Urban Soils as Hotspots for Carbon Storage: A case study of the urban greenspaces of The Hague, the Netherlands

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Abstract

The services that society extracts from urban ecosystems are becoming increasingly important with increasing urbanization. A potentially crucial ecosystem service is soil carbon (C) storage, as negative soil C balances have the potential to offset some of the anthropogenic greenhouse gas emissions mitigating climate change. This research studied the soil C storage in the urban greenspaces of 2 districts in a typical Dutch city (The Hague districts' City Centre and Scheveningen, 21 km^2, 37% greenspace) as a case study. The following research question was addressed: *'What is the carbon storage potential of urban soils in The Hague?'*

Soil samples were collected along a transect going from the suburban seaside towards the city centre of The Hague. The transect crossed a toposequence from sandier dune soils to peaty inland soils. Besides soil C densities, several soil-quality characteristics were measured namely dissolved organic C levels, pH, electrical conductivity, nitrogen, phosphorus, and sulphur levels, calcium carbonate, the water-holding capacity of the soil and the degradability of soil organic C.

Although urban soil can be highly disturbed or altered by anthropogenic activities, the high C densities in The Hague suggested that its potential to store C appeared unaffected. Along the transect, a mean C density of 88 t/ha, of which 82 t/ha was considered organic C, was detected, which was higher than the values currently assigned to urban soils in national C inventories. The urban soil C storage was dependent on the type of vegetation, urbanization extent and land ownership. The hypothesized links between land use and soil type were not apparent in this case study, suggesting that processes driving soil C storage are controlled by different factors.

The total soil C storage of the upper 30 cm of the greenspaces in The Hague was estimated at 18.8 kt of C. The use of high spatial resolution GIS data with a scale of 10 x 10 m enabled the inclusion of small patches in the total soil C storage of The Hague, which proved to be significant as the smaller urban greenspaces, which are typical for dense urban centres, contained similar soil C density as the larger urban greenspaces, such as urban forests.

Soil C storage in urban ecosystems is highly variable. How generalizable these results are across other Dutch cities requires further research. Moreover, to translate current soil C stocks to annual C fluxes further research is required. This study found that urban soil C stocks are underestimated, which potentially also is the case for urban soil sequestration rates that are currently applied in C modelling studies.

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1. Introduction

Urbanized areas are hotspots of anthropogenic carbon (C) emissions (Pouyat et al., 2002). However, their urban soils can also act as significant C sinks to offset some of those emissions (Edmondson et al., 2012; Lorenz & Lal, 2015; Vasenev & Kuzyakov, 2018). This concept is in dispute as urban soils are often solely perceived as the support of their greenspaces, and are consequently almost totally neglected for their role in ecosystem services (Morel et al., 2015). Furthermore, as urbanization increases, more people are becoming dependent on the ecosystem services that arise from urban soil functioning, such as soil C sequestration and storage, local water storage, pollution attenuation and regulation of biodiversity (Lorenz, 2016).

Soil organic matter (SOM) plays a key role in the delivery of soil-derived ecosystem services (Rawlins et al., 2015). Thus, soil C storage can be managed for optimizing ecosystem services (Lorenz, 2016). Moreover, the sequestration of soil C, an important component of SOM, is an ecosystem service in itself (Minasny et al., 2017; Vasenev & Kuzyakov, 2018). Considering the long residence time of C in soils, enhancing soil C stocks is a suitable method to effectively offset some of the anthropogenic C emissions by achieving negative emissions (Lorenz & Lal, 2015). Accurate assessment of soil C stocks is therefore crucial to understand the anthropogenic changes in urban soil in relation to the global C cycle (Edmondson et al., 2012).

C storage in urban soils was studied by e.g. Canedoli et al. (2019) in Milan, Italy, Edmondson et al. (2012) in Leicester, U.K., Richter et al. (2020) in Berlin, Germany, and Yoon et al. (2016) in several Korean cities. These studies reported a high variance in soil C storage and higher or similar urban soil C densities compared to regional, non-urban soils. Canedoli et al. (2019) detected a high variability in urban soil properties, with overall higher C densities in urban parks than urban non-parks. Soil organic C (SOC) levels in urban parks were comparable with those of regional forests, pastures and grasslands and higher than those in croplands. Edmondson et al. (2012) also observed significant greater C storage in urban soils than regional agricultural land. Yoon et al. (2016) confirm the C stock variability within a country with total C storage of 106, 44 and 27 gG C in the cities of Seoul, Daegu and Daejeon, respectively. Lastly, Richter et al. (2020) found that when evaluating the distribution of soil C storage across a city, the soil C densities increase towards the city's boundaries.

It is estimated that the upper 1 m of global agricultural soils compensate approximately 20 to 25% of the global anthropogenic greenhouse gas emissions by bio-sequestration (Minasny et al., 2017). It is uncertain whether urban soils hold the same potential as agricultural soils, for it is unclear if urban soils display similar mechanistic links between C, climate, vegetation and soil type as been established in non-urban soils (Lorenz & Lal, 2015). Urban soils differ from their natural equivalents because they are strongly affected by anthropogenic activities, including soil sealing, pollution and vegetation management, which may change the soil's characteristics and functioning (Lehmann & Stahr, 2007; Pavao-Zuckerman, 2008; Vasenev & Kuzyakov, 2018). Moreover, the natural C cycle may be disrupted by the deposition of organic C bearing anthropogenic materials, such as potentially polluted organic amendments, or technogenic materials, such as dust (Richter et al., 2020).

Consequently, urban soils are prone to changes that could alter the soil's physical and chemical characteristics (Pouyat et al., 2002; Richter et al., 2020). These factors result in an incomplete understanding of the effects of urbanization on soils, which hampers the modelling and predicting of chemical and physical properties of urban soils. Moreover, modelling efforts are further impeded by the high heterogeneity of urban soils (Candoli et al., 2019; Edmondson et al., 2012). Additionally, it is unknown if and how natural processes in soils can be used as an engineering tool to foster urban resilience.

The aim of this study was to quantify the amount of C stored in urban soils and to assess the inter-zone variance of different soil C pools. This objective was achieved by investigating the soil C storage in the urban greenspaces in the city of The Hague, the Netherlands as a case study. The Hague is a densely packed city in the province of Zuid-Holland representative of most Western European Cities. What makes The Hague relatively unique is its proximity to the North Sea, which means that over a relatively small area from the seaside to the city centre, the toposequence varies from sandier dune soils to peaty inland soils (BRO, n.d.). A variety of urban soils were studied in their real-life setting to assess the interaction of soil C with other soil-quality characteristics.

This research addressed the following question: *'What is the carbon storage potential of urban soils in The Hague?'* It was hypothesized that urban soil C storage was dependent on the type of soil and the type of greenspace (land use, vegetation type, size of greenspace, status of 'Ecozone', greenspace management, urbanization extent & land ownership). By establishing a basis of soil C stocks in The Hague, the capacity of soils to capture and store C can be safeguarded and enhanced, raising the benefits that society receives from urban soils (Rawlins et al., 2015).

2. Literature review

The literature review begins with a description of soil carbon and all its fractions, after which the fluxes of C in the soil system are discussed. Thereafter, the role of C for soil physical and chemical properties are examined. Then the concept of resilience in its content to urban and soil resilience is defined. This section is concluded with a discussion about soil-derived ecosystem services from the perspective of soil C.

2.1 Soil carbon

Soil C comprises soil organic carbon (SOC) and soil inorganic carbon (SIC). SOC originates from the biological, physical and chemical transformation of organic materials and by-products of microbial activity (Lehman & Kleber, 2015; Lal, 2019). SIC is derived from primary carbonates inherited from parent material or dust, or secondary carbonates with a biological or weathered origin (Lal, 2010 in Lorenz, 2016). Combined with the bulk density of the soil, SIC and SOC determine the total soil C storage (Weissert et al., 2016).

Dissolved organic C (DOC) and dissolved inorganic C (DIC) form a fraction of SOC and SIC. Despite that only a small fraction of SOM is water-soluble, which makes DOC insignificant from the C balance point of view, the sorption of DOC can result in the transfer of C into the stable fraction. Moreover, DOC is produced during the breakdown of larger SOM molecules. DOC can then leave the soil system by water transport and its increased mobility may make it more accessible for decomposer organisms, but concurrently, opportunities exist for protecting against further decompositions by the incorporation of DOC into aggregates (Lehmann & Kleber, 2015). Assessment of DOC levels can therefore be relevant from the C storage perspective. The bicarbonates that compromise DIC can either sequester atmospheric C during precipitation or emit C to the atmosphere during dissolution (Monger et al., 2015). After dissolution, DIC may exit the soil system by leaching into the groundwater (Lal, 2016a).

Global soils and vegetation store approximately 2 Tt of C which is nearly three times the amount of C held by the atmosphere (Falkowski et al., 2000). This imbalance postulates that a relatively small flow of C from the biosphere to the air could overwhelm the atmosphere, reinforcing climate change

(Lal, 2019). Additionally, this inequality suggests that enhanced soil C sequestration could achieve the contrary, being a deceleration of climate change. In order to offset some of the anthropogenic greenhouse gas emissions, C must remain stored in the soil for a time scale that is comparable to the residence time of atmospheric C (Hansen et al., 2013).

2.2 Soil C fluxes

The SOC balance consists of fresh C inputs (e.g. plant litter inputs through litterfall and root exudation, by-products of microbial activity), C mineralization, C sequestration and C stocks. The quality and quantity of plant litter entering the soil determine the rate of SOC turnover, which is also established in urban soils (Vauramo & Setälä, 2011). In urban soils, plant litter is often disturbed by litter management (i.e. the removal of plant litter). Consequently, some urban soils receive less fresh C inputs. Moreover, it has been suggested that soil food web structures and behaviour of soil biota are altered in urban soils through the reduced litter inputs, but also through altered litter quality (Pavao-Zuckerman & Coleman, 2005; Vauramo & Setälä, 2011).

For soil C to contribute to long-term C storage, its persistence is of importance. SOC persistence is regarded as an emergent ecosystem service, rather than the chemical recalcitrance of plant litter (Caruso et al., 2018; Schmidt et al., 2011). SOC storage relies on balancing access of decomposing organisms to SOM and protection of SOC by organic-mineral associations. This balancing act demonstrates the necessity to study C fluxes in addition to C stocks (Lehmann & Kleber, 2015). SIC storage can be controlled by reducing erosion losses after and during physical removal of soil during the development of urban areas (Lorenz & Lal, 2015; Lorenz, 2016).

When increasing soil C storage to achieve negative emissions, soil C saturation must be considered. It is expected that soil C concentrations increase for the coming decades when improving the soil C storage potential (Smith, 2016). Increasing soil C storage is therefore an effective measure for decarbonizing society by mitigating anthropogenic C emissions that are difficult to avoid with current technologies (Hauck et al., 2016). However, once soil C saturation is reached, soil C storage cannot be further increased to sequester more C, which makes improved C storage a short-term solution (when implemented now). Although, it should also be noted that the C saturation capacity is merely a concept applied in modelling studies (Janzen, 2015). Soil C is comprised of C fractions of countless different degradabilities that range from minutes to millennia (Smith et al., 2011). This wide continuum of potential turnover times disputes the concept of a definitive saturation capacity (Janzen, 2015). Regardless of whether soil C can overflow, the additional benefits from enhanced soil C storage will last indefinitely. Once soil is healthy and C-rich, it is able to mitigate the long-term stress that climate change imposes upon urban environments (Lorenz & Lal, 2015).

2.3 C storage in urban soils

In natural soil C inventories, soil C stocks and sequestration rates are often modelled as a smaller fraction of soil C stocks and sequestration of non-urban soils on account of the general assumption that urban soils are C depleted (e.g. Lof et al., 2017; Rawlins et al., 2015). A growing body of research reveals that this C depletion often is not the case (Table 1). The Table is organized by climate classification as the climate has a significant influence on the C storage potential. Additionally, the sample depths between the studies differed significantly, which makes the data not directly comparable as C concentrations vary non-linearly with depth (Renforth et al., 2011). C storage is expressed either in total C or SOC density.

Table 1. Soil C densities in different urban areas.

City	Climate (Köppen-Geiger climate classification)	Sample Depth (cm)	C storage (kg C m^{-2})	Reference
Urban conterminous U.S.	-	0-100	14.7-26.8 (total C)	Churkina et al., 2010; Pouyat et al., 2006
Beijing, China	Dfa	0-10	3.1 (SOC)	Liu et al., 2018
Boston, U.S.	Dfb	0-10	3.6-4.2 (SOC)	Raciti et al., 2012
Moscow, Russia	Dfb	0-10	2.81-7.07 (SOC)	Vasenev et al., 2013
New York, U.S.	Dfb	0-10	3.5-5.0 (SOC)	Pouyat et al., 2002
Berlin, Germany	Dfb	0-20	2.16-9.52 (SOC)	Richter et al., 2020
Helsinki, Finland	Dfb	0-90	10.4 (total C)	Lindén et al., 2020
Denver, U.S.	Bks	0-20	4.5 (SOC)	Pouyat et al., 2009
Fort Collins, U.S.	Bks	0-15	4.8 (total C)	Kaye et al., 2005
Baltimore, U.S.	Bks	0-10	6.0-8.0 (SOC)	Pouyat et al., 2009
New York, U.S.	Cfa	0.30	11.3 (SOC)	Cambou et al., 2018
Paris, France	Cfb	0-30	9.9 (SOC)	Cambou et al., 2018
Liverpool, U.K.	Cfb	0-15	1.0-5.0 (total C)	Beesley et al., 2012
Leicester, U.K.	Cfb	0-21	14.4 (SOC)	Edmondson et al., 2012
Auckland, N.Z.	Cfb	0-10	5.2 (SOC)	Curran-Cournane et al., 2015
Auckland, N.Z.	Cfb	0-30	9.3-16.4 (SOC)	Weissert et al., 2016
Anna's Tuin & Ruigte, the Netherlands	Cfb	0-30	11.6 (total C)	Kortleve, 2019
Milan, Italy	Cfb	0-40	1.32-12.88 (SOC)	Candoli et al., 2019
Kaifeng, China	Cwa	0-10	0.87-5.01 (SOC)	Sun et al., 2010
Daejeon, Korea	Cwa	0-30	1.28-1.92 (total C)	Yoon et al., 2016

2.4 Relating SOM to soil-quality characteristics

Besides soil C, this study assessed several soil-quality characteristics. Soil quality is defined as the 'capacity of the soil to function' (Karlen et al., 1997 in Lal, 2016a). Soil C plays an important role in soil functioning. Appropriate levels of SOC sustain soil structure and aggregate formation, water, nutrient and contamination retention and rhizospheric processes (Lal, 2016a). Soil functions can be measured through the assessment of soil-quality characteristics. In addition to soil C concentration, this study measured the following characteristics: bulk density, clay content, pH, electrical conductivity (EC), nutrient level (N, P & S), calcium carbonate ($CaCO_3$) levels, the water-holding capacity of the soil, and the mineralization of SOC.

These properties are indicative of soil quality but are also important for soil C storage. Data on soil bulk density is required to estimate the C density of soil, but also provides a measure for soil compaction, which may decrease SOC content through limited fresh organic input into the subsoil (Selhorst, 2016). Measuring clay content is relevant as fine-fractioned soils contain elevated levels of SOC pools (Selhorst, 2016). The parameters pH and N, P and S content affect the microbial community (Selhorst, 2016) and EC can be a measure of soil fertility (Blume et al., 2010).

$CaCO_3$ is an important carbonate in the soil buffer system and a structure-stabilizing substance (Blume et al., 2010). Moreover, its assessment is often used as a measure to approximate SIC levels (e.g. Saviozzi et al., 2013). However, SIC may also consist of other primary or secondary carbonates (e.g. dolomite, sodium carbonate & siderite, Lal, 2010 in Lorenz, 2016).

Data on the water-holding capacity of the soil is required for respiration experiments, but also provides a parameter for the assessment of soil quality itself. A high water-holding capacity not only means that the soil can retain more water, which is relevant as a flood risk mitigation strategy, but it also means that the water-leachable anions and cations (e.g. nutrients, contaminants) are retained from reaching the groundwater. Moreover, the interaction of SOM and the available water-holding capacity requires further research data (Lal, 2009).

The degradability of SOC is evaluated to gain insights into the C dynamics of the soil. The degradability of SOC is approximated by measuring mineralization: the complete microbial decomposition (Blume et al., 2010). Different mineralization rates suggest different C availability for the microbial community. Stabilized SOM against mineralization equals a low turnover rate of SOM, which results in a long residence time in soil (Blume et al., 2010).

2.5 Resilience

Resilience is defined as the capacity of a system to survive and persist within a variable environment (Meadows, 2008). This capacity depends on being able to respond to unprecedented and unexpected changes (Ahern, 2011). Resilience arises from the system's rich structure of feedback loops that are able to restore the system after large perturbations (Meadows, 2008). Those loops can learn and evolve towards more complex restorative structures through self-organization: the ability of the system to structure itself (Meadows, 2008).

The status of system resilience is difficult to determine and may only be apparent from a holistic perspective (Meadows, 2008). Because of this complexity, resilience is often overshadowed by more evident system properties such as stability and productivity (Meadows, 2008). Awareness of the system's resilience may identify approaches to preserve and enhance the system's inherent restorative powers (Meadows, 2008). Resilience, therefore, needs to be managed (Meadows, 2008) by building resilience capacity (Ahern, 2011). In addition, urban resilience is defined as the potential of an urban system to maintain or restore its beneficial functions after perturbation, to adapt to change and to transform its (sub)systems that restrict its adaptive capacity (Meerow et al., 2016).

Soil resilience, on the other hand, is an ecological concept that is employed to give insight into soil processes and their dynamics when soil is under disturbance (Lal, 2016a). It refers to the ability of soils to restore their productivity and environmental moderation capacity as soils have the potential to self-regulate and self-maintain (Lal, 1997 in Lal, 2016a; Lal, 2016a). Studying soil resilience gives insights into exogenous and endogenous factors and processes that govern resilience (Lal, 2016a; Tenywa, 2016).

For the purpose of this study, urban soil resilience is defined based on its capacity to deliver soil-derived ecosystem services when under disturbance (Jansson, 2013). Previous attempts to quantify soil resilience are predominantly based on the soil's agricultural potential (e.g. Lal, 2016a; Park, 2016). This parameter is of less importance for urban soils, and as Meadows (2008) argued above, resilience is not properly reflected by the system property productivity alone. Instead, this study proposes to measure urban soil C, as SOC drives most soil-derived ecosystem services (Lal, 2016b). Urban soils are by definition formed under the strong predominance of anthropogenic factors and endure disturbances in the form of soil sealing, pollution, vegetation management and disruptions in the natural C cycle by the addition of organic C-bearing materials (Richter et al., 2020; Vasenev & Kuzyakov, 2018). The study, therefore, proposed to measure urban soil C stocks as a parameter to assess the capacity of urban soils to deliver ecosystem services and thereby appraise their resilience.

2.6 Ecosystem services

Healthy urban soils potentially provide the same supporting, provisioning, regulating and cultural ecosystem services as their natural equivalents (Ajmone-Marsan et al., 2016). Urban soils support primary production, cycling of nutrients and carry structures and piped utilities. They provision urban agriculture and C sequestration. They regulate floods, local temperatures (cooling effect of evapotranspiration), biodiversity and attenuate pollution. From a cultural perspective, they serve recreation, tourism and cultural heritage (Lorenz & Lal, 2015; Morel et al., 2015; Rawlins et al., 2015).

Soil C plays an important role in the delivery of these soil-derived ecosystem services (Lorenz, 2016; Rawlins et al., 2015). Thus, urban soil C stocks can be managed to enhance the provision of ecosystem services. The capacity of urban soils to sequester C is especially true if they are managed in an appropriate way considering fertilization, irrigation, adding organic materials and reducing soil disturbance (Lorenz & Lal, 2015; Renforth et al., 2011) with application of appropriate technologies involving enhanced biosequestration (Whitmore et al., 2015).

Enhanced biosequestration of atmospheric C has several additional benefits. It augments soil structure and soil conditions which in turn advance microbial and floral communities as well as cycling and retention of nutrients and water (Lal, 2016b). Improvement of these properties contributes to more resilient urban climates, including indirect mitigation of the threats of climate change on urban temperatures and urban hydrology (e.g. the urban heat island effect, stormwater management, Lorenz & Lal, 2015).

Quantifying soil C thus ties together the ecosystem services that are of more importance for urban soils. However, the relation between soil C and ecosystem services can be more complex. For example, enhanced C sequestration can drive biodiversity by providing an energy-rich substrate for soil organisms, but biodiversity also drives C sequestration by soil fauna possessing SOM, creating a positive feedback loop. In order to capture this complexity, a variety of urban soils will be investigated to assess the influence of several parameters including the greenspace's age and vegetation type (Raciti et al., 2011; Zhu et al., 2018).

3. Research approach

The greenspaces of The Hague act as a case study to gain an understanding of the issue in a real-life setting (Harrison et al., 2017). The case is bounded by space (geographical border) and studied in the context of its natural environment, which makes fieldwork intrinsic to the process. Several methods of data collection were required including field observations, soil sampling and analyses. In The Hague, urban soil C levels were assessed sporadically in addition to potential soil contamination when planning for construction of e.g. a belowground waste container. However, measurements of soil C concentrations rarely took place inside urban greenspaces, but rather under sealed surfaces.

Cities present a small-scale patchwork of divergent soil features, which results in a high spatial variability (Vasenev et al., 2014). Spatial variability is present both vertically (buried soil horizons) and horizontally (varying land uses, vegetations & topography) (Zhu et al., 2018). Moreover, decision-making on every scale can influence soil C stocks (Richter et al., 2020). Soil is therefore sampled along a transect going from the seaside (North-West) towards the city centre of The Hague (South-East, Fig. 1, 2 & 3). By assessment of a transect along a toposequence and the urban-suburban gradient, effects of soil type, urbanization and type of greenspace on C storage could be evaluated with a limited amount of soil samples.

National soil maps of the Netherlands often exclude soil types of cities, which is also the case for The Hague (Fig. 2). Nonetheless, a pattern can be derived with sandier dune soils along the coastline (depicted in yellows & oranges) towards peaty and/or clayey soils more inland (depicted in blues & purples). It was hypothesised that these layers are continuous and therefore could be extrapolated. A toposequence is also observed in the geomorphological map (Fig. 1).

With the hypothesis that the strips of soil types and geomorphological elements are continuous (Fig. 1 & 2), extrapolation over the urban area of The Hague was possible. Additionally, these maps were supplemented with municipal data on soil pollution, land ownership, specific ecological function, greenspace management practices and age. The latter is of importance as the notion of C sequestration potential suggests that urban soils are in a steady-state, which may not be the case for younger soils or soils that are actively managed.

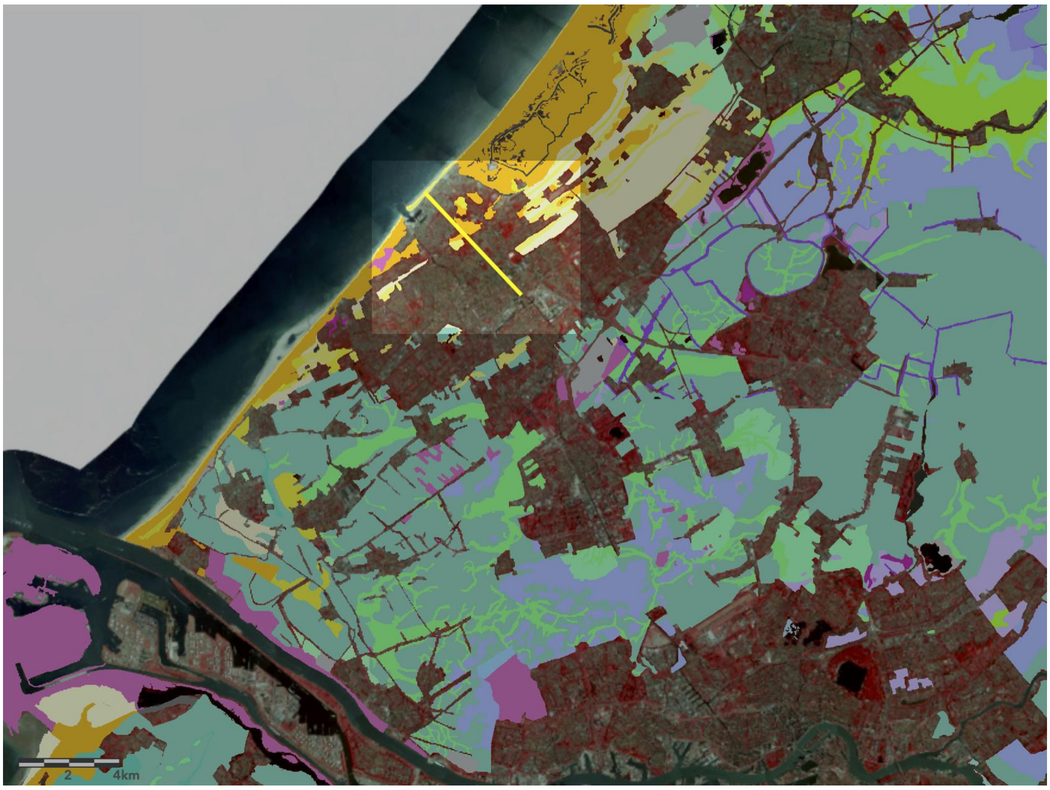

Fig. 1. Geomorphological map projected on infrared satellite image (adapted from BRO). Lighter colours indicate (artificial) dune areas whilst darker colours indicate plains (1:50,000). The yellow line represents the transect of Fig. 3.

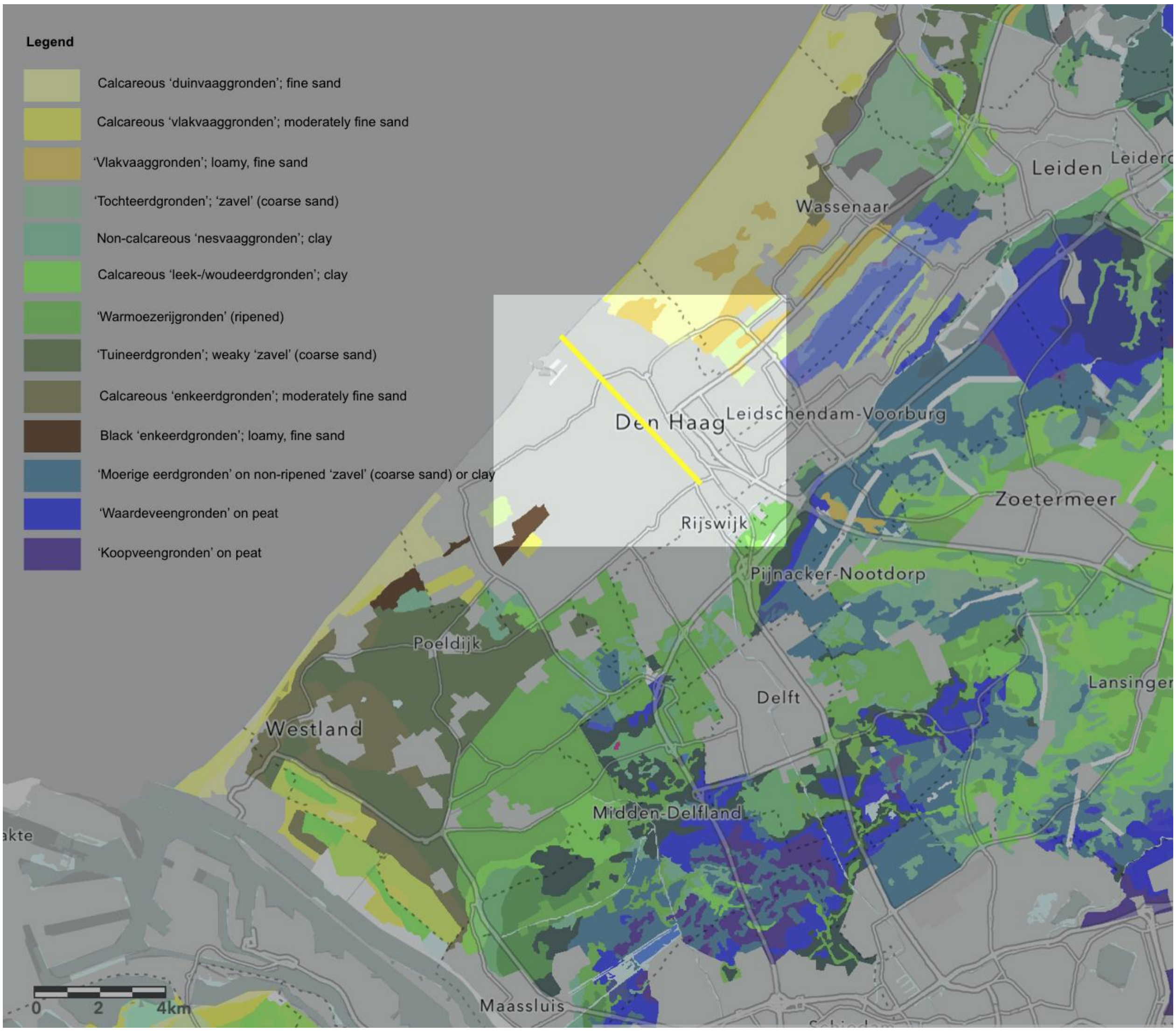

Fig. 2. Soil map of The Hague and surrounds (adapted from BRO, n.d.). Soil classification according to the Dutch soil classification system (De Bakker et al., 1989) (1:50,000 – 1:100,000). The yellow line represents the transect of Fig. 3.

4. Research method

4.1 Sampling locations

For the purpose of this research, urban greenspaces are defined as unsealed soils and encompass all green surface areas detected by infrared satellite images. The soil and geographical maps and green surface maps of the RIVM (2017) were used to manually select 25 geo-referenced sample plots (Fig. 3). The transect crosses several 'Ecozones': green areas that are part of the ecological main structure of the Netherlands (Den Haag Dataplatform, 2020), which were included in this sampling campaign.

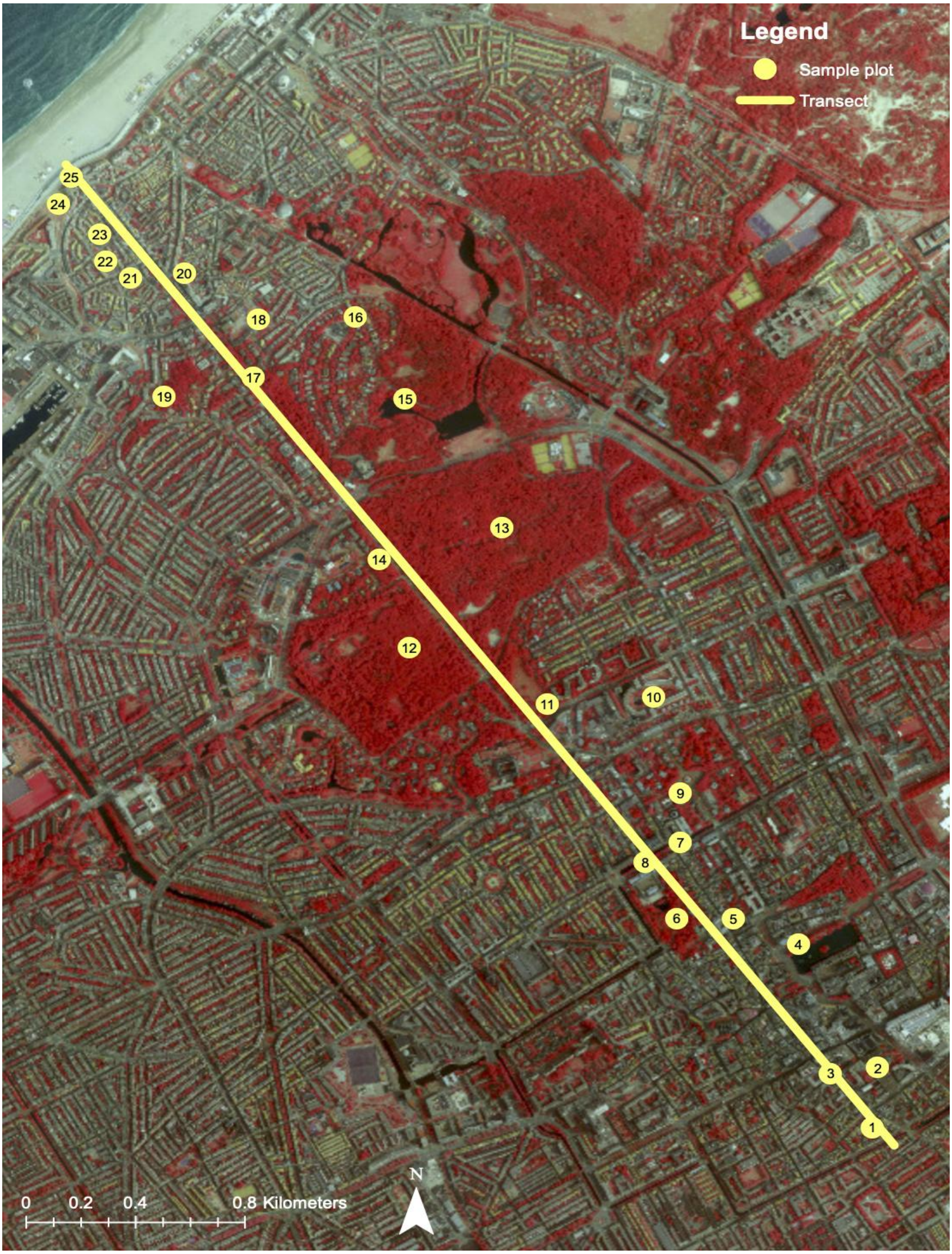

Fig. 3. Sample transect of ~5 km running from North-West to South-East with 25 sample plots (projected on infrared map (25 cm resolution) from Data.overheid (2019).

4.2 Sampling method

Within each sample plot, three sampling sites were selected (noted as A, B & C, n = 75). At each site, 5 subsamples were taken within a radius of 2 m (Fig 4.). Subsamples were taken with a gouge auger (3 cm diameter) at a depth of 0-30 cm and they were mixed to avoid local inhomogeneities. The bulk density of each sampling site was determined using the cylindrical core method at the middle point with five bulk density rings of 250 ml (Fig. 4).

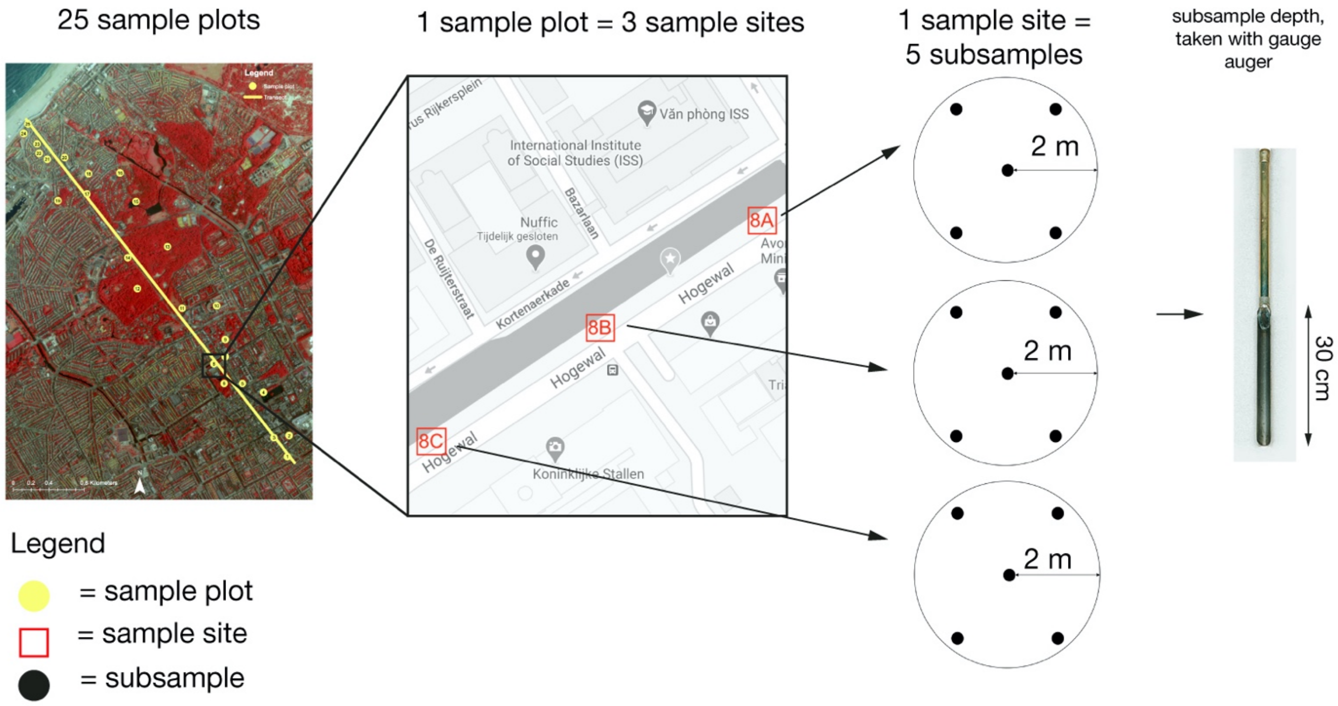

Fig 4. Schematic presentation of the sample method. Each sample plot (n = 25) consists of 3 sample sites (n = 75). Each sample site consists of 5 subsamples that are mixed to avoid local inhomogeneities (n = 75). Each subsample is taken with a gauge auger to a depth of 30 cm.

4.3 Soil analysis

Collected soil samples were transported to the Delft University of Technology to determine the bulk density, particle size distribution, pH value, EC, SOM content and dissolved organic C (DOC) content of each sample site (n = 75). At Delft University of Technology, mixed samples were prepared of each sample plot (n = 25) that were sent to Agrolab, Deventer, the Netherlands to measure total C (ISO 10694 (2008)) and TOC (ISO 10694 (2008)), and by the difference SIC. Additionally, N, P (NEN 6966), S (NEN 6966) and $CaCO_3$ (NEN-ISO 10693) were determined. To allow for comparison, it was assumed that the parameters that were measured in the mixed samples were equal for each sample site (Fig. 4). To evaluate the soil analyses performed externally, a replica of sample plot 1 was sent to Agrolab.

4.3.1 Loss-on-ignition

To determine the SOM content, 10-12 g of each soil sample was dried at 105°C for at least 3 hours. After cooling down in a desiccator, 5 g of dry soil (< 2 mm, on a 3-decimal scale) was placed in a crucible in the oven at 550 °C (oven warms up 10 °C min^{-1} after which it remains at 550 °C for 3 hours). Before removing the crucibles from the oven, they were cooled down to at least 100 °C. After removal from the oven, the crucibles were placed in a desiccator and weighed again on a 3-decimal scale. The weight loss represents the loss-on-ignition (LOI).

4.3.2 pH, EC and DOC

For pH, EC and DOC determination, 20 g of each soil sample was air-dried at 20°C for at least one week, after which extractions with Aqua Demin were prepared (40 ml: 10 g soil of < 2mm). After shaking and settlement for approximately 24 hours, pH and EC measuring took place with pH and EC measuring devices (standardized to 25°C). The same extract was also used (after another cycle of shaking, settlement & filtering over a 0.45 µm cellulose membrane filter) to measure dissolved organic carbon (DOC) using ultraviolet-visible absorption spectrum at 254 nm. Samples with Abs values over 2 were diluted with Aqua Demin (2:1) as it is believed that Abs_{254} and DOC concentration are non-linearly related above this value.

4.3.3 Water-holding capacity

The water-holding capacity of the soil was determined by placing 20 g of field fresh soil into funnels with filters after which successively 100 ml of Aqua Demin was added. The funnels were then covered with aluminium foil and left overnight, after which the gravitational water content was determined, which is assumed to correspond to 100% of the WHC of the soil.

4.3.4 Degradability of soil organic matter

An aerobic incubation procedure was used to determine the potential of urban soils to mineralize SOC. The test was performed on the mixed samples (sites A, B and C for each sample plot) with a replica of each sample plot. Approximately 50 g of field fresh soil was incubated at 20 °C and moistened to 60% of the water-holding capacity in 1000 ml glass bottles with rubber stoppers. The pressure was increased by injecting 120 ml of air. Soil respiration was monitored weekly for 6 weeks using a Micro-DaVinci-Gas Chromatograph (Delft, the Netherlands). Bottles were aerated with air for 10 minutes if 3% of CO_2 was exceeded, as these CO_2 concentrations are believed to inhibit soil respiration. Volume percentages were translated to C production per unit of SOC using *Eq 1.* where the V_m (molar volume) of CO_2 was assumed to be 12.0 l/mol and the *M* (molar mass) 24.1 g/mol.

$$\text{C mineralization [mg C/ g TOC]} = CO_2\,[\%] / 100 * \text{volume bottle [ml]} / 1000 / V_m\,[\text{l/mol}] * M * 1000 / \text{soil weight [g]} / \text{SOC}\,[\%] * 100 \quad \textbf{(1)}$$

After 6 weeks, the samples that were aerated were weighted to inspect if water was lost during aeration. If water was lost, Aqua Demin was supplemented again to reach 60% of the water-holding capacity and a seventh measurement took place to assess whether drying out of the soil sample had impacted soil respiration.

4.3.5 Bulk density

Bulk density was determined by drying one of the five bulk density rings at 105°C for at least 24 hours after which the moisture content was determined on a 2-decimal scale (BS 1337-2, 1990). The moisture content was then used to calculate the dry bulk density (g cm^{-3}) of the remaining four rings.

4.3.6 Particle size distribution

The particle size distribution was determined according to the classification key of KA5 Ad-hoc AG Boden, 2005 (Appendix C). The texture classes were then translated to the mean clay, silt and sand percentages using the texture triangle in Appendix C.

4.3.7 C density

Inorganic, organic and total C concentrations were transformed to soil C stocks (kg C m^{-2}) according to equations 2, 3 and 4, where TC, SOC and SIC are the total, organic and inorganic C concentrations (%), BD is the bulk density (kg m^{-3}) and D the sampling depth (m) (Weissert et al., 2016).

Total C stocks = TC * BD * D **(2)**
SOC stocks = SOC * BD * D **(3)**
SIC stocks = SIC * BD * D **(4)**

4.4 Urban soil classification

This study adopted the definition of Vasenev and Kuzyakov (2018) who defined urban soils as "semi-natural four-dimensional bodies at the Earth's surface, developed and functioned by a combination of physical, chemical, and biological processes under strong predominance of anthropogenic factors and being an essential part of all urban ecosystems" (p. 1608).

The World Reference Base for Soil Resources (2014) classifies urban soils as Technosols and Antrosols. However, the spatial and temporal variability of urban soil can be so high that their complexity is not fully captured by those two classes. A broader framework was therefore introduced by Ajmone-Marsan et al. (2016) who developed a faceted system with full classification entries in order to organize the information on urban soils to support decision-making. The facets include physical and chemical properties of conventional soil sciences, but also includes intangible concepts such as social, historical and aesthetic value which are relevant for the use and management of urban soils.

Field and municipal data were gathered to classify urban soils according to the framework of Aimone-Marsan et al. (2016). Soils were classified based on their (1) physical and chemical properties (section 4.3), (2) pollution (municipal data), (3) landscape metrics (such as number of patches & particular patch type, derived from the most recent Google Earth Satellite imagery (April 2020), (4) ownership (public vs. private), (5) aesthetical value, (6) specific ecological function (derived from municipal maps), (7) social and (8) historical value.

4.5 Data management

Collected data was gathered in Google Drive as documents, spreadsheets and GIS files. The document format was used to gather municipal data to classify the urban soils according to the urban soil framework (Aimone-Marsan et al., 2016) and to store pictures and maps of the sample plots. The spreadsheet format was used to store data of each measured soil parameter in a separate spreadsheet. GIS files were stored in Google Drive as an online backup.

4.6 Statistical analysis

Collected data were analysed in Matlab (R2017b) using the non-parametric Kruskal-Wallis and Wilcoxon rank sum test as the assumptions of the ANOVA and Student's *t*-test test were not met. This test was used to compare the C densities of different types of greenspaces and different types of soil (Table 2). Mean values were reported with the corresponding standard deviation (mean value ± standard error). Lastly, the data were tested for correlations with the chemical and physical soil characteristics of section 4.3. Correlations were tested with Spearman's rank correlation coefficient, as the data was non-linearly distributed.

4.7 Categorization of urban soil samples

The urban soil samples were categorized according to their soil type, land use, vegetation class, litter management, greenspace management, land ownership, size of greenspace and status of 'Ecozone' (Table 2).

The soil type was derived using the Dutch soil map (Fig. 2) in combination with the assumption that soil types could be extrapolated over urban areas. 'Duinvaag' soils are defined as poorly developed sandy soils of which the sand particles are coated with iron. 'Vlakvaag' soils are characterized as lightly coloured, humus-poor, poorly developed sandy soils. 'Beekeerd' soils consist of a nutrient-rich humus layer on top of a nutrient-poor sandy layer. The soil is dominated by oxidation processes. ‘Meerveen’ soils are defined by their mineral topsoil on top of a eutrophic peat layer (De Bakker et al., 1989).

The category land use consisted of urban forest, street trees, parks and non-parks. The category park included playgrounds and plots of herbaceous vegetation used for recreational purposes, as well as cemeteries. The category non-park included plots of shrubbery on pavements that could not be considered a park because of their small size and/or inaccessibility for recreation inside the greenspace.

The vegetation was divided into three classes, namely trees (vegetation higher than 2.5 m), shrubs (vegetation higher than 1 m) and herbaceous vegetation (vegetation lower than 1 m). This division was consistent with the green maps of The Netherlands (RIVM, 2017).

The type of greenspace management was based on the greenspace management packages of the municipality of The Hague (van Droesberg, 2017). Management packages that contained similar management regarding fertilizing, pruning and plant litter management were grouped to form the following categories: (1) privately managed (i.e. not by the municipality), (2) natural forest, (3) trees on sealed surfaces, (4) trees on unsealed surfaces, (5) fertilized grass, (6) unfertilized grass, (7) shrubs, and (8) dune thickets. The category ‘private’ contained the greenspaces that were privately managed (i.e. not by the municipality) and contained vegetation types that could be placed in the categories ‘shrubs’, ‘natural forest’, and ‘unfertilized grass’. The main difference between trees on sealed and unsealed surfaces was that trees on sealed surfaces received yearly fertilization targeted at the trees, whilst the soil beneath trees on unsealed surfaces received yearly fertilization targeted and the undercover (either herbaceous vegetation or shrubs). The class natural forest and dune thickets received no artificial fertilization.

The category land ownership was based on who managed the greenspace. Publicly owned greenspaces included all greenspaces that were under municipal management. Privately owned greenspaces were not managed by the municipality and included e.g. a playground managed by the local community, the Jewish cemetery managed by volunteers, and communal greenspaces by apartment buildings.

Finally, the size of the greenspace was assessed with Google Earth Pro (version 7.3) using the most recently available satellite imagery (April 2020) and the status of ‘Ecozone’ was assessed using municipal maps (Den Haag Dataplatform, 2020).

Table 2. Categorical data of each sample plot.

Sample plot	Soil type	Land ownership	Ecozone status	Greenspace size	Land use class	District	Vegetation class	Litter management class	Management class
1	Meerveen	Private	Non-ecozone	Medium	Park	The Hague Centre	Grass	Litter removed	Private
2	Meerveen	Public	Non-ecozone	Small	Street tree	The Hague Centre	Trees	Litter removed	Trees on sealed surface
3	Meerveen	Public	Non-ecozone	Medium	Park	The Hague Centre	Grass	Litter removed	Fertilized grass
4	Beekeerd	Public	Ecozone	Medium	Park	The Hague Centre	Trees	Litter removed	Trees on unsealed surface

5	Beekeerd	Public	Non-ecozone	Small	Street tree	The Hague Centre	Trees	Litter removed	Trees on sealed surface
6	Beekeerd	Public	Ecozone	Large	Park	The Hague Centