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RESEARCH ARTICLE

Plant functional type affects nitrogen dynamics in urban park soils similarly to boreal forest soils

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Abstract
Purpose Although plant functional type can modulate soils and their processes in natural, nitrogen (N)-limited ecosystems, little is known about their ability to influence soil N dynamics in urban ecosystems that have high excess N input. We investigated whether i) plant functional type effects on soil N dynamics in urban parks follow the same pattern as those in undisturbed natural/semi-natural forests, and ii) park age influences plant functional type effects on soil N dynamics under boreal climate.
Methods We selected 13 urban parks of varying ages (young: 10 to 15, old: >70 years), and 5 undisturbed natural/semi-natural forests (>80 years) in southern Finland. In these parks and forests, we measured soil total N concentration, availability of inorganic N, nitrous oxide (N_2O) flux and earthworm biomass under three plant functional types (evergreen tree, deciduous tree, lawn).
Results Our results showed that plant functional type influenced N dynamics also in urban greenspace soils, which may relate to the clear effect of plant functional type on earthworm biomass. Evergreen trees tended to have the highest ability to foster N accumulation and reduce N_2O emissions in urban parks. Moreover, with increasing park age, N accumulation increased under trees but decreased under lawns, further emphasising the role of vegetation in affecting soil N dynamics in urban greenspaces.
Conclusions Our results show that, similar to natural/semi-natural forests, plant functional type, irrespective of park age, can influence soil N dynamics in urban parks.

Keywords Inorganic nitrogen · Nitrous oxide · Evergreen tree · Earthworms · Ecosystem service

Introduction

Urban areas are typified by high nitrogen (N) input mainly through traffic and industrial emissions (Decina et al. 2020). As a result, urban greenspace soils are often saturated with N (Lovett et al. 2000; Fang et al. 2011), which has resulted in the contamination of ground waters and eutrophication of surface waters within urbanised catchments (Valtanen et al. 2014; Zhang et al. 2015). Furthermore, the small proportion of permeable soils in urban environments (Liu et al. 2014) limits the absorption of

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N deposition efficiently, and the existing vegetation in urban greenspaces is often sparse and thus less N is likely sequestered in vegetation biomass in these systems compared to more natural systems (De Deyn et al. 2009).

Plants with divergent traits in terms of litter quality differ in their ecological strategies and can be grouped into different plant functional types (sensu Grime 1974, 1998). It is well established that in natural/semi-natural ecosystems, plant functional types play a role in controlling nutrient dynamics (e.g., Finzi et al. 1998; Knops et al. 2002; Lovett et al. 2004). For example, in forested ecosystems, plants producing recalcitrant litter, such as conifers, often associate with higher soil organic matter (OM) and C/N ratios compared to plants shedding labile litter, such as herbs and grasses (Hobbie 1992; Wardle 2002; Hobbie et al. 2007; Bardgett and Wardle 2010). Recent evidence suggests that plant functional type can also modulate soils and their processes in managed urban greenspaces (Edmondson et al. 2014; Setälä et al. 2016; Hui et al. 2017; Francini et al. 2018). For example, the low soil pH and moisture content under evergreen trees (Setälä et al. 2016) can lower nitrification rates (Ste-Marie and Paré, 1999) and thus reduce denitrification rates (ŠImek and Cooper 2002) compared to soils under deciduous trees and lawns. Furthermore, plant functional type can affect the biomass and diversity of earthworms (Schelfhout et al. 2017; Francini et al. 2018) that are known to stimulate nitrification (Haimi et al. 1992; Lavelle et al. 2004) and enhance soil nitrous oxide (N_2O) emissions (Lubbers et al. 2013). Consequently, the influence of plant functional type on earthworms may indirectly affect the loss and/or retention of N in the urban plant-soil systems. Additionally, due to the positive relationship between soil OM content and N immobilisation rates (Barrett and Burke 2000; Zhu and Wang 2011), higher soil OM content under evergreen trees than under deciduous trees and lawns (Setälä et al. 2016; Lu et al. 2021) can also enhance N accumulation in evergreen soils.

Besides plant functional type, the length of time during which plant-soil interactions have taken place can affect N dynamics within ecosystems (Paré and Bergeron 1996; Mueller et al. 2012). In boreal urban greenspaces, the effects of plant functional type on soils and their biota are accentuated with park age (Setälä et al. 2016; Hui et al. 2017; Francini et al. 2018; Lu et al. 2021). For example, Setälä et al. (2017) reported increased soil bulk densities under deciduous trees and lawns with park age, while evergreen soils showed the opposite. High bulk density can result in anaerobic soil conditions that stimulate denitrification (Li et al. 2014; Robertson and Groffman 2015). Furthermore, Lu et al. (2021) found that OM and carbon (C) concentrations under evergreen trees increased significantly with park age, while these concentrations were mostly unresponsive to park age under deciduous trees and lawns. Given the close association between C and N in the biogeochemical cycle (Vitousek et al. 1997), park age (time since parks establishment) in concert with plant functional type may thus drive N dynamics in urban greenspaces. However, to our knowledge, no empirical studies in which the potential of park age to modulate plant functional type effects on soil N dynamics exist.

It is widely agreed that the main drivers that control patterns and processes in urban systems are anthropogenic by nature (Grimm et al. 2000; Pickett et al. 2001; Byrne 2007). Intense disturbances, including park management practices, undoubtedly modify nutrient dynamics and other ecosystem processes (Kaye et al. 2006). While the raking of litter decreases N input into urban soils (Templer et al. 2015), dog urine (Allen et al. 2020), in concert with traffic-derived deposition (Decina et al. 2017), increases soil organic- and inorganic-N concentrations in urban greenspaces. These disturbances in urban soils likely give rise to divergent soil N dynamics between urban and natural/semi-natural ecosystems (Groffman et al. 2009). Consequently, plant functional type effects on N dynamics are likely less influential in urban parks with constant, external N input compared to e.g., natural boreal ecosystems, where N is commonly a growth limiting factor (Högberg et al. 2017). However, virtually nothing is known about whether plant functional type effects on soil N dynamics differ between urban and natural/semi-natural ecosystems.

In this study, we investigated whether plant functional type effects on soil N dynamics (the accumulation of total N, availability of nitrate (NO_3-N) and ammonium (NH_4-N), and N_2O flux) in urban parks follow the same pattern as those in undisturbed natural/semi-natural forests under boreal climate (Fig. 1a). In the absence of N deposition data at our study sites, we

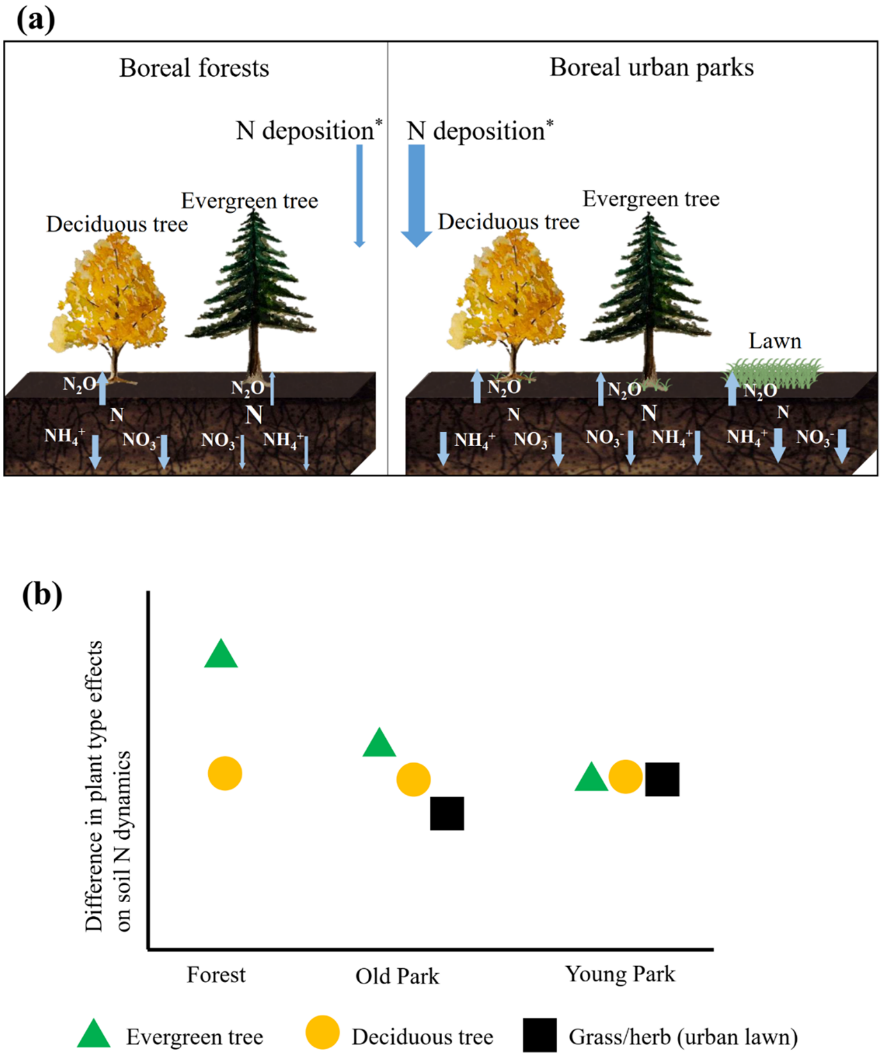

Fig. 1 Schematic presentation of how soil N-dynamics can be influenced by plant functional type (evergreen and deciduous trees, lawns) in ecosystems with low (forests) and high (urban parks) N deposition (a), and hypothesised outcomes of these plant-soil interactions in forests, old parks and young parks (b). N deposition data were taken from the literature (indicated with an asterisk). Detailed information of the study design is presented in the "Study area" section. In (b), the difference in the gap between plant functional types relates to the difference in plant functional type effects on soil N dynamics among the three habitats (forest, old park, and young park)

used atmospheric concentration of NO_2 as a proxy for the potential dry and wet deposition of N. In southern Finland, average NO_2 deposition is 30 μg per m^3 within the city boundaries of Lahti and Helsinki (Viippola et al. 2018) and 4 μg per m^3 in a rural area in Lahti (H. Setälä, unpublished results) and 2–5 μg per m^3 in Helsinki (Malkki et al. 2018). Given the strong influence of excess N input in cities (Groffman et al. 2009; Decina et al. 2020), we hypothesise that 1) plant functional type effects on soil N dynamics in urban parks are less pronounced than in undisturbed natural/semi-natural forests of similar age where N is a limiting factor (Fig. 1b). Despite the high N input in these systems, an evergreen tree effect in park soils is expected to follow that in forest soils due to their strong ability to modify soil characteristics under urban conditions (Setälä et al. 2016, 2017; Kotze et al. 2021). In terms of park age, we hypothesise that 2) plant functional type effects on soil N dynamics are minimal in young parks that are characterised by strong, recent disturbance due to park construction and thus a limited time that plants have interacted with soils (Fig. 1b).

Materials and methods

Study area

The study was conducted in Helsinki (60°10′15″ N, 24°56′15″ E, population within the greater Helsinki area ca. 1.3 million), located in the boreal climatic zone in southern Finland, with an annual mean precipitation of 656 mm and an annual mean temperature of 5.8 ℃ (Finnish Meteorological Institute: https://en.ilmatieteenlaitos.fi/). More detailed climatic and edaphic information of Helsinki can be found in Setälä et al. (2016).

We selected 13 public parks in the city of Helsinki and 5 natural/semi-natural forests within the Helsinki Metropolitan area (see Supplementary Material, Table S1). These selected urban parks were divided into two age classes: young (10 to 15 y old) and old parks (more than 70 y old). Park size ranged from ca. 0.1 to several hectares (0.5 ha on average). Tree height varied between 3 to 4 m in the young parks. Both young and old parks were frequently mowed but mowing residues were not removed. Leaf litter in these parks is raked and removed twice a year (in fall and spring). Urban parks are not fertilized or irrigated after park establishment (see Setälä et al. 2016 for more information about park construction). A fully factorial field design with 5 young and 5 old parks was used, with three plant functional types (evergreen tree, deciduous tree and lawn) in each park. The three plant functional types were: evergreen trees (spruce, mostly *Picea* sp.), deciduous trees (linden, *Tilia x vulgaris*, except in one young park in which the tree was Norway maple (*Acer platanoides*)), and lawn (grass/herb, mostly *Festuca* and *Poa* species, and some scattered *Plantago major*, *Trifolium pratense* and *Taraxacum* spp.). However, three of the parks included only one of the two tree types. As a result, three additional parks with one tree type were selected to ensure 5 replicates per plant functional type per park age. All selected parks were covered with lawn, which also extended under the tree canopies. In essence, the study design was lawn with and without evergreen or deciduous trees. The study plots, ca. 2 m^2 in size, were located underneath the outer canopy edge of the two tree types and in the middle of the lawn. Under the two tree types, the study plots were placed one to several meters away from the trunk of selected trees, depending on tree age. Similarly, to minimise the effects of adjacent trees on lawn soils, distance between the lawn study plots and the nearest trees was always greater than the height of the tree.

