UNIVERSITY OF HELSINKI

https://helda.helsinki.fi

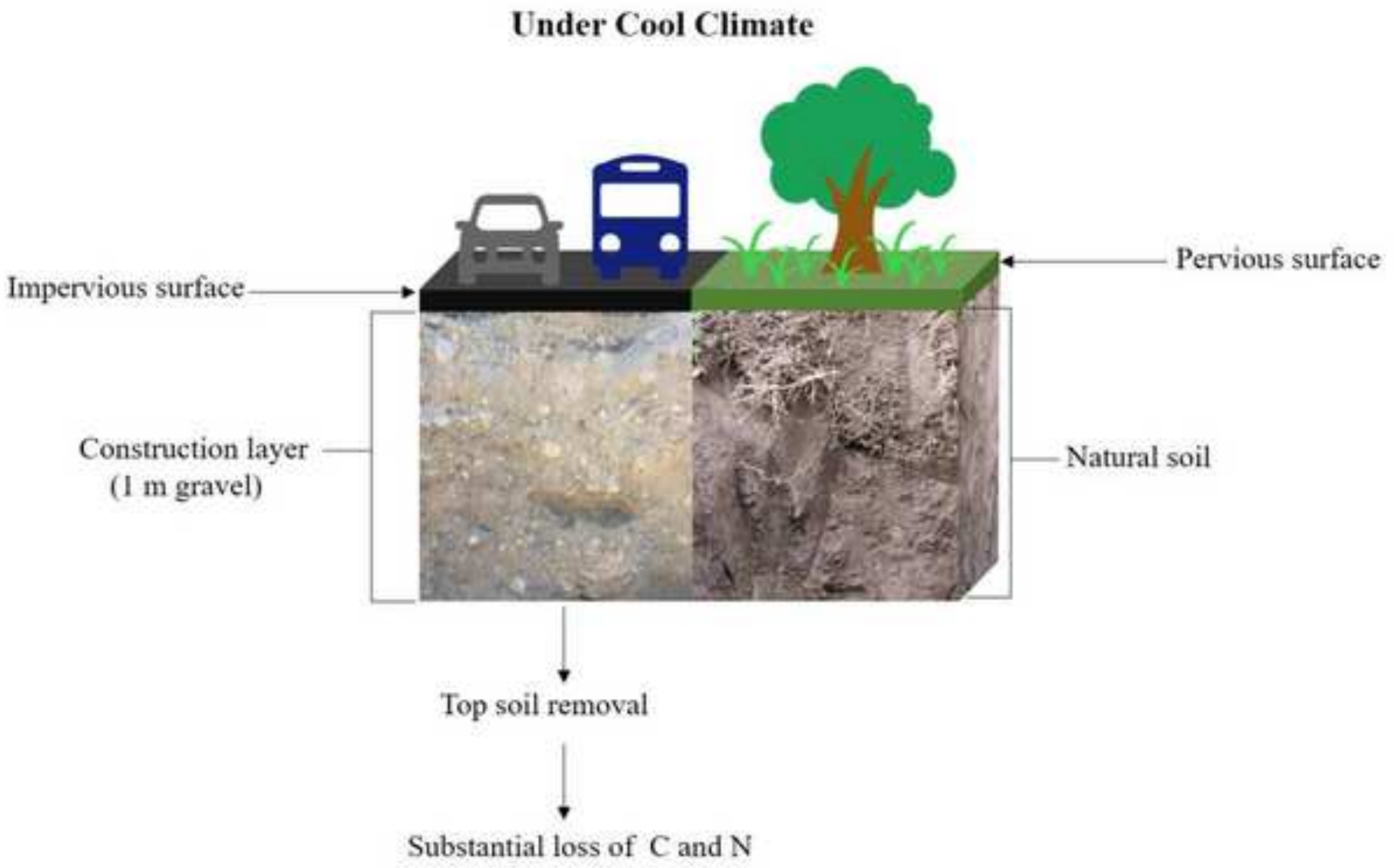
Soil sealing causes substantial losses in C and N storage in urban soils under cool climate

Lu, Changyi; Kotze, Johan; Setälä, Heikki

2020-07-10
Elsevier B.V.
http://hdl.handle.net/10138/346043
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

Downloaded from Helda, University of Helsinki institutional repository. https://helda.helsinki.fi
This is an electronic reprint of the original article.
This reprint may differ from the original in pagination and typographic detail.
Please cite the original version.

