Soil sealing causes substantial losses in C and N storage in urban soils under cool climate

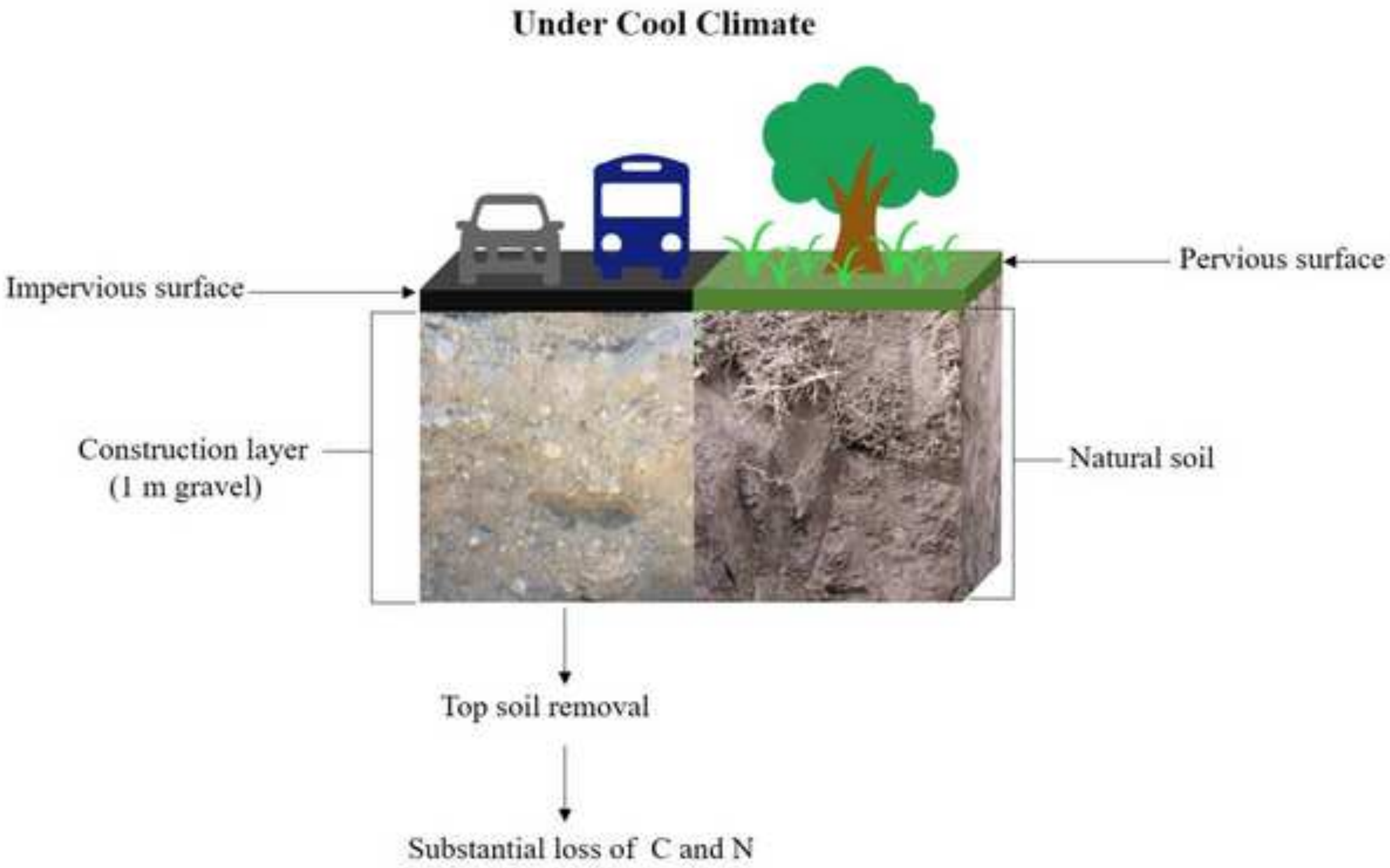
Lu, Changyi

2020-07-10

Lu , C , Kotze , J & Setälä , H 2020 , ' Soil sealing causes substantial losses in C and N storage in urban soils under cool climate ' , The Science of the Total Environment , vol. 725 , 138369 . https://doi.org/10.1016/j.scitotenv.2020.138369

http://hdl.handle.net/10138/346043
https://doi.org/10.1016/j.scitotenv.2020.138369

***Graphical Abstract**



***Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)**

HIGHLIGHTS

- Under cold climate, soil underneath impervious surfaces contain little C and N
- These sealed soils harboured much lower C and N than in warmer countries
- Sealed soils had 15 times less C than pervious park soil
- The removal of natural soil below asphalt is responsible for C and N losses in cities

Soil sealing causes substantial losses in C and N storage in urban soils under cool climate

Changyi Lu, D. Johan Kotze, Heikki M. Setälä
Faculty of Biological and Environmental Sciences, Ecosystems and Environment Research Programme, University of Helsinki, Niemenkatu 73, FIN-15140 Lahti, Finland

Abstract

Urban soil can store large amounts of carbon (C) and nitrogen (N). To accurately estimate C and N storage in urban soils, C and N contents underneath impervious surfaces - the most prevalent land cover type in cities - should be taken into account. To date, however, only few studies have reported urban soil C and N content underneath impervious surfaces, and no data exist for cities under cold/cool climates, such as the Boreal zone. Here, we studied, for the first time, the effects of sealing on soil C and N storage in a Boreal city. Sealed soils were sampled for physico-chemical and biological parameters from 13 sites in the city of Lahti, Finland, at three depths (0-10 and 45-55 cm, representing the construction layer composed of gravel, other moraine material and crushed rock, and the native soil layer beneath the ca. 1 m thick construction layer). Our results show that urban soils underneath impervious surfaces in Finland contain 11 and 31 times less C and N content, respectively, compared with warmer regions. This is due to a deep C and N deficient construction layer below sealed surfaces. Even though impervious surfaces cover ca. twice the area of pervious surfaces in the centre of Lahti, we estimate that only 6% and 4% of urban soil C and N, respectively, are stored underneath them. Furthermore, we found very little C and N accumulation underneath the sealed surfaces via root growth and/or leakage through ageing asphalt. Our results show that soil sealing, in concert with a massive top soil removal typical to cold climates, induces a considerable loss of C and N in Boreal urban areas.

Keywords: Impervious surfaces; Top soil removal; Construction layer

1. Introduction

Urban sprawl and densification have changed urban land cover considerably in recent decades (Abrantes et al., 2016; Catalán et al., 2008), with an increasing demand for land often taking place at the expense of greenspace (Haaland and van den Bosch, 2015; Lin et al., 2015; Pauleit et al., 2005; Rafiee et al., 2009). Urban greenspaces, such as parks, gardens and remnant forests, play an increasingly important role for urbanites in terms of recreation and physical exercise (Niemelä et al., 2010). Furthermore, urban greenspaces, especially their soils, can provide many other significant functions or ecosystem services, such as carbon (C) and nitrogen (N) sequestration, climate regulation and water purification (Bolund and Hunhammar, 1999; Raciti et al., 2011; Setälä et al., 2016). For example, urban soil, including remnant forest soils, and park and garden soils, plays a significant role in sequestering atmospheric C (Pouyat et al., 2006) and studies have shown that urban soils can store even more C and N than agricultural and forest soils (Cambou et al., 2018; Edmondson et al., 2012; Pouyat et al., 2009; Pouyat et al., 2006; Raciti et al., 2011). However, soil C pools in urban areas are a reflection of various land use activities that typify urbanization (Pouyat et al., 2002), of which soil sealing is perhaps the most prominent (Dorendorf et al., 2015; Pataki et al., 2006; Pouyat et al., 2006). Most research has overlooked soils beneath impervious surfaces as providers of ecosystem services, even though land covered by buildings, roads and other grey infrastructure, are the most typical cover types in urban areas (Liu et al., 2014). Consequently, it is necessary to consider the influence of soil sealing on, e.g. carbon and nitrogen content when determining the C and N budgets of urban areas.

As of 2010, approximately 600 000 km^2 of impervious surface area has been built around the world (Elvidge et al., 2010; Liu et al., 2014). Soil sealing, one of the most important threats to soils (van der Putten et al., 2018), produces many negative effects on the ecology of soils, including the hampering of energy transfer, gas exchange, water movement and microbial activity (Scalenghe and Marsan, 2009). Due to the inaccessibility of soil beneath impervious surfaces and the lack of interest, only few studies have investigated these soils in terms of soil C, N and organic matter (OM) content, or biological activity. These studies have shown that C and N storage under sealed soils are significantly lower than in non-sealed soils at the same locality (Piotrowska-Długosz and Charzyński, 2015; Raciti et al., 2012a; Wei et al., 2014a; Wei et al., 2014b; Yan et al., 2015). This can be due to the removal of the original C and nutrient rich top soil that is replaced by C- and N-devoid constructing material, and/or because the natural plant-soil feedback system feeding soils with C and nutrients is hindered when the soil is sealed (Majidzadeh et al., 2017; Majidzadeh et al., 2018). Such adverse effects have been shown to reduce microbial biomass, activity (Majidzadeh et al., 2018; Wei et al., 2013; Zhao et al., 2012) and alter soil microbial community composition (Hu et al., 2018) in temperate and subtropical climates.

All of the aforementioned studies were conducted in temperate or subtropical climates, with no study, to our knowledge, being conducted under cold climatic conditions, such as the Boreal zone. Temperature affects many soil processes, such as C and N mineralization (Bond-Lamberty and Thomson, 2010; Davidson and Janssens, 2006; Fang and Moncrieff, 2001). This seems to hold also for urban milieus (Majidzadeh et al., 2018). As most of the terrestrial carbon in cold climates is stored in soils because of the slow rate of decomposition due to low temperatures and sometimes anoxic soil conditions (Liski and Westman, 1997), the ability of soils underneath impervious surfaces in the Boreal zone to sequester and store C and N is of interest not only at the local/regional scale but also at the global scale to improve estimates of C and N storage in urban areas. Thus far, due to the lack of data, sealed soils have usually been considered to contain zero carbon (Dorendorf et al., 2015; Eigenbrod et al., 2011; Tomlinson and Milne, 2006) or calculations have been based on literature that are not necessarily specific to the site (Churkina et al., 2010;

Kuittinen et al., 2016; Raciti et al., 2012b). The lack of information on the capacity of sealed soils to sequester/store C and N from various climatic regions likely over- or under-estimates the C budget of urban soils – both locally and globally.

The main aim of this study is, for the first time, to (i) evaluate the effects of soil sealing on C and N storage in the Boreal urban environment, and (ii) to compare the effects of soil sealing on urban C and N storage between warm and cool climates. We hypothesize that 1) Boreal cities lose a disproportionally high amount of their C and N pools in highly sealed areas with a dense traffic network and high building density, and 2) these losses, due to construction activities, are much larger in comparison to cities in warmer climates. This is because the OM-rich soils that typify Boreal regions are replaced by a ca. 1 m layer of OM-free construction fill to prevent the destructive effects of freezing-thawing events on infrastructure during the cold season (Mika Lastikka, personal communication, Lahti City, Street maintenance unit). In addition, we hypothesize that 3) soils immediately below the asphalt receive more C and N with time than soils deeper down the construction layer. This is because impervious surfaces, such as asphalt, often have cracks and crevices through which water soluble materials can infiltrate into the soil immediately underneath the asphalt. Finally, we aim to calculate the C and N budgets of the city centre of Lahti to assess how much sealed soils contribute to urban C and N storage in a typical mid-size Boreal city.

