AMA substrate. This is also in line with the findings of Ow and Ghosh (2017) who argued that the better tree health in the structural cells that they compared to a structural soil, was due to the higher volumes of root-available substrate that could fit in between the cells. That is, the more root available substrate, the better. Meanwhile, Bretzel et al. (2020) showed that in comparison to compacted soil, a coarse planting substrate had a positive influence on tree health. In our experiment, we employed best management practice and largely avoided compaction of the non-structural substrates. However, failure to implement appropriate measures during the implementation of an urban tree-planting installation, or the utilisation of non-structural substrates in circumstances where compaction cannot be prevented, will result in a high risk of non-structural substrates becoming compacted over time, with negative impacts on tree health.

Growth was consistently higher, and leaf colour was consistently healthier in the more traditional horticultural soil (AMA) than in the different structural soils (RM, SM). This is in line with the results from Schütt et al. (2022), showing that tree growth was negatively affected by the two different urban substrates included in their study, as compared to a reference soil, but contrast the findings of Grabosky et al. (2002), who found trees to perform equally well in structural soil as in a park-like environment, where the soil would be most comparable to AMA. Notably, the structural soil of the Grabosky et al. (2002) study had a more traditional horticultural soil mix in the voids in between the rocks, compared to those used in our experiment. This difference could reasonably explain the contrasting results between our study and theirs, and illustrates the complex array of factors that need to be considered when analysing substrate performance.

If the mycorrhiza treatments were helping supply the trees with needed nutrients and thus relieving stress related to low nutrient availability, we would expect positive responses in parameters related to tree growth, perhaps coupled to lower dissolved nutrient export, from plots treated with the mycorrhizal inoculum. However, we saw no evidence for this effect, either in the runoff nutrient data, or the tree growth data. Our results lend support to the study of Appleton et al. (2003) who found no effect of mycorrhizal inoculum on tree growth, but contrast with the results of Garbage et al. (1999) who found an increase in height and diameter growth following mycorrhizal inoculation. Some studies have suggested that other urban soil amendments such as soil organic matter (Van Geel et al., 2019) or biochar (Manea et al., 2023) might be of greater importance than mycorrhizae for tree vitality.

4.2. Water infiltration, drainable porosity and soil characteristics

If the planting beds are to be used for detention of stormwater, the results show that of the tested substrates, RM had the highest capacity for short term water detention, and that AMA had the lowest. However, the effectiveness of the planting bed as a detention basin is highly dependent on the technical installation of the bed, the subgrade, and the drainage system connected to it. If drainage is restricted, the RM will indeed provide the highest detention due to its high degree of unfilled voids, but if drainage is not restricted, the AMA will hold more water over time, due to its higher field capacity, and thereby more readily reduce the pressure on the stormwater system during heavy rains. Still, this requires that the AMA substrate is installed in a manner that prevents further compaction and allows for infiltration. And if stormwater detention is a high priority at the location, PU had the highest field capacity. The detention times experienced in this experiment were very low for the coarser substrates RM and SM, which were almost completely emptied within 10 min. Thus, for the coarse engineered mixtures to be efficient as runoff reducers, they must be used in systems specifically constructed for that purpose. Using them in "regular" planting beds with the traditional drainage systems, will not give the expected outcomes, indicating that the expected trade-off with reduced tree growth and vitality might instead be a ”lose-lose”.

Soil compaction is a common urban problem leading to low tree vitality and as a result, urban tree managers have increasingly turned to structural or pumice-based soils when planting new trees in Swedish cities, even in places where the need for load-bearing capacity is low. However, the results of this study show that this practice evidently comes with a trade-off. Our results indicate that the higher water availability in combination with the availability of nutrients in the traditional substrate AMA as compared to the two structural substrates (SM and RM) had a significant positive impact on tree growth and vitality. Pumice in general has a positive effect on substrate water-holding capacity, but the particle size distribution of the material will also influence aeration (Gizas and Savvas, 2007). PU substrate showed the highest measured field capacity value, but this was not related to superior tree growth in this experiment, possibly due to the rapid water drainage, which might have resulted in reduced water availability as the material was quite coarse.