Additionally, five unmanaged forests, located in conservation areas in the greater Helsinki area, were chosen as reference sites, allowing comparison of tree effects on soils between natural/semi-natural forests and old urban parks. Two of the five unmanaged forests are close to residential areas and were thus considered semi-natural forests, while the rest were located ca. 10 km from the city boundary in a forested area. The age of the dominating evergreen (Norway spruce, *P. abies*) and deciduous (linden, *T. cordata*) trees in the reference forests was similar (more than 80 y old) to those in the old urban parks. In each reference forest, both evergreen and deciduous trees formed almost monocultural type stands (ca. half a hectare in size). Tree density was at least twice as high in the reference forests than in old urban parks. Overall, a total of 40 study plots were selected, including 30 plots in urban parks (3 plant functional types × 2 park ages × 5 replicates) and 10 plots in reference forests (2 plant functional types × 5 replicates). Lawn plots are lacking from reference forests.

Soil sampling and analyses

Soils were sampled in the middle of the lawn plot (in parks only) and underneath the canopy edge of evergreen and deciduous trees in May 2020. At each sampling plot, three soil subsamples, situated ca. 1 m apart, were taken to a depth of 10 cm using a metal soil corer (2.54 cm diameter) and pooled into one composite sample. A total of 40 soil samples were collected and placed in zipper bags and transported to the laboratory. Before analyses, all visible roots, larger mineral particles and plant litter were removed by sieving the soils through a 2 mm sieve. Soil pH was measured in a 1:5 v/v fresh soil/distilled water suspension. Soil total N and C/N ratio were obtained by dry combustion at 1350 °C using a LECO CNS-2000 Elemental Analyser (0.07% C and 0.09% N detection limits). Soil moisture (%) was determined by drying the soils at 105 °C for 24 h.

Availability of soil inorganic N was assessed by quantifying availability of NH_4^+ and NO_3^- using ion exchange resin bags (UNIBEST International, WA, USA), which absorb exchangeable nutrients from the soil solution. In mid-November 2018, in each plot, one resin bag was buried to a depth of 10 cm by first making a soil hole using a metal pipe (2 cm in diameter), then placing a resin bag at the bottom of the hole and finally filling the hole with the extracted soil. Each resin bag was attached to a nylon string with a nail to help locating the resin bags before extraction using a metal detector. After 6 months, the resin bags were retrieved and replaced by a new set of resin bags in the same holes for another 6 months. After collection, the resin bags were rinsed with distilled water in the laboratory to remove adhered soil on the surface of the resin bags and then frozen (-20 °C) before delivering them back to the supplier for analysis. The extracts were analysed for NH_4^+ and NO_3^- using a flow injection analyser. Unfortunately, NH_4^+ and NO_3^- data of the second set of resin bags were lost during transportation. Therefore, a third set of resin bags was placed in the same plots in mid-July 2020 and retrieved in mid-November 2020. Consequently, data from the first and third sets of resin bags (80 in total) are presented in this study.

Soil N_2O flux under the three plant functional types was quantified using the static chamber method (Kanerva et al. 2007). Gas samplings were conducted during three seasons: late June (summer, 2019), mid-October (fall, 2019) and early May (spring, 2020). Two opaque aluminium chambers (0.25 cm diameter and 12 cm height at the highest point, 0.0028 m^3) were placed ca. 50 cm apart at each plot. Each gas chamber was equipped with a thermometer and a gas port sealed with a silicon septum. The chambers were placed in the middle of the lawn and underneath the canopy edge in the tree plots. To minimise gas exchange by the living plant material, all surface plant litter and vegetation was carefully cut and removed before placing the chamber. The chambers were gently placed into the soil 2 min before sampling the air inside the chambers. The lower rim of the chamber reached a depth of 2 cm. After mixing the air inside the chamber, a 20 ml gas sample was taken with a 30 ml polypropylene syringe at time 0, and 30 min thereafter (Kanerva et al. 2007). The gas sample was stored in a 12 ml glass vacuum vial (Exetainer, Labco, UK). At each point in time of sampling (0 and 30 min), air temperature inside and outside the chamber was recorded. After gas sampling, two soil subsamples per plot were taken and then pooled for determining soil moisture (results are presented in Lu et al. (2021)). A total of 480 gas samples were taken (40 plots × 2 chambers × 2 sampling time points × 3 sampling seasons). In the laboratory, the gas samples were analysed for N_2O flux using a gas chromatograph (see Kanerva et al. 2007 for details). As the slight disturbance of the soil while pushing the chambers into the soils may stimulate N_2O production (Rochette and Eriksen-Hamel 2008), the method was thoroughly tested before commencing the measurements and proved operational (see Lu et al. 2021).

Earthworms were sampled using the hot-mustard liquid method (Gunn 1992) in October 2020. Briefly, 15 g of hot mustard powder was dispersed in 100 ml of water, and then the mustard paste was allowed to sit for at least 4 h. Immediately prior to sampling, the prepared mustard paste was added to ca. 3.5 L tap water in a watering can. In each sampling plot, 2 cylindrical metal frames (diameter = 25 cm) were placed on the ground and pushed slightly into the soil to a depth of 5 cm. All vegetation and leaf litter inside the frames were removed carefully and properly checked for earthworms. After that, a total of 3.5 L mustard liquid was poured in each frame: first, half of the mustard liquid was poured evenly across the quadrat; after 15 min, the remaining mustard liquid was poured. The emerging earthworms were picked up and placed into a plastic jar with clean water. After sampling, the collected earthworms were placed in plastic bags filled with 70% ethanol and then transported to the laboratory. The earthworms were stored in the laboratory for 48 h before identifying and weighing them.

Statistical analysis

All statistical analyses were performed in R 3.6.1 (R Core Team 2019). Histograms and Shapiro-Wilks test were used to determine normality of the eight response variables (soil pH, moisture content, N content, C/N ratio, NH_4^+ and NO_3^- content in resin bags, N_2O flux, and earthworm biomass), and data were either square-root or Ln transformed, where necessary. Two comparisons (see below) were tested using linear mixed models (LMM).

Old parks vs. Reference forests, a linear mixed model was used to test differences in these eight response variables among old parks and reference forests. The models included i) plant functional type (a factor with two levels: Deciduous tree, Evergreen tree, as reference forests do not have lawns), ii) habitat (a factor with two levels: Old park, Reference forest), and their interaction. Site identity was included in the models as a random term. To select the best model, the two-way interaction was removed if *p*-values were > 0.05, yet the main effects (plant functional type, habitat) were kept irrespective of their significance. Histograms of residuals and residual plots were used to examine the normality and homoscedasticity assumption of LMM.

Young vs. Old parks, a linear mixed model was used to test differences in these eight response variables against i) plant functional type (a factor with three levels: Deciduous tree, Evergreen tree, Lawn), ii) park age (a factor with two levels: Young, Old), and their interaction. Similarly, park identity was included in the models as a random term. Model selection and assumption checking were the same as described above.

Results

Soil total N concentration and the C/N ratio

In terms of soil total N, in reference forests, soils under evergreen trees had ca. 25% higher %N than those under deciduous trees, but the difference was not statistically significant (Fig. 2A, Table 1). Soil N concentration, independent of tree type, did not differ between old parks and reference forests. In old parks, the highest %N was found under evergreen and deciduous trees, while in young parks, the highest %N was detected in lawn soils (Fig. 2B, Table 2). Soil %N under evergreen and deciduous trees was higher in old parks than in young parks, but lawn soils had an opposite pattern. In terms of the soil C/N ratio, in reference forests, soils, especially under evergreen trees, had a significantly higher C/N ratio than those in old parks (Fig. 2C, Table 1). In reference forests, the soil C/N ratio was ca. 1.5 times higher under evergreen trees than under deciduous trees. In both young and old parks, soils under deciduous trees had the highest C/N ratio, followed by evergreen soils, and lawn soils had the lowest C/N ratio (Fig. 2D, Table 2). Young parks had higher soil C/N ratios than old parks.

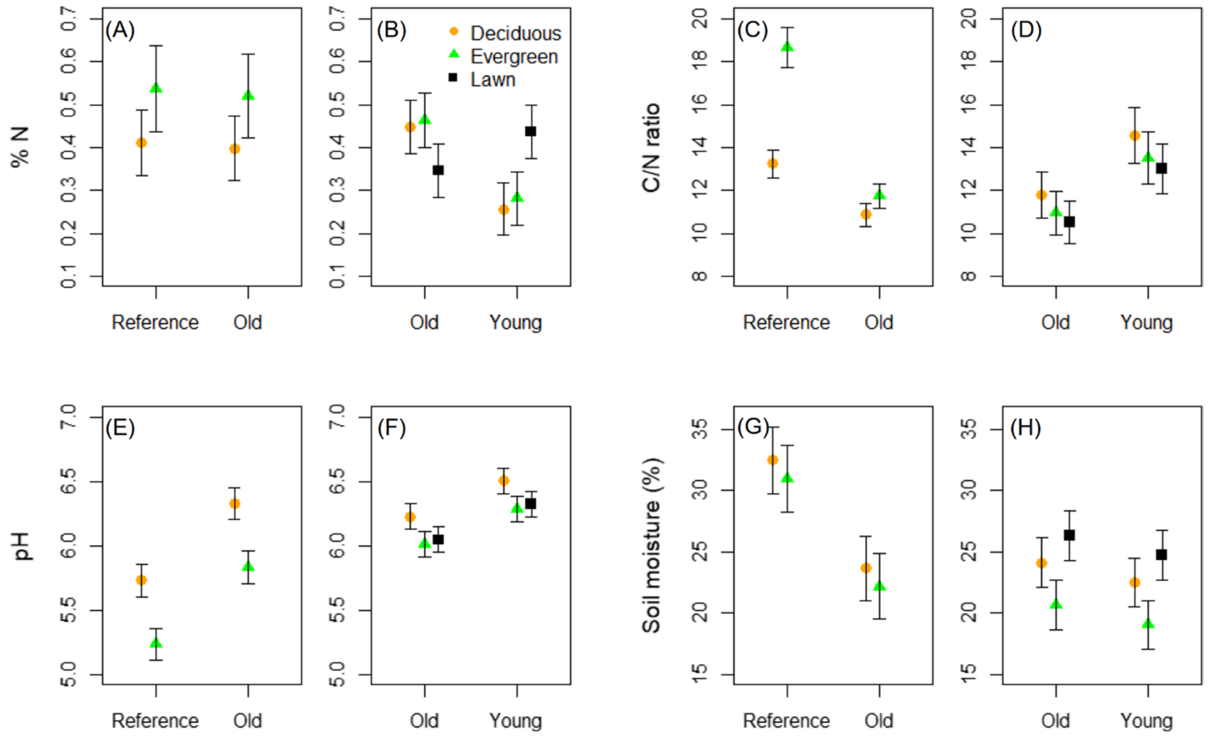

Fig. 2 Soil total N concentration, C/N ratio, pH and moisture content (predicted mean ± SE) between reference forests and old parks (A, C, E, G), and between old and young parks (B, D, F, H) under different plant functional types (deciduous tree, evergreen tree, lawn). Values for old parks in the two plots per soil characteristic differ slightly because we present model predicted values. For raw values of soil characteristics, see Fig. S1 in the supplementary material

Table 1 LMM results, testing the effect of plant functional type (deciduous tree and evergreen tree) and habitat (old park and reference forest) and their interaction on soil pH, moisture content, nitrogen content, C/N ratio, resin bag absorbed NO_3^- and NH_4^+, soil N_2O flux and total earthworm biomass