*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

*Manuscript (double-spaced and continuously LINE and PAGE numbered)-for final publication
Click here to view linked References

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

126 total of 38 samples were collected from 13 sites; one native sample could not be collected from
127 underneath the block of flats. Soil samples were stored in a freezer at -20°C. Before analyses, the
128 thawed samples were divided into two subsamples. One subsample was stored at 4 °C for the
129 analysis of soil physical-chemical properties and the other part was stored at -20 °C for soil
130 microbial activity analyses. In this study, we did not sample soil from pervious areas, but used data
131 collected from underneath lawns in old urban park soils (30 samples) in the same city at three
132 depths (see Setälä et al. 2016) for comparative purposes.
133
134 **2.3 Soil physical and chemical analyses**
135
136 Air-dried soils were sieved through a 2 mm mesh, checked for potential roots and other organic
137 debris, and both the sieved soil and the material remaining on the sieve were stored separately in
138 plastic bags for later use. Soil pH was measured in 1/5 (v/v) fresh soil/ultrapure water using a glass
139 electrode. Soil water content was determined by drying the soils at 105 °C for 24 h. Total carbon
140 (TC) and nitrogen (TN) were analyzed by dry combustion at 1350 °C using a LECO CNS-2000
141 Elemental Analyzer (0.07% C and 0.09% N detection limits). Soil OM percentage was calculated
142 by loss on ignition via incinerating soils at 550 °C in a muffle furnace for 5 h. The soil samples,
143 especially those that were taken from the first two depths underneath the sealed surfaces, contained
144 a high percentage of gravel (particle size > 2 mm). In order to measure the percentage OM of the
145 gravel-sized fraction, we divided each sample into two subsamples (particle size < 2 mm and > 2
146 mm) and analyzed their OM content separately. After that, we calculated % OM for each gravel-
147 sized fraction and then combined the results according to the gravel percentage (in mass). Due to
148 the high gravel content making the soils loose in structure and thus difficult to sample per volume,
149 approximate soil bulk density (BD) was determined in the laboratory: the soil was placed into a
150 cylindrical container with known volume and pressed as compact as possible, after which the soil

151 samples were oven-dried at 105 °C for 24 h. Soil BD was calculated based on soil volume and dry
152 mass.
153
154 **2.4 Soil microbial activity**
155
156 CO_2 production was measured as an indicator of soil microbial activity. Soil respiration was
157 measured using an Apollo 9000Hs TOC analyzer in the laboratory at 22 °C. The values do not
158 represent field conditions in southern Finland (mean soil temperature about + 7 °C) (Yli-Halla and
159 Mokma, 1998) but those measured under laboratory conditions. We placed ca. 15 g of non-sieved,
160 melted soil with known water content into a 40 ml sample vial. All vials were placed in a sample
161 tray for 2 h before closing the cap. Thereafter, all vials were sealed airtight for the measurement of
162 CO_2 production. CO_2 production of each vial was measured twice with a time interval of 2 h
163 between measurements. CO_2 concentration was calibrated with a known amount of CO_2 being
164 released from a $NaHCO_3$ solution with 21% H_3PO_4. Respiration rate was calculated as the
165 difference in CO_2 concentration between the two measurements. Data for respiration rates in
166 pervious park soils are lacking.
167
168 **2.5 Statistical analyses**
169
170 All statistical analyses were carried out in R 3.0.2 (R Core Team, 2013). The Shapiro-Wilks test was
171 used to test for normality of the response variables. If the assumptions of normality were not met,
172 data were either Ln or square-root transformed. In this study, all variables, except OM and bulk
173 density data, were normally distributed after transformation. We used a multivariate analysis of
174 variance (MANOVA) to determine the effect of soil depth on pH, water content, OM, C, N, the C/N
175 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.

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

287 It is well-established that ageing asphalt and other soil sealing materials do not completely
288 isolate the above-ground from the below-ground milieus (Krebs et al., 2014), which can result in the
289 accumulation of OM underneath sealed surfaces (Burghardt, 2006). In addition, soils underneath
290 sealed surfaces may be enriched with OM deriving from plant roots entering this matrix from both
291 below and from the side (Burghardt, 2006). However, the relative importance of this OM build-up is
292 not known. Even though cracks were frequently observed in the asphalt during sampling, our results
293 indicate that constructed soils underneath impervious surfaces do not receive substantial amounts of
294 OM, C and N from above. Furthermore, we detected no roots beneath the asphalt in our study, even
295 though some of the sites were close to street trees. This suggests that root growth in Boreal city
296 soils is hampered by the low availability of nutrients and water, high soil BD, as well as high pH
297 that typify soils underneath impervious surfaces. These observations further emphasize the adverse
298 effects of soil transportation (see below) and sealing on soil C and N stocks, and the capacity of
299 these constructed soils to sequester C and N in cities under cold climate.
300

301 **4.2 C and N storage at the city scale in Boreal areas**

302

303 To estimate how much C and N is lost in cities under cold climate due to i) the removal of a ca. 1 m
304 thick fertile top soil, ii) replacing it with a C- and N- deficient construction layer and then iii) soil
305 sealing, we calculated soil C and N budgets for downtown Lahti. This area is 407.8 ha in size, with
306 261.5 ha of impervious surfaces and 146.3 ha of pervious surfaces (Sinivuo, 2007). Using our C and
307 N density data, we estimated that in the Lahti city centre (Fig. 1), soils underneath impervious
308 surfaces down to a depth of 1 m store 3 112 tonnes of C and 105 tonnes of N, while the respective
309 numbers underneath pervious surfaces are 46 538 tonnes of C and 2 750 tonnes of N. So, of the
310 total amount of C and N stored in soils in the centre of Lahti, only 6% of C and 4% of N were
311 stored underneath impervious surfaces, even though the area of impervious surfaces is almost
312 double that of pervious surfaces. Presuming that the original top soil that was transported and
313 dumped outside the city contained the same amount of C and N as urban park soil, top soil removal
314 causes a loss of 83 183 tonnes of C and 4 916 tonnes of N from the city centre. This means that 1.8
315 times more C and N were lost from the city due to soil removal than what is stored under pervious
316 surfaces today. These results suggest that the negative effects of top soil removal on urban C and N
317 stocks can not be compensated for by C and N sequestration provided by urban greenspace soils in
318 Boreal areas.

319 To conclude, our results show that soils underneath impervious surfaces contribute very little to
320 the storage of C and N in Boreal urban areas, which stems from the need to remove C and N rich
321 top soil before sealing. It is commonly reported that urban soils can be richer in OM, C and N than
322 soils in adjacent rural sites, which make urban areas an important sinks for these elements (Cambou
323 et al., 2018; Edmondson et al., 2012; Pouyat et al., 2009; Pouyat et al., 2006; Raciti et al., 2011).
324 However, if the proportion of sealed surfaces is high and substantial amounts of top soil is removed
325 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

376 Case Study in Beijing, China. Front Microbiol 2018; 9: 226.
377 Kida K, Kawahigashi M. Influence of asphalt pavement construction processes on urban soil
378 formation in Tokyo. Soil Science and Plant Nutrition 2015; 61: 135-146.
379 Krebs G, Kokkonen T, Valtanen M, Setala H, Koivusalo H. Spatial resolution considerations for
380 urban hydrological modelling. Journal of Hydrology 2014; 512: 482-497.
381 Kuittinen M, Moinel C, Adalgeirsdottir K. Carbon sequestration through urban ecosystem services:
382 A case study from Finland. Sci Total Environ 2016; 563-564: 623-32.
383 Liikenneviraston O. Tierakenteen suunnittelu. 2018. https://julkaisut.vayla.fi/pdf8/lo_2018-
384 38_tierakenteen_suunnittelu_web.pdf. ISSN-L 1798-663X; ISSN 1798-6648; ISBN 978-
385 952-317-632-4.
386 Lin B, Meyers J, Barnett G. Understanding the potential loss and inequities of green space
387 distribution with urban densification. Urban Forestry & Urban Greening 2015; 14: 952-958.
388 Liski J, Westman CJ. Carbon storage in forest soil of Finland .2. Size and regional patterns.
389 Biogeochemistry 1997; 36: 261-274.
390 Liu Z, He C, Zhou Y, Wu J. How much of the world's land has been urbanized, really? A
391 hierarchical framework for avoiding confusion. Landscape Ecology 2014; 29: 763-771.
392 Majidzadeh H, Lockaby BG, Governo R. Effect of home construction on soil carbon storage-A
393 chronosequence case study. Environ Pollut 2017; 226: 317-323.
394 Majidzadeh H, Lockaby BG, Price R, Governo R. Soil Carbon and Nitrogen Dynamics beneath
395 Impervious Surfaces. Soil Science Society of America Journal 2018; 82.
396 Niemelä J, Saarela SR, Söderman T, Kopperoinen L, Yli-Pelkonen V, Väre S, et al. Using the
397 ecosystem services approach for better planning and conservation of urban green spaces: a
398 Finland case study. Biodiversity and Conservation 2010; 19: 3225-3243.
399 Pataki DE, Alig RJ, Fung AS, Golubiewski NE, Kennedy CA, McPherson EG, et al. Urban
400 ecosystems and the North American carbon cycle. Global Change Biology 2006; 12: 2092-