The AMA substrate used in our experiment settled significantly more as compared to all other substrates. In this short-term experiment, the settling did not seem to affect tree performance, but continued settling could impact both infiltration and aeration. However, Weltecke and Gaertig (2012) showed that gas exchange was largely dependent on soil cover and surface sealing and that technical installations to improve aeration, which has become standard practice when installing structural soils, had little effect on coarse-grained substrates (Weltecke et al., 2025).

4.3. Runoff water quality

Evidence from the analysis of leaf nutrient content, leaf ^{13}C and runoff nutrient concentrations indicated ample availability of nutrients and a lack of water stress for the trees in the AMA substrate. In contrast, trees in the RM substrate in particular showed evidence of water stress based on leaf ^{13}C, and may have also been limited by the availability of nitrogen based on high leaf C/N and very low TN and DIN concentrations in runoff. Leaf colour has been shown to correlate with leaf chlorophyll content (Hunt et al., 2013), and the high values of LAB B (the yellow colour) in the RM treatment gave further indications of low plant-available nitrogen in that treatment. Variation in leaf ^{15}N most likely reflects variation in soil N source among the different substrate treatments. High ^{15}N (AMA) likely indicates an N source which consists of more organic N that has undergone microbial processing in the soil (mineralization, nitrification) over time which can give rise to a higher ^{15}N for the remaining soil N (Bateman et al., 2007; Einersson, 2011). At the other end of the spectrum, the low leaf ^{15}N value for the RM treatment likely indicates a source dominated by mineral fertiliser sources.

The dissolved nutrients in runoff represent a potential pollutant source to the surrounding/downstream environment, which could be a factor in determining the ideal structural soil to use. All else being equal, we would prefer a system that is not leaking out high levels of dissolved nutrients, especially N and P which could result in eutrophication downstream, or additional challenges for a wastewater treatment plant. In this experiment, the main water quality concern from these plots would be phosphate, which remains at high levels in the drainage water relative to reference values for tertiary wastewater effluent (EC, 2024), even during the second growing season. The leaching was particularly high for SM and PU, and was less of an issue for the traditional AMA substrate, suggesting another advantage for using this substrate. It is important to note that the actual environmental impact of nutrient leaching will depend on how the drainage system is plumbed, i.e. what the residence time is for water in the tree planting pits, and what the water path is further downstream in the drainage network.

4.4. Study limitations

In this experiment, we used bare-rooted young trees, planted directly into either a structural soil, or tree planting substrates. This partly differs from standard procedures, as using bare-rooted trees are currently not the dominant practice in urban tree planting projects, due to the potential for higher sensitivity during transport and handling (Koeser et al., 2014). However, if carefully handled, bare-rooted trees can perform similarly post-transplant compared to trees that have undergone other standard nursery practices, such as being balled & burlapped or air-potted (Levinsson, 2013). Experimental considerations focusing on the effect of substrate on plant establishment meant that the use of bare-rooted plants was seen as the preferred choice, to avoid influence of the nurseries' substrates. This was also the reason for installing the trees into uniform substrates, contrary to the current practice in Sweden when using structural soils, where trees are often installed in a small planting pit with a horticultural substrate mix closest to the root system and a coarser structural soil in the surrounding rootable space. However, the trees are supposed to establish their root systems in the structural soil over time, and the pit can only support the root system of a very small tree. In the long run, the trees need to rely on the volumes surrounding the small primary pit for water, oxygen and nutrients. Furthermore, the study focused on commonly used substrates in a Swedish context, and even though one of the structural soils (SM) has received international attention (Ow et al., 2018) there may be influential factors that vary by climate and/or country, indicating that the results may need to be translated to the local setting to be applicable. For example, the differences between the substrates, expressed in the tree growth rates, might be further emphasised if employed in a warmer, dryer climate than what is considered normal conditions in southern Sweden.