Variable	Intercept	Evergreen	Old park	Plant functional type × Habitat
pH	5.731 (0.124) <0.001	**-0.494** **(0.137)** **0.005**	**0.598** **(0.146)** **0.003**	
Soil moisture (%)	32.472 (2.715) <0.001	-1.469 (2.594) 0.584	**-8.802** **(3.330)** **0.026**	
Nitrogen content (%)	0.410 (0.075) <0.001	0.126 (0.124) 0.227	-0.013 (0.085) 0.889	
C/N ratio	13.237 (0.662) <0.001	**5.416** **(1.288)** **<0.001**	**-2.367** **(0.772)** **0.013**	*
NO_3^- (mg bag^{-1}, November -May)	0.001 (0.021) 0.892	0.073 (0.175) 0.482	**2.854** **(1.102)** **0.001**	
NO_3^- (mg bag^{-1}, July–October)	0.001 (0.019) 0.889	0.008 (0.050) 0.811	0.599 (0.510) 0.057	
NH_4^+ (mg bag^{-1}, November -May)	0.111 (0.035) <0.001	-0.052 (0.020) 0.091	**0.238** **(0.137)** **0.016**	
NH_4^+ (mg bag^{-1}, July–October)	0.303 (0.049) <0.001	-0.061 (0.039) 0.198	**0.243** **(0.110)** **0.018**	
N_2O (mg m^{-2} h^{-1}, June)	0.003 (0.003) 0.318	-0.006 (0.003) 0.111	**0.008** **(0.003)** **0.031**	
N_2O (mg m^{-2} h^{-1}, October)	0.002 (0.002) 0.426	-0.003 (0.002) 0.203	**0.009** **(0.003)** **0.009**	
N_2O (mg m^{-2} h^{-1}, May)	0.001 (0.001) 0.456	-0.002 (0.001) 0.265	**0.004** **(0.002)** **0.028**	
Total earthworm biomass (g fresh mass m^{-2})	63.633 (20.581) <0.001	**-43.463** **(7.428)** **0.004**	-24.495 (20.557) 0.323	

Deciduous trees in reference forests are in the intercept. Coefficients, standard errors (in parentheses) and *p*-values are presented. Significant effects ($p < 0.05$) are highlighted in bold and the one significant interaction term is indicated with an asterisk

Soil pH and moisture

Soils in reference forests had lower pH than those in old parks (Fig. 2E, Table 1). In the reference forests, soil under evergreen trees was more acid than that under deciduous trees. In both young and old urban parks, soils under deciduous trees had the highest pH, followed by lawn soils and, as expected, evergreen soils had the lowest pH. Old parks had lower soil pH than young parks (Fig. 2F, Table 2). In terms of soil moisture, soil water content in the reference forests was clearly higher than in old parks (Fig. 2G, Table 1). In reference forests, soil moisture content was slightly higher under deciduous trees than under evergreen trees, but the difference was not statistically significant. In both young and old parks, lawn soils had the highest moisture content, followed by deciduous soils, while evergreen soils were the driest (Fig. 2H, Table 2). Old parks had slightly higher soil moisture content than young parks.

Table 2 LMM results, testing the effects of plant functional type (deciduous tree, evergreen tree, and lawn), park age (young, old) and their interaction on soil pH, moisture content, nitrogen content, C/N ratio, resin bag absorbed NO_3^- and NH_4^+, soil N_2O flux and total earthworm biomass

Variable	Intercept	Deciduous	Evergreen	Young	Plant functional type ×Park age
pH	6.047 (0.100) < 0.001	0.179 (0.112) 0.129	-0.036 (0.112) 0.751	**0.278** **(0.106)** **0.028**	
Soil moisture (%)	26.330 (2.039) < 0.001	-2.209 (2.160) 0.321	**-5.662** **(2.159)** **0.018**	-1.586 (2.245) 0.499	
Nitrogen content (%)	0.346 (0.063) < 0.001	0.101 (0.062) 0.153	0.117 (0.059) 0.101	0.090 (0.087) 0.324	*
C/N ratio	10.517 (0.969) < 0.001	1.246 (1.013) 0.207	0.418 (0.942) 0.651	2.471 (1.379) 0.078	
NO_3^- (mg bag^{-1}, November -May)	0.227 (0.288) 0.130	**2.447** **(1.403)** **0.012**	**3.706** **(1.701)** **0.002**	-0.155 (0.230) 0.632	*
NO_3^- (mg bag^{-1}, July–October)	0.479 (0.335) 0.008	-0.064 (0.392) 0.876	0.015 (0.415) 0.970	-0.349 (0.177) 0.189	
NH_4^+ (mg bag^{-1}, November–May)	0.166 (0.054) < 0.001	0.194 (0.130) 0.058	-0.024 (0.051) 0.673	-0.098 (0.023) 0.090	
NH_4^+ (mg bag^{-1}, July–October)	0.390 (0.045) < 0.001	0.102 (0.072) 0.121	0.043 (0.061) 0.462	-0.007 (0.045) 0.874	
N_2O (mg m^{-2} h^{-1}, June)	0.014 (0.003) < 0.001	-0.003 (0.004) 0.535	-1.008 (0.004) 0.060	**-0.009** **(0.003)** **0.017**	
N_2O (mg m^{-2} h^{-1}, October)	0.006 (0.002) < 0.001	0.001 (0.003) 0.843	-0.001 (0.002) 0.643	**-0.005** **(0.000)** **0.001**	
N_2O (mg m^{-2} h^{-1}, May)	0.003 (0.001) < 0.001	-0.000 (0.001) 0.932	**-0.002** **(0.001)** **0.045**	**-0.002** **(0.000)** **0.002**	
Total earthworm biomass (g fresh mass m^{-2})	50.013 (14.285) < 0.001	-27.298 (11.677) 0.087	**-38.392** **(8.625)** **0.014**	**-34.600** **(8.433)** **0.042**	

Old park lawns are in the intercept. Coefficients, standard errors (in parentheses) and *p*-values are presented. Significant effects ($p < 0.05$) are highlighted in bold and significant interaction terms are indicated with an asterisk

Soil NH_4^+ and NO_3^- availability

Compared to reference forests, soils in old parks had much higher NO_3^- and NH_4^+ availability in both the cold and warm season (Fig. 3A, B, E & F, Table 1). In reference forests, NO_3^- availability did not differ between the two tree types, while NH_4^+ availability was higher under deciduous trees than under evergreen trees, but the difference was not statistically significant.