2. Materials and methods

2.1 Study area

This study was conducted in the city of Lahti (60°59′00″N, 25°39′20″E, with a population of ca. 120 000), located in southern Finland. This area belongs to the Boreal climatic zone, with an annual mean precipitation and temperature of 653 mm and 4.4 °C, respectively (Finnish Meteorological

Institute: https://en.ilmatieteenlaitos.fi/). The National Resource Conservation Service (NRCS) classifies Lahti soils primarily in the Spodosol suborder, and the bedrock of Lahti is characterized by mica schist, mica gneiss and microcline granite. The city centre is 407.8 ha in size, excluding water areas (Fig. 1), with an impervious cover of 64.1% (Sinivuo, 2007).

2.2 Soil sampling

We collected soil samples from June to August 2018. Sampling was opportunistic, selecting urban road construction sites where road or pavement surfaces were temporarily removed and soil pits being exposed. Information about these localities and sampling permission were obtained from the City Construction Office of Lahti. We selected 13 sites (including six main streets, six roadside pavements and one block of flats; Table S1, Fig. S1) distributed across the city centre. In Finland, all roads and buildings are typically constructed on top of a ca. 1 m deep construction layer (mostly gravel) to prevent up-lifting of asphalt or houses due to freezing-thawing events during the cold period. In southern Finland, as elsewhere under cold climate, materials used in the construction layer and its depth depend on the native soil type. The depth of the construction layer varies between 60 – 120 cm when the native soil is mineral. In the city of Lahti, the support layer is gravel or crushed rock and the bearing layer is commonly crushed rock. At the very bottom, there can sometimes be a filtering layer made of sand, but in Lahti, this is not commonly the case (Liikennevirasto, Tierakenteen suunnittelu 2018). Consequently, all material used in the construction layer are virtually free of organic matter. We took soil samples from the exposed wall of each soil pit at three depths: immediately underneath (0 – 10 cm) the asphalt surface, from 45 - 55 cm below the asphalt and from the native soil layer right beneath the construction layer. The depth at which the native soil occurred varied from 60 cm to 120 cm (mean = 96 cm) below the asphalt. From each depth, we collected 500 cm^3 of soil that was placed into a sterile plastic bag. A total of 38 samples were collected from 13 sites; one native sample could not be collected from underneath the block of flats. Soil samples were stored in a freezer at -20°C. Before analyses, the thawed samples were divided into two subsamples. One subsample was stored at 4 °C for the analysis of soil physical-chemical properties and the other part was stored at -20 °C for soil microbial activity analyses. In this study, we did not sample soil from pervious areas, but used data collected from underneath lawns in old urban park soils (30 samples) in the same city at three depths (see Setälä et al. 2016) for comparative purposes.

2.3 Soil physical and chemical analyses

Air-dried soils were sieved through a 2 mm mesh, checked for potential roots and other organic debris, and both the sieved soil and the material remaining on the sieve were stored separately in plastic bags for later use. Soil pH was measured in 1/5 (v/v) fresh soil/ultrapure water using a glass electrode. Soil water content was determined by drying the soils at 105 °C for 24 h. Total carbon (TC) and nitrogen (TN) were analyzed by dry combustion at 1350 °C using a LECO CNS-2000 Elemental Analyzer (0.07% C and 0.09% N detection limits). Soil OM percentage was calculated by loss on ignition via incinerating soils at 550 °C in a muffle furnace for 5 h. The soil samples, especially those that were taken from the first two depths underneath the sealed surfaces, contained a high percentage of gravel (particle size > 2 mm). In order to measure the percentage OM of the gravel-sized fraction, we divided each sample into two subsamples (particle size < 2 mm and > 2 mm) and analyzed their OM content separately. After that, we calculated % OM for each gravel-sized fraction and then combined the results according to the gravel percentage (in mass). Due to the high gravel content making the soils loose in structure and thus difficult to sample per volume, approximate soil bulk density (BD) was determined in the laboratory: the soil was placed into a cylindrical container with known volume and pressed as compact as possible, after which the soil samples were oven-dried at 105 °C for 24 h. Soil BD was calculated based on soil volume and dry mass.

2.4 Soil microbial activity

CO_2 production was measured as an indicator of soil microbial activity. Soil respiration was measured using an Apollo 9000Hs TOC analyzer in the laboratory at 22 °C. The values do not represent field conditions in southern Finland (mean soil temperature about + 7 °C) (Yli-Halla and Mokma, 1998) but those measured under laboratory conditions. We placed ca. 15 g of non-sieved, melted soil with known water content into a 40 ml sample vial. All vials were placed in a sample tray for 2 h before closing the cap. Thereafter, all vials were sealed airtight for the measurement of CO_2 production. CO_2 production of each vial was measured twice with a time interval of 2 h between measurements. CO_2 concentration was calibrated with a known amount of CO_2 being released from a $NaHCO_3$ solution with 21% H_3PO_4. Respiration rate was calculated as the difference in CO_2 concentration between the two measurements. Data for respiration rates in pervious park soils are lacking.

2.5 Statistical analyses

All statistical analyses were carried out in R 3.0.2 (R Core Team, 2013). The Shapiro-Wilks test was used to test for normality of the response variables. If the assumptions of normality were not met, data were either Ln or square-root transformed. In this study, all variables, except OM and bulk density data, were normally distributed after transformation. We used a multivariate analysis of variance (MANOVA) to determine the effect of soil depth on pH, water content, OM, C, N, the C/N ratio, respiration rate and bulk density of both sealed and pervious park soils, separately. This is because the three sampling depths differed between sealed and pervious park soils: the top layer (0-10 cm; pervious and impervious), the middle layer (pervious park soil: 11-20 cm; sealed soil: 45-55 cm) and the native layer (pervious park soil: 21-50 cm; sealed soil: 60-130 cm, i.e. right below the construction layer).

3. Results

3.1 Soil C, N, OM concentrations and the C/N ratio

Construction soil below impervious surfaces had substantially lower soil C, N and OM concentrations than those in pervious park soils in the top and middle layer (Fig. 2A, B & C, Table 1, Table S2). Underneath impervious surfaces, % C, N and OM was much higher in the native soil than in the top and middle layers, and % C and OM in the top layer were similar to the middle layer. N concentration in the construction soil did not differ between the top and middle layer. Conversely, in urban parks, soil in the top layer had the highest % C, N and OM and soil in the bottom layer the lowest. Despite the somewhat different sampling depths, C, N and OM concentrations in the native soil did not differ between the impervious and pervious soils (Fig. 2). In the top layer, the soil C/N ratio was more than two-fold higher underneath impervious surfaces compared to pervious park soils (Fig. 2D, Table 1). In soils underneath asphalt, the C/N ratio in the top layer was 74% and 93% higher than in the middle layer and native soil, respectively. However, in the pervious park soils, the C/N ratio in the bottom layer was 27% and 23% higher than in the top and middle layers, respectively.

3.2 Soil moisture content, pH and bulk density

Soils underneath impervious surfaces had a lower soil moisture content compared with those in pervious park soils (Fig. 2E, Table 1). Underneath impervious surfaces, native soil was 5.5 times more moist than soils in the top layer, the latter of which was slightly higher than soils in the middle layer. However, in pervious park soils, soil moisture in the bottom layer was much lower than that in the top layers. Soil underneath impervious surfaces had higher pH and bulk density values compared with those in pervious park soils (Fig. 2F & G, Table 1). In pervious park soils, even though the bottom soil layer had the highest pH and bulk density, there were no statistically significant differences in these parameters among the three sampling depths. However, underneath impervious surfaces, soil pH in the top layer was considerably higher than that in the middle and native soil layers. BD was the same in the top and middle soil layers but was substantially higher than in the native layer.

3.3 Soil respiration rate

Underneath impervious surfaces, native soils had the highest soil respiration rate, which was significantly higher than that in soils of the two constructed layers (Fig. 2H, Table 1). Soil respiration rates did not differ between the top two constructed layers.

4. Discussion

Results support our first hypothesis that soil sealing in Boreal urban areas has highly negative effects on soil C and N storage due to the massive removal of top soil typical to construction activities in colder climates. As a consequence, and as expected from our second hypothesis, C and N densities underneath impervious surfaces are considerably lower in cold than in warmer countries. For example, soil C density underneath (0-100 cm) impervious surfaces in the city of Lahti (1.2 kg

C m^{-2}) was more than 8 times lower than in New York city, USA (9.6 kg C m^{-2}) (Cambou et al., 2018) and the city of Leicester, UK (13.5 kg C m^{-2}) (Edmondson et al., 2012). However, our third hypothesis according to which soils immediately underneath asphalt/impervious surfaces receive more C and N with time compared to soils deeper down the construction layer was not supported: concentrations/densities of these two elements were very much the same in the two construction layers. These results are discussed in detail below.

4.1 Effects of soil sealing on soil C and N storage

C and N concentrations at 0-10 cm depth were, respectively, 24 and 56 times higher in pervious park soils than in impervious constructed soils. The difference between the two soil types is larger than hitherto reported in cities in warmer climates. For instance, in the two temperate cities, New York (Raciti et al., 2012a) and Beijing (Hu et al., 2018), C and N content in pervious soils were between 1.6 and 2.5 (for C) and 2.0 to 21 times (for N) higher than in sealed soils at 0-15 cm. Likewise, removal of the top 10 cm soil before sealing caused a ca. 45% decrease of C and N compared with pervious soil at the same depth (Majidzadeh et al., 2018). Cambou et al. (2018) reported that, even though pervious soils in New York contained substantially more C than sealed soils in the top 30 cm, deeper soils (30-100 cm) had similar C concentrations between sealed and pervious soils. In the current study, the native soil at 1 m depth underneath impervious surfaces contained C and N at about similar concentrations as those detected under pervious park soils. This indicates that deep soils underneath constructed layers still retain C and N that likely derives from times prior to soil sealing. The very low microbial activity – yet higher than that in the construction layer – detected in this soil layer, as also reported by Piotrowska-Długosz and Charzyński (2015) and Wei et al. (2013), suggests that OM degradation is a slow process underneath impervious surfaces. Interestingly, Majidzadeh et al. (2017) reported that C accumulation under sealed surfaces can be a dynamic process with C loss taking place during the first 53 years after soil sealing while after that C starts to accumulate under warm climate conditions. These results clearly imply that (i) initial C and N loss underneath impervious surfaces is mainly due to top soil removal and (ii) these decreases are substantially larger in cities under cold climatic conditions.

To enable comparison of our results and those of previous studies, we transformed our C and N concentration data into densities (kg C or N m^{-2}) using the fine soil fraction (< 2 mm) according to Wei et al. (2014b). The proportion of this soil fraction in the top, middle and native layers underneath impervious surfaces was 46, 49 and 72%, respectively. We estimate that soils underneath impervious surfaces (at 0 to 100 cm depth) in a Boreal city can store 1.20 kg C m^{-2}. This C density is considerably lower than those reported for cities in temperate and subtropical areas. For example, C densities under sealed soils in warmer climates vary from 3.3 to 9.6 kg m^{-2} (0-100 cm depth) in some cities in the United States (Cambou et al., 2018; Pouyat et al., 2006; Raciti et al., 2012a). In Leicester (temperate climate), UK, the respective density under sealed soils is 13.5 kg m^{-2} (15-100 cm depth) (Edmondson et al., 2012), and 5.36 kg m^{-2} (0-80 cm) in the temperate city Urumqi, China (Yan et al., 2015). These findings show that C density under sealed soil is 3 to 11 times lower in Boreal cities than in cities located in temperate and subtropical areas.

Comparing N density values between cities is difficult because of varying sampling depths among studies. Furthermore, no previous estimates of N density at 0-100 cm depth under impervious surfaces exist. In the city of Lahti, N density in the constructed soil layer was 0.04 kg m^{-2} (0-100 cm depth). Raciti et al. (2012a) and Wei et al. (2014b) reported 0.014 kg N m^{-2} (0-15 cm) in New York and 0.25 kg N m^{-2} (0-20 cm) in Yixing city (subtropical climate), respectively. Assuming that deep soils have approximately the same N concentrations than top soils, sealed soil from 0-100 depth in New York and Yixing city is estimated to contain 0.10 and 1.25 kg N m^{-2}, respectively. These estimates suggest that N density under sealed soils in Boreal areas is 2.5 to 31 times lower than in temperate and subtropical areas, thereby supporting our hypothesis.

The difference in sealed soil C and N densities between Boreal and temperate/sub-tropical cities likely results from different depths of the constructing layer, since soil C and N storage correlates negatively with soil mineral matter content (Qin et al., 2015), and because the construction layer – deriving from sand pits and stone quarries – is virtually devoid of soil organic matter (SOM). Consequently, it is not surprising that the loss of C and N under impervious soils is relatively small in cities where the depth of the construction layer can be as low as 10 cm in Tokyo, Japan (Kida and Kawahigashi, 2015), 15 cm in Leicester, UK (Edmondson et al., 2012) and 20 cm in Nanjing, China (Wei et al., 2013). Interestingly, in warmer climates, C density does not necessarily differ between pervious and impervious soil when the thickness of the construction layer does not exceed 15 cm (Edmondson et al., 2012), emphasising that the depth of the construction layer influences the pools of C and N in the city.

It is well-established that ageing asphalt and other soil sealing materials do not completely isolate the above-ground from the below-ground milieus (Krebs et al., 2014), which can result in the accumulation of OM underneath sealed surfaces (Burghardt, 2006). In addition, soils underneath sealed surfaces may be enriched with OM deriving from plant roots entering this matrix from both below and from the side (Burghardt, 2006). However, the relative importance of this OM build-up is not known. Even though cracks were frequently observed in the asphalt during sampling, our results indicate that constructed soils underneath impervious surfaces do not receive substantial amounts of OM, C and N from above. Furthermore, we detected no roots beneath the asphalt in our study, even though some of the sites were close to street trees. This suggests that root growth in Boreal city soils is hampered by the low availability of nutrients and water, high soil BD, as well as high pH that typify soils underneath impervious surfaces. These observations further emphasize the adverse effects of soil transportation (see below) and sealing on soil C and N stocks, and the capacity of these constructed soils to sequester C and N in cities under cold climate.

4.2 C and N storage at the city scale in Boreal areas

To estimate how much C and N is lost in cities under cold climate due to i) the removal of a ca. 1 m thick fertile top soil, ii) replacing it with a C- and N- deficient construction layer and then iii) soil sealing, we calculated soil C and N budgets for downtown Lahti. This area is 407.8 ha in size, with 261.5 ha of impervious surfaces and 146.3 ha of pervious surfaces (Sinivuo, 2007). Using our C and N density data, we estimated that in the Lahti city centre (Fig. 1), soils underneath impervious surfaces down to a depth of 1 m store 3 112 tonnes of C and 105 tonnes of N, while the respective numbers underneath pervious surfaces are 46 538 tonnes of C and 2 750 tonnes of N. So, of the total amount of C and N stored in soils in the centre of Lahti, only 6% of C and 4% of N were stored underneath impervious surfaces, even though the area of impervious surfaces is almost double that of pervious surfaces. Presuming that the original top soil that was transported and dumped outside the city contained the same amount of C and N as urban park soil, top soil removal causes a loss of 83 183 tonnes of C and 4 916 tonnes of N from the city centre. This means that 1.8 times more C and N were lost from the city due to soil removal than what is stored under pervious surfaces today. These results suggest that the negative effects of top soil removal on urban C and N stocks can not be compensated for by C and N sequestration provided by urban greenspace soils in Boreal areas.

To conclude, our results show that soils underneath impervious surfaces contribute very little to the storage of C and N in Boreal urban areas, which stems from the need to remove C and N rich top soil before sealing. It is commonly reported that urban soils can be richer in OM, C and N than soils in adjacent rural sites, which make urban areas an important sinks for these elements (Cambou et al., 2018; Edmondson et al., 2012; Pouyat et al., 2009; Pouyat et al., 2006; Raciti et al., 2011). However, if the proportion of sealed surfaces is high and substantial amounts of top soil is removed due to construction of urban infrastructure, the contribution of urban soils to C sequestration and storage is scant. It is worth noting that C and N budgets describing the Lahti city centre area assumes that the depth of the construction layer is 1 m deep. Since the depth of this layer can vary according to different purposes (buildings, roads, pavements, parking lots, etc.), future studies should take this variation into account not only in Boreal cities but also in cities under warmer climates. Our study suggests that previous estimates on C and N storage beneath impervious surfaces deriving from cities in warmer climate are not applicable to cities in colder climate, simply because the depth and thus the amount of top soil removal prior to street/building construction can be substantially different.

Acknowledgements

We thank Emilia Niemistö and John Allen for help in the field and laboratory, and Santeri Savolainen for help with sample analysis. This research was funded by the China Scholarship Council fellowship (201704910875), an Academy of Finland grant (Grant number: 315987/Parktraits), and the Lahti foundation from the University of Helsinki.

References

Abrantes P, Fontes I, Gomes E, Rocha J. Compliance of land cover changes with municipal land use planning: Evidence from the Lisbon metropolitan region (1990–2007). Land Use Policy 2016; 51: 120-134.

Bolund P, Hunhammar S. Ecosystem services in urban areas. Ecological Economics 1999; 29: 293-301.

Bond-Lamberty B, Thomson A. Temperature-associated increases in the global soil respiration record. Nature 2010; 464: 579-82.

Burghardt W. Soil sealing and soil properties related to sealing. Geological Society, London 2006;

Special Publications, 266: 117-124.

Cambou A, Shaw RK, Huot H, Vidal-Beaudet L, Hunault G, Cannavo P, et al. Estimation of soil organic carbon stocks of two cities, New York City and Paris. Sci Total Environ 2018; 644: 452-464.

Catalán B, Saurí D, Serra P. Urban sprawl in the Mediterranean?: Patterns of growth and change in the Barcelona Metropolitan Region 1993–2000. Landscape and Urban Planning 2008; 85: 174-184.

Churkina G, Brown DG, Keoleian G. Carbon stored in human settlements: the conterminous United States. Global Change Biology 2010; 16: 135-143.

Davidson EA, Janssens IA. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 2006; 440: 165-73.

Dorendorf J, Eschenbach A, Schmidt K, Jensen K. Both tree and soil carbon need to be quantified for carbon assessments of cities. Urban Forestry & Urban Greening 2015; 14: 447-455.

Edmondson JL, Davies ZG, McHugh N, Gaston KJ, Leake JR. Organic carbon hidden in urban ecosystems. Sci Rep 2012; 2: 963.

Eigenbrod F, Bell VA, Davies HN, Heinemeyer A, Armsworth PR, Gaston KJ. The impact of projected increases in urbanization on ecosystem services. Proceedings of the Royal Society B: Biological Sciences 2011; 278: 3201-3208.

Elvidge CD, Tuttle BT, Sutton PC. Collaborative tool for collecting reference data on the density of constructed surfaces worldwide. Proc SPIE 2010; 7840: 1-8.

Fang C, Moncrieff JB. The dependence of soil CO2 efflux on temperature. Soil Biology & Biochemistry 2001; 33: 155-165.

Haaland C, van den Bosch CK. Challenges and strategies for urban green-space planning in cities undergoing densification: A review. Urban Forestry & Urban Greening 2015; 14: 760-771.

Hu Y, Dou X, Li J, Li F. Impervious Surfaces Alter Soil Bacterial Communities in Urban Areas: A

Case Study in Beijing, China. Front Microbiol 2018; 9: 226.

Kida K, Kawahigashi M. Influence of asphalt pavement construction processes on urban soil formation in Tokyo. Soil Science and Plant Nutrition 2015; 61: 135-146.

Krebs G, Kokkonen T, Valtanen M, Setala H, Koivusalo H. Spatial resolution considerations for urban hydrological modelling. Journal of Hydrology 2014; 512: 482-497.

Kuittinen M, Moinel C, Adalgeirsdottir K. Carbon sequestration through urban ecosystem services: A case study from Finland. Sci Total Environ 2016; 563-564: 623-32.

Liikenneviraston O. Tierakenteen suunnittelu. 2018. https://julkaisut.vayla.fi/pdf8/lo_2018-38_tierakenteen_suunnittelu_web.pdf. ISSN-L 1798-663X; ISSN 1798-6648; ISBN 978-952-317-632-4.

Lin B, Meyers J, Barnett G. Understanding the potential loss and inequities of green space distribution with urban densification. Urban Forestry & Urban Greening 2015; 14: 952-958.

Liski J, Westman CJ. Carbon storage in forest soil of Finland .2. Size and regional patterns. Biogeochemistry 1997; 36: 261-274.

Liu Z, He C, Zhou Y, Wu J. How much of the world’s land has been urbanized, really? A hierarchical framework for avoiding confusion. Landscape Ecology 2014; 29: 763-771.

Majidzadeh H, Lockaby BG, Governo R. Effect of home construction on soil carbon storage-A chronosequence case study. Environ Pollut 2017; 226: 317-323.

Majidzadeh H, Lockaby BG, Price R, Governo R. Soil Carbon and Nitrogen Dynamics beneath Impervious Surfaces. Soil Science Society of America Journal 2018; 82.

Niemelä J, Saarela SR, Söderman T, Kopperoinen L, Yli-Pelkonen V, Väre S, et al. Using the ecosystem services approach for better planning and conservation of urban green spaces: a Finland case study. Biodiversity and Conservation 2010; 19: 3225-3243.

Pataki DE, Alig RJ, Fung AS, Golubiewski NE, Kennedy CA, McPherson EG, et al. Urban ecosystems and the North American carbon cycle. Global Change Biology 2006; 12: 2092-

2102.

Pauleit S, Ennos R, Golding Y. Modeling the environmental impacts of urban land use and land cover change—a study in Merseyside, UK. Landscape and Urban Planning 2005; 71: 295-310.

Piotrowska-Długosz A, Charzyński P. The impact of the soil sealing degree on microbial biomass, enzymatic activity, and physicochemical properties in the Ekranic Technosols of Toruń (Poland). Journal of Soils and Sediments 2015; 15: 47-59.

Pouyat R, Groffman P, Yesilonis I, Hernandez L. Soil carbon pools and fluxes in urban ecosystems. Environ Pollut 2002; 116: S107-S118.

Pouyat RV, Yesilonis ID, Golubiewski NE. A comparison of soil organic carbon stocks between residential turf grass and native soil. Urban Ecosystems 2009; 12: 45-62.

Pouyat RV, Yesilonis ID, Nowak DJ. Carbon storage by urban soils in the United States. J Environ Qual 2006; 35: 1566-75.

Qin Y, Yi S, Chen J, Ren S, Ding Y. Effects of gravel on soil and vegetation properties of alpine grassland on the Qinghai-Tibetan plateau. Ecological Engineering 2015; 74: 351-355.

R Core Team. R: A Language and Environment for Satistical Computing. Vienna: R Foundation for Statistical Computing. 2013.

Raciti SM, Groffman PM, Jenkins JC, Pouyat RV, Fahey TJ, Pickett STA, et al. Accumulation of Carbon and Nitrogen in Residential Soils with Different Land-Use Histories. Ecosystems 2011; 14: 287-297.

Raciti SM, Hutyra LR, Finzi AC. Depleted soil carbon and nitrogen pools beneath impervious surfaces. Environ Pollut 2012a; 164: 248-51.

Raciti SM, Hutyra LR, Rao P, Finzi AC. Inconsistent definitions of "urban" result in different conclusions about the size of urban carbon and nitrogen stocks. Ecological Applications 2012b; 22: 1015-1035.

Rafiee R, Salman Mahiny A, Khorasani N. Assessment of changes in urban green spaces of Mashad city using satellite data. International Journal of Applied Earth Observation and Geoinformation 2009; 11: 431-438.

Scalenghe R, Marsan FA. The anthropogenic sealing of soils in urban areas. Landscape and Urban Planning 2009; 90: 1-10.

Setälä HM, Francini G, Allen JA, Hui N, Jumpponen A, Kotze DJ. Vegetation Type and Age Drive Changes in Soil Properties, Nitrogen, and Carbon Sequestration in Urban Parks under Cold Climate. Frontiers in Ecology and Evolution 2016; 4.

Sinivuo M. Lahden kaupungin urbanisaatioasteen kartoitu. 2007.(in Finishi) https://www.helsinki.fi/en/researchgroups/urban-ecosystems/publications (accessed 3 January 2020).

Tomlinson RW, Milne RM. Soil carbon stocks and land cover in Northern Ireland from 1939 to 2000. Applied Geography 2006; 26: 18-39.

van der Putten W, Poesen J, Lisá L, Winding A, Moora M, Lemanceau P, et al. Opportunities for soil sustainability in Europe. EASAC policy reports 2018; 36: 41.

Wei Z-Q, Wu S-H, Zhou S-L, Li J-T, Zhao Q-G. Soil Organic Carbon Transformation and Related Properties in Urban Soil Under Impervious Surfaces. Pedosphere 2014a; 24: 56-64.

Wei Z, Wu S, Yan X, Zhou S. Density and stability of soil organic carbon beneath impervious surfaces in urban areas. PLoS One 2014b; 9: e109380.

Wei Z, Wu S, Zhou S, Lin C. Installation of impervious surface in urban areas affects microbial biomass, activity (potential C mineralisation), and functional diversity of the fine earth. Soil Research 2013; 51.

Yan Y, Kuang W, Zhang C, Chen C. Impacts of impervious surface expansion on soil organic carbon--a spatially explicit study. Sci Rep 2015; 5: 17905.

Yli-Halla M, Mokma DL. Soil temperature regimes in Finland. Agricultural and Food Science in

Finland 1998; 7: 507-512.

Zhao D, Li F, Wang R. The effects of different urban land use patterns on soil microbial biomass nitrogen and enzyme activities in urban area of Beijing, China. Acta Ecologica Sinica 2012; 32: 144-149.

Figure 1. Map of Lahti city centre indicated by a red line: area of 407.8 ha, https://kartta.lahti.fi/ims/en/Map.

Figure 2. The effects of soil cover type (pervious parks soils (green triangles) vs. soils underneath impervious surfaces (black squares)) and soil depth (top, middle, and native) on soil physical-chemical-biological properties. Mean ± SE values are presented. The unit of soil respiration is µg C g^{-1} soil h^{-1}, and for soil bulk density g cm^{-3}. Data of pervious park soils are modified from Setälä et al. (2016).

Table 1. MANOVA results, testing the effects of soil depth on eight variables (%C, %N, %OM, C/N ratio, moisture, pH, bulk density and respiration) of both sealed and pervious park soils.

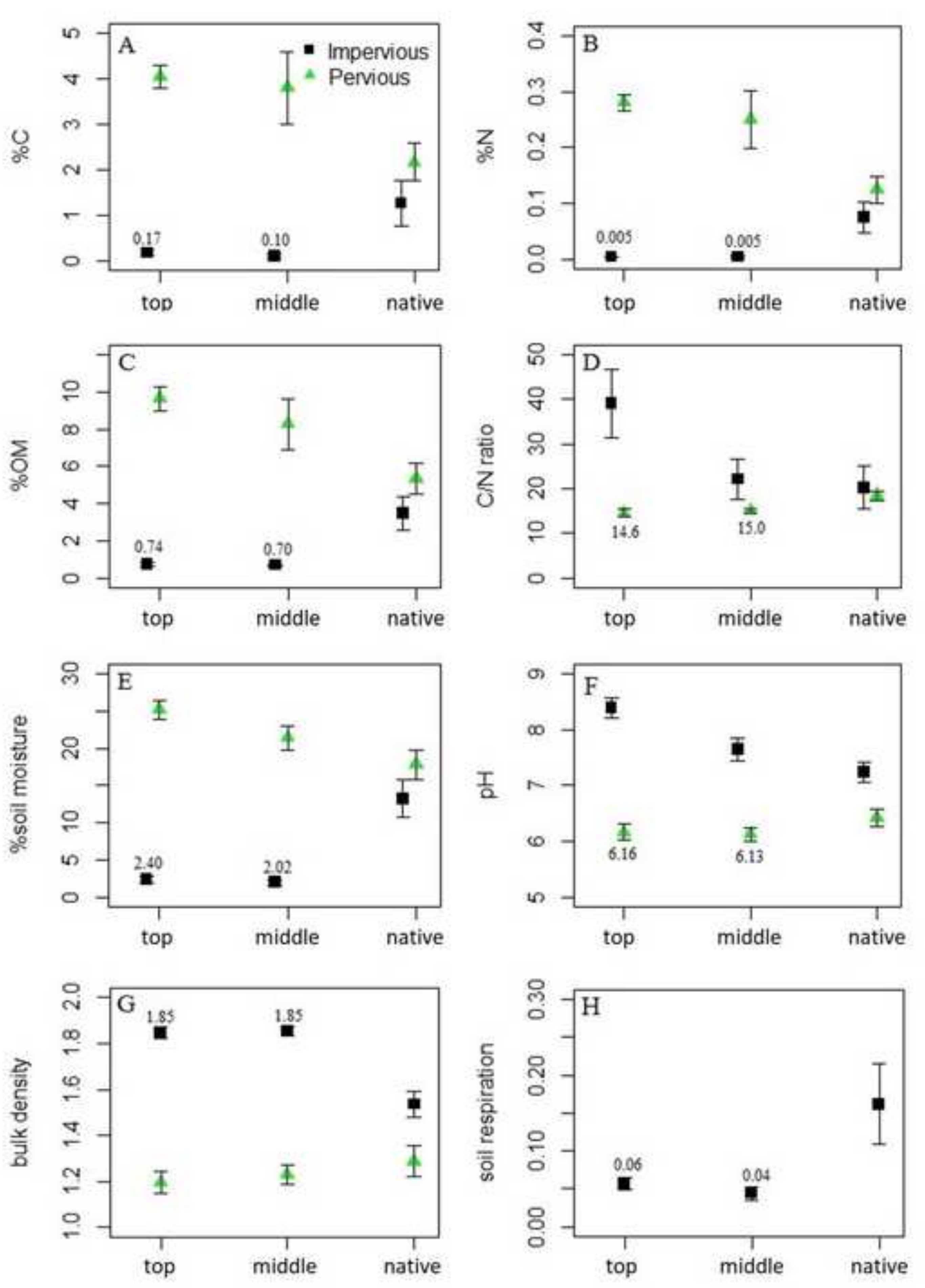
	Sealed soil				Pervious park soil			
Variable	SS	MS	F	*p*	SS	MS	F	*p*
%C	43.228	21.614	18.028	<0.001	3.261	1.630	7.254	0.003
-residuals	41.963	1.199			6.068	0.225		
%N	49.763	24.881	25.521	<0.001	0.201	0.101	9.276	<0.001
-residuals	34.123	0.9749			0.293	0.011		
%OM	14.336	7.168	21.654	<0.001	2.341	1.170	8.204	0.002
-residuals	11.586	0.331			3.852	0.143		
C/N ratio	20.823	10.412	3.172	0.054	0.326	0.163	8.173	0.002
-residuals	114.884	3.282			0.539	0.020		
Moisture	23.044	11.522	14.392	<0.001	0.784	0.392	5.150	0.013
-residuals	28.021	0.801			2.056	0.076		
pH	8.492	4.246	8.750	<0.001	0.013	0.007	1.393	0.266
-residuals	16.984	0.485			0.128	0.005		
Bulk density	0.812	0.406	23.482	<0.001	0.043	0.021	0.754	0.480
-residuals	0.605	0.017			0.764	0.028		
Respiration	8.196	4.098	5.048	0.012				
-residuals	28.410	0.812						

Degrees of freedom = 2, 35 and 2, 27 in the sealed and pervious park soil analyses, respectively. %C, %N, %OM, moisture and respiration were Ln transformed, and the C/N ratio was square-root transformed in the sealed soil analysis. %C, %OM, pH, moisture and the C/N ratio were Ln transformed, and %N was square-root transformed in the pervious park soil analysis. Overall results of the MANOVA are presented in the supplementary material (Table S2).

Figure 1

Click here to download high resolution image

Figure 2


A
Impervious
Pervious
%C
0
1
2
3
4
5
0.17
0.10
top
middle
native
B
%N
0.0
0.1
0.2
0.3
0.4
0.005
0.005
C
%OM
0
2
4
6
8
10
0.74
0.70
D
C/N ratio
0
10
20
30
40
50
14.6
15.0
E
%soil moisture
0
5
10
20
30
2.40
2.02
F
pH
5
6
7
8
9
6.16
6.13
G
bulk density
1.0
1.2
1.4
1.6
1.8
2.0
1.85
1.85
H
soil respiration
0.00
0.10
0.20
0.30
0.06
0.04

***conflict of Interest Statement**

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

CREDIT AUTHOR STATEMENT

Changyi Lu: Writing - Original Draft, Data Curation, Investigation. **D. Johan Kotze**: Review & Editing, Methodology & Statistics, Supervision. **Heikki M. Setälä**: Conceptualization, Review & Editing, Supervision.