In this experiment, we used *Tilia x europaea,* which is one of the most common street and park trees in northern and central Europe (Bengtsson, 2005; Sjöman et al., 2019). It shows a strong intermediate character between its two parent species *Tilia cordata* Miller and *Tilia platyphollos* Scop (Rotherham, 2012). Based on the natural distribution of the parent species (Ellenberg, 1988; Lawesson and Oksanen, 2002), functional drought traits (Hirons et al., 2021), and practical experience, it should be seen as a semi drought-tolerant species with a capacity to withstand some short-term flooding (Lyr, 1993; Jaegere et al., 2016). Furthermore, earlier studies of structural soils have utilised bare rooted *Tilia cordata* as the indicator species (Grabosky and Bassuk, 1995). Common ectomycorrhizae connected to *Tilia* have been found to be able to survive in dry soils on *Tilia cordata* roots (Pigott, 1982). As such, the *Tilia x europaea* clones used within this experiment should be seen as a good bioindicator for the given experimental evaluation, since they exhibit low within-species variation while neither being extremely robust or sensitive to drought or low oxygen levels, thus neither hiding nor exaggerating ecophysiological responses.

In practice, implementation within cities should endeavour to match tree species to the specific location and system, for example selecting more drought or waterlogging tolerant species depending on the soil used (Levinsson et al., 2024). The lower sensitivity to drought might partly explain why Grabosky and Bassuk (2016) using two more drought tolerant oak species did not find any large difference between lawn and structural soils (Kress, 2024). In the study by Grabosky and Bassuk (2016) and the subsequent evaluation of various urban growing substrates, the significance of selecting the optimal tree for the designated substrate was emphasised. In this context, our results show that SM and RM necessitate trees that exhibit high physiological tolerance to drought, despite their utilisation for stormwater management, since these substrates are susceptible to rapid drying and thus heightened drought intensity between rainfall events. Meanwhile, if they are to be efficient for stormwater management, trees grown in these substrates should also exhibit a tolerance to waterlogging (Levinsson et al., 2024). Detailed descriptions of different urban substrates, as in this study, are needed to help in matching plant material to different substrate and local conditions. This will in turn allow for site and situation-specific plant use with greater opportunities to create long-term sustainable and multifunctional tree plantations for urban environments.

Finally, in our study, there was no surface sealing included in the setup. Although many sites in an urban context traditionally have sealed surfaces, open surfaces are becoming more common, and the ambition of our study was to investigate differences using a best management approach.

5. Conclusion

Making informed decisions concerning both tree species and the technical installation, including which substrate to use, when planting urban trees is essential to promote long-term tree survival and vitality. The results from this two-year study of young trees in four different engineered substrates clearly showed that the more traditional horticultural mix was superior both in terms of plant performance and levels of leached phosphorus (lowest levels), as compared to two structural soils and a pumice-based planting substrate. However, the horticultural mix also showed clear settling after the second season, indicating that longitudinal studies are needed to explore long-term development. Furthermore, when multifunctionality is desired, there are clear limitations with the horticultural mix, as it has limited load-bearing capacity, and a slower infiltration rate compared to the other three substrates. Thus, urban planners must explicitly consider desired substrate functions and clearly define priorities, as there are trade-offs between e.g. nutrient leaching, plant growth and structural stability. Our results indicate that there can be stormwater management advantages in using highly porous tree planting substrates, but that there is a risk that tree vitality will suffer, and that a more intensive tree maintenance regime might be needed to ensure tree health and long-term vitality. Furthermore, more research is needed to improve substrate design in relation to nutrient leaching when urban trees are implemented in areas with sensitive stormwater recipients.

CRediT authorship contribution statement

Anna Levinsson: Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Ishi Buffam:** Writing – review & editing, Methodology, Investigation. **Björn Wiström:** Writing – review & editing, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Frida Andreasson:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Anna Lund:** Writing – review & editing, Methodology, Investigation. **Henrik Sjöman:** Writing – review & editing, Funding acquisition, Conceptualization. **Tobias Emilsson:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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