In urban parks, plant functional type and park age had a clear effect on soil NO_3^- and NH_4^+ availability during the cold season (November to May), but not during the warm season (July to October) (Fig. 3, Table 2). During the cold season, NO_3^- availability was significantly higher under the two tree types than under lawns in old parks, but not in young parks (Fig. 3C). At the same time, NO_3^- availability under the two tree types was significantly higher in old parks than in young parks, while NO_3^- availability under lawns did not

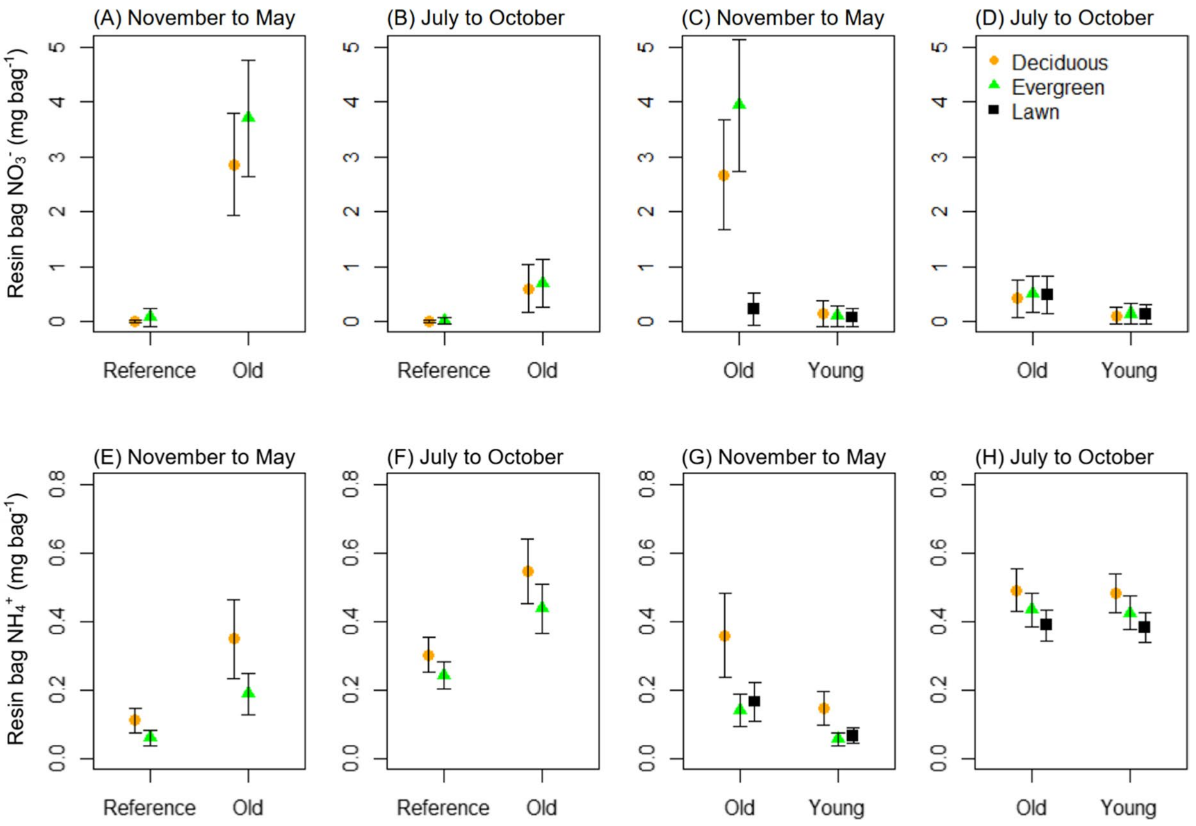

Fig. 3 Resin bag absorbed NO_3^- (upper panels; mg bag^{-1}, predicted mean ± SE) and NH_4^+ (lower panels; mg bag^{-1}, predicted mean ± SE) in reference forests and old urban parks (A, B, E, and F), and in old and young parks (C, D, G, and H) under different plant functional types (deciduous tree, evergreen tree, lawn) during cold (November – May) and warm (July – October) seasons. Values for old parks in the two plots per inorganic N form differ slightly because we present model predicted values. For raw values, see Fig. S2 in the supplementary material

differ between young and old parks. During the warm season, NO_3^- availability did not differ among the three plant functional types, while NO_3^- availability was higher in old parks than in young parks, but the difference was not statistically significant (Fig. 3D). In terms of NH_4^+, soils under deciduous trees had a higher NH_4^+ availability than evergreen trees and lawns in both young and old parks, independent of sampling seasons (Fig. 3G & H). Additionally, NH_4^+ availability, irrespective of plant functional type, was significantly higher in old parks than in young parks during the cold season, but not during the warm season.

N_2O flux

Compared to old parks, soil N_2O flux was significantly lower in reference forests, independent of plant functional type (Fig. 4A, Table 1). Additionally, in reference forests, soils under deciduous trees had higher N_2O fluxes than those under evergreen trees, where the mean value of soil N_2O flux was negative during all three sampling seasons.

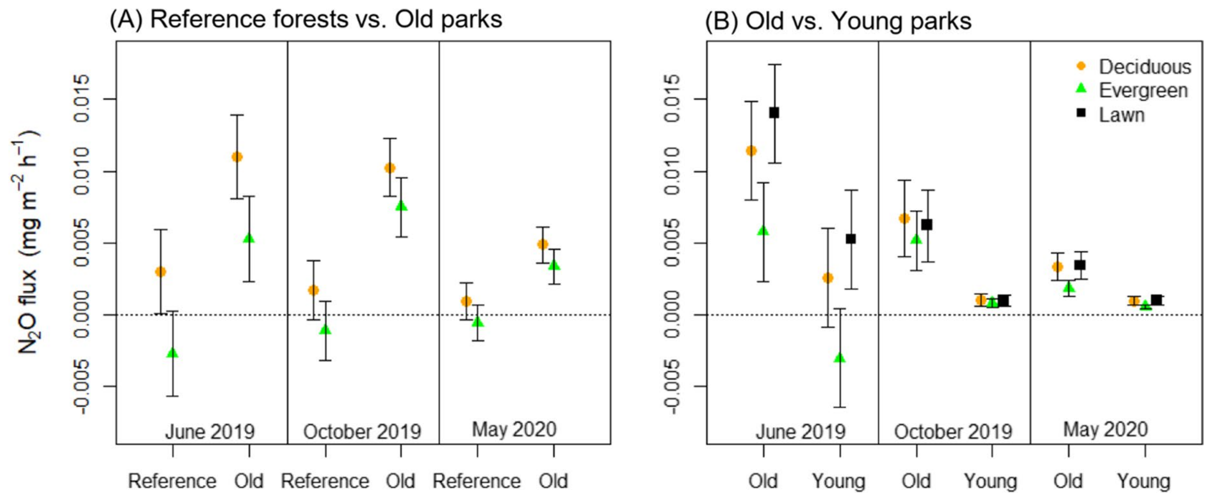

Fig. 4 Differences in soil N_2O flux (mg m^{-2} h^{-1}; predicted mean ± SE) between reference forests and old parks (A), and old and young parks (B) under different plant functional types (deciduous tree, evergreen tree, lawn). Values for old parks in the two plots differ slightly because we present model predicted values. For raw values, see Fig. S3 in the supplementary material

Plant functional type and park age had a clear effect on soil N_2O flux (Fig. 4B, Table 2). In both young and old parks, soil N_2O flux under evergreen trees was always lower than under deciduous trees and lawns across the three sampling seasons, especially in June. At the same time, independent of plant functional type, soils in old parks always had a significantly higher N_2O flux than those in young parks. Differences in soil N_2O fluxes among plant functional types, as well as between young and old parks, were greater in June than in May and October.

Earthworm biomass

Compared to old parks, soils in reference forests, especially under deciduous trees, had higher earthworm biomass, but the difference was not statistically significant (Fig. 5A, Table 1). In reference forests, earthworm biomass under deciduous trees was more than twice as high compared to evergreen trees.

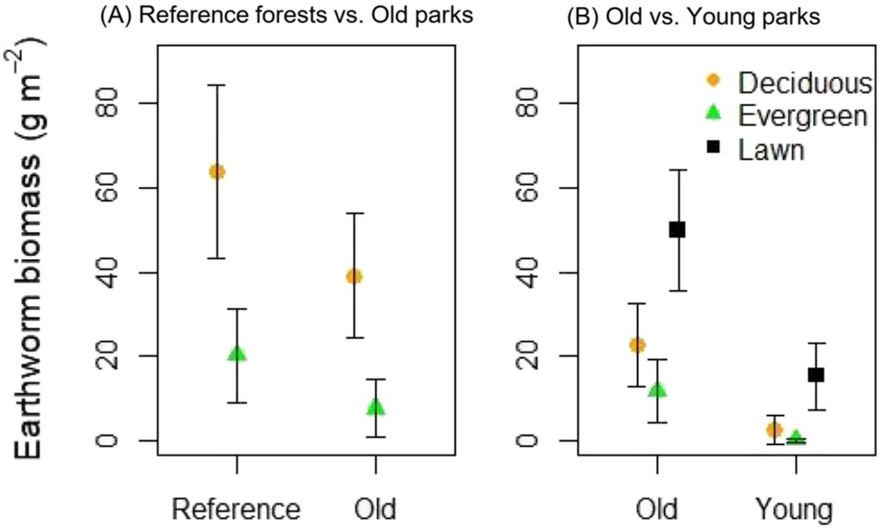

Fig. 5 Differences in total earthworm biomass (g fresh mass m^{-2}, predicted mean ± SE) between reference forests and old parks (A), and old and young parks (B) under different plant functional types (deciduous tree, evergreen tree, lawn). Values for old parks in the two plots differ slightly because we present model predicted values. For raw values, see Fig. S4 in the supplementary material

Plant functional type and park age had a clear effect on total earthworm biomass (Fig. 5B, Table 2). In both young and old parks, soils under lawns had the highest earthworm biomass, followed by deciduous trees, and soils under evergreen trees had the lowest earthworm biomass. Furthermore, independent of plant functional type, soils in old parks had significantly higher earthworm biomass than those in young parks.

Discussion

The main purpose of this study was to explore whether the excess N in urban environments (Malkki et al. 2018; Viippola et al. 2018) would influence plant functional type effects on soil N dynamics in urban parks, and whether N dynamics differ from those in natural/semi-natural boreal forests where N is a limiting factor for net primary production (NPP). We first assessed the potential of plant functional type to modulate N turnover in the N limited reference forests, after which we investigated whether the patterns observed in these forests take place in the N-enriched, strongly managed urban parks. Contrary to our hypothesis, plant functional type effect on soil N dynamics in old urban parks was similar to natural/semi-natural forests. Moreover, irrespective of park age, excess N inputs in urban environments did not minimise the effect of plant functional type on soil N dynamics, which was also unexpected. These results are discussed in detail below.

Effects of plant functional type on soil N dynamics in natural/semi-natural forests

Previous studies conducted at our study sites have shown that soil OM and C accumulation are strongly controlled by plant functional type, and that the highest concentrations and densities of soil OM and C are associated with evergreen trees in reference forests (e.g., evergreen tree: 23.86% OM and 7.89% C; deciduous tree: 10.46% OM and 4.82% C; see Setälä et al. (2016) and Lu et al. (2021) for further details). Given that C and N tend to be intimately linked in biogeochemical cycles (Vitousek et al. 1997), we may expect that N dynamics in these forests would also be affected by plant functional type. Indeed, our results showed that soil total N concentration under evergreen trees was ca. 25% higher than under deciduous trees. As N forms complex, poorly decomposable compounds with C in soils influenced by evergreens and other plants producing recalcitrant litter (see Knops et al. 2002), it is likely that the high soil %N under evergreens reflects the much higher OM and C content observed under these trees than under deciduous trees (Setälä et al. 2016; Lu et al. 2021). However, the difference in soil NO_3^- and NH_4^+ availability between evergreen and deciduous trees was insignificant. This is unexpected given that evergreen trees had a clear negative influence on soil pH and earthworm biomass, both of which are associated with reduced nitrification (Haimi et al. 1992; Ste-Marie and Paré, 1999; Lavelle et al. 2004). Moreover, soils under evergreen trees had clearly lower N_2O emissions than soils under deciduous trees. The reason for this remains open, but may be due to the lower soil pH and the slow litter decomposition rate that typify coniferous forest soils (Hansson et al. 2011) and urban park soils (Setälä et al. 2016; Lu et al. 2021). The consistently negative N_2O fluxes under evergreen trees suggest that forest soils under evergreen trees can serve as a N_2O sink (see also Goldberg and Gebauer 2009a, b). Taken together and supporting our previous studies (Setälä et al. 2016; Kotze et al. 2021), our results show that N turnover is influenced by plant functional type in boreal forests, which was associated with e.g., a higher capacity of evergreen soils to retain N compared to deciduous trees.

Effects of plant functional type on soil N dynamics in urban parks

As plant functional type has been shown to clearly associate with soil %OM and %C not only in natural/semi-natural forests but also in urban parks (Setälä et al. 2016; Lu et al. 2021), and due to the close linkage between C and N dynamics in various ecosystems (Vitousek et al. 1997), we might expect plant functional type to have a similar effect for N dynamics in urban parks. On the other hand, we hypothesised that the plant functional type effect on N dynamics should be diluted in urban parks, where N – unlike in boreal forests – is unlikely a limiting factor for NPP (and decomposition). Partially supporting our hypothesis, soil under evergreen trees in old parks was associated with slightly higher total N than those under deciduous trees and lawns. However, in contrast to our hypothesis, the difference in soil total N between the two tree types was not greater in the reference forests than in the unfertilized old parks (see Fig. 2A), suggesting that the plant functional type effect manifests itself even in urban parks with excess N input. This is not surprising given the strong plant functional type influence on soil %OM and %C in these managed parks (Setälä et al. 2016; Lu et al. 2021).

As with soil total N, evergreen trees in urban parks were associated with reduced availability of soil NH_4^+ when compared to deciduous trees. The low NH_4^+ availability under evergreen trees is likely attributable to recalcitrant litter (Silver and Miya 2001; Lu et al. 2021) and the low earthworm biomass under those trees, both of which contribute to low rates of N mineralisation (Steinberg et al. 1997; Knops et al. 2002; Lavelle et al. 2004). On the other hand, our results showed that lawn soils producing labile litter had similar availability of NH_4^+ with evergreen trees, which can be explained by the rapid N turnover under lawns due to frequent, substantial input of labile grass/herb clippings that likely enhance N transformation and microbial immobilisation in urban lawns (Raciti et al. 2008). However, unlike NH_4^+ availability, soil NO_3^- availability was almost identical among the three plant functional types. Similarly to Nidzgorski and Hobbie (2016), our results suggest that plant functional type does not have clear effects on reducing leaching of NO_3^- in urban greenspaces. This is likely due to the similar soil C/N ratio beneath the three plant functional types (see also Setälä et al. 2016), given that nitrification is strongly controlled by the soil C/N ratio (Finzi et al. 1998; Lovett et al. 2004; Gundersen et al. 2009). Furthermore, we showed that soils under evergreen trees always had lower N_2O emissions compared to deciduous trees and lawns, irrespective of sampling season. Besides the positive effects that earthworms can exert on N_2O emissions (see above), soil moisture content can boost nitrification and/or denitrification in urban environments (Robertson and Groffman 2015). Our results are in line with this: differences in N_2O emissions among the three plant functional types correlated positively with soil moisture in all sampling seasons (for soil moisture data, see Lu et al. 2021). It is worth noting that our studied parks are not irrigated, suggesting that the lower soil moisture content under evergreen trees compared to deciduous trees and lawns is related to plant functional type itself. Furthermore, the low soil bulk density under evergreen trees (see Setälä et al. 2017) can, at least partly, also explain lower N_2O emissions under evergreen trees than under lawns, corroborating findings by Li et al. (2014). Taken together, our results showed that the availability of NH_4^+, but not NO_3^-, and emissions of N_2O are influenced by plant functional type in urban parks and that evergreen trees were associated with reduced availability of NH_4^+ and emissions of N_2O, which can, at least partly, explain the high soil total N under evergreen trees.

Effects of park age on the ability of plant functional type to affect soil N dynamics

In terms of park age, we hypothesised that plant functional type effects on N dynamics are minimal in young parks due to (i) recent, large-scale park construction induced disturbances and (ii) the short time that plants have interacted with soils there. Refuting our hypothesis, plant functional type had an influence on soil N in young parks: soil total N was much higher under lawns than under the two tree types. This may be explained by grass clippings remaining on lawns after mowing that are a considerable source of N input (Qian et al. 2003; Kaye et al. 2005), and the less dense grass/herb cover under tree canopies than in lawn plots. However, in old parks, soils under lawns had the lowest N concentrations, which is in line with previous studies reporting the reduced capacity of lawns to retain N with age (Porter et al. 1980; Frank et al. 2006). This, combined with the low N outputs (especially N_2O emissions) under lawns in young parks, may explain the high soil total N there. On the contrary, soil total N under the two tree types increased with park age, which may relate to the increased tree root biomass with stand age (Yuan and Chen 2010). Our results thus suggest that, even in strongly disturbed parks prone to constant management practices, plant functional type effects on soil total N are clearly detectable. However, these effects are modulated by park age, most likely due to the stabilization of plant-soil interactions with time (Raciti et al. 2011; Setälä et al. 2016).

Also the availability of soil inorganic N (NH_4^+ and NO_3^-) and N_2O emissions in young parks were sometimes influenced by plant functional type, which, again, refuted our hypothesis. Surprisingly, despite the fact that plant functional type effects on soil total N were clearly associated with park age, plant functional type effects on the availability of inorganic N and N_2O emissions were insensitive to park age. This can be explained by the same pattern of plant functional type effects on soil pH, moisture content, C/N ratio and earthworm biomass in young parks as in old parks, assuming that differences in e.g., soil temperature and precipitation did not vary much among the sampling sites that are located in close proximity to one another. Additionally, our results showed that young parks had consistently lower N_2O emissions than old parks in all three sampling seasons. This may be due to the substantially lower earthworm biomass (Borken et al. 2000; Lubbers et al. 2013) – together with slightly lower available NO_3^- and moisture content – in young parks than in old parks. Overall, the results of this study strongly suggest that, despite the recent disturbances and short time of plant-soil interaction in young parks, the effects of plant functional type on soils and their biota are already visible in these parks (see also Setälä et al. 2016; Francini et al. 2018).

Conclusions

Similar to natural/semi-natural forests, plant functional type, irrespective of park age, influenced soil N dynamics in urban parks. Results of our study suggest that the excess N inputs that expunges N as a limiting factor in urban environments do not minimise the effect of plant functional type on soil N dynamics. Evergreen trees tend to have the highest ability to enhance soil N accumulation and reduce N_2O emissions from soil to the atmosphere, thereby contributing to minimising climate change. Further, given the fact that our studied parks are not fertilized, the similarity in soil total N concentrations under trees in old parks and natural/semi-natural forests strongly suggests that urban parks under cool climate have considerable capacity to accumulate N in soils. In summary, our study highlights the strong effects of plant functional type on soil N dynamics in urban parks. Choosing appropriate plant functional types – for example evergreen trees instead of plain lawn – in future urban planning could enhance soil provisioned ecosystem services.

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Author's contribution **Changyi Lu**: Writing—original draft, Methodology, Formal analysis, Investigation. **D. Johan Kotze**: Writing—review & editing, Methodology. **Heikki M. Setälä**: Conceptualization, Writing—review & editing, Methodology.

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