401 2102.
402 Pauleit S, Ennos R, Golding Y. Modeling the environmental impacts of urban land use and land
403 cover change—a study in Merseyside, UK. Landscape and Urban Planning 2005; 71: 295-
404 310.
405 Piotrowska-Długosz A, Charzyński P. The impact of the soil sealing degree on microbial biomass,
406 enzymatic activity, and physicochemical properties in the Ekranic Technosols of Toruń
407 (Poland). Journal of Soils and Sediments 2015; 15: 47-59.
408 Pouyat R, Groffman P, Yesilonis I, Hernandez L. Soil carbon pools and fluxes in urban ecosystems.
409 Environ Pollut 2002; 116: S107-S118.
410 Pouyat RV, Yesilonis ID, Golubiewski NE. A comparison of soil organic carbon stocks between
411 residential turf grass and native soil. Urban Ecosystems 2009; 12: 45-62.
412 Pouyat RV, Yesilonis ID, Nowak DJ. Carbon storage by urban soils in the United States. J Environ
413 Qual 2006; 35: 1566-75.
414 Qin Y, Yi S, Chen J, Ren S, Ding Y. Effects of gravel on soil and vegetation properties of alpine
415 grassland on the Qinghai-Tibetan plateau. Ecological Engineering 2015; 74: 351-355.
416 R Core Team. R: A Language and Environment for Satistical Computing. Vienna: R Foundation for
417 Statistical Computing. 2013.
418 Raciti SM, Groffman PM, Jenkins JC, Pouyat RV, Fahey TJ, Pickett STA, et al. Accumulation of
419 Carbon and Nitrogen in Residential Soils with Different Land-Use Histories. Ecosystems
420 2011; 14: 287-297.
421 Raciti SM, Hutyra LR, Finzi AC. Depleted soil carbon and nitrogen pools beneath impervious
422 surfaces. Environ Pollut 2012a; 164: 248-51.
423 Raciti SM, Hutyra LR, Rao P, Finzi AC. Inconsistent definitions of "urban" result in different
424 conclusions about the size of urban carbon and nitrogen stocks. Ecological Applications
425 2012b; 22: 1015-1035.

426 Rafiee R, Salman Mahiny A, Khorasani N. Assessment of changes in urban green spaces of Mashad
427 city using satellite data. International Journal of Applied Earth Observation and
428 Geoinformation 2009; 11: 431-438.
429 Scalenghe R, Marsan FA. The anthropogenic sealing of soils in urban areas. Landscape and Urban
430 Planning 2009; 90: 1-10.
431 Setälä HM, Francini G, Allen JA, Hui N, Jumpponen A, Kotze DJ. Vegetation Type and Age Drive
432 Changes in Soil Properties, Nitrogen, and Carbon Sequestration in Urban Parks under Cold
433 Climate. Frontiers in Ecology and Evolution 2016; 4.
434 Sinivuo M. Lahden kaupungin urbanisaatioasteen kartoitu. 2007.(in Finishi)
435 https://www.helsinki.fi/en/researchgroups/urban-ecosystems/publications (accessed 3
436 January 2020).
437 Tomlinson RW, Milne RM. Soil carbon stocks and land cover in Northern Ireland from 1939 to
438 2000. Applied Geography 2006; 26: 18-39.
439 van der Putten W, Poesen J, Lisá L, Winding A, Moora M, Lemanceau P, et al. Opportunities for
440 soil sustainability in Europe. EASAC policy reports 2018; 36: 41.
441 Wei Z-Q, Wu S-H, Zhou S-L, Li J-T, Zhao Q-G. Soil Organic Carbon Transformation and Related
442 Properties in Urban Soil Under Impervious Surfaces. Pedosphere 2014a; 24: 56-64.
443 Wei Z, Wu S, Yan X, Zhou S. Density and stability of soil organic carbon beneath impervious
444 surfaces in urban areas. PLoS One 2014b; 9: e109380.
445 Wei Z, Wu S, Zhou S, Lin C. Installation of impervious surface in urban areas affects microbial
446 biomass, activity (potential C mineralisation), and functional diversity of the fine earth. Soil
447 Research 2013; 51.
448 Yan Y, Kuang W, Zhang C, Chen C. Impacts of impervious surface expansion on soil organic
449 carbon--a spatially explicit study. Sci Rep 2015; 5: 17905.
450 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

Click here to download Table: Table 1.doc

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).

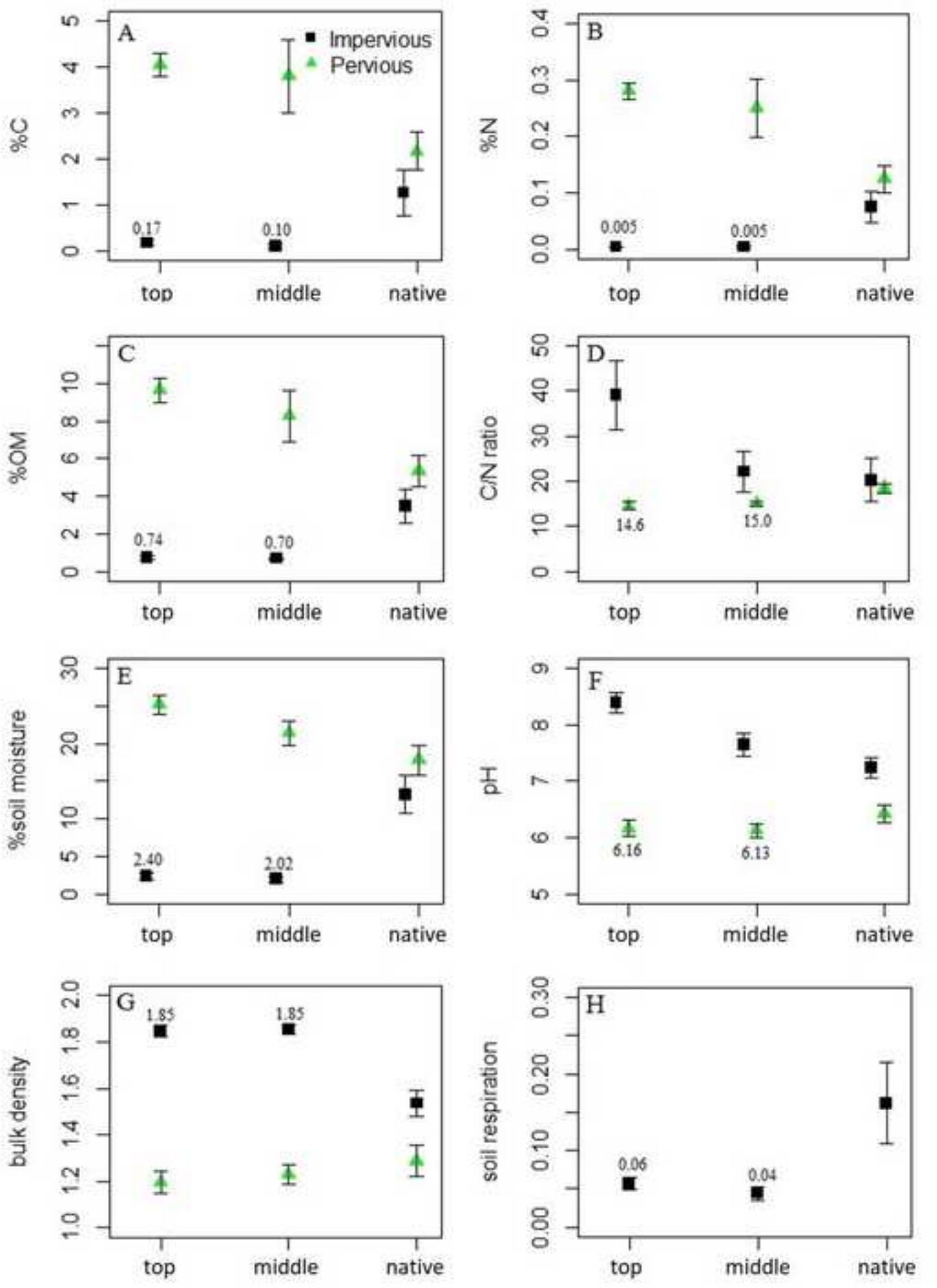
Figure 1

Click here to download high resolution image



Figure 2

Click here to download high resolution image



Supplementary material for on-line publication only

Click here to download Supplementary material for on-line publication only: Supplementary material.doc

***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**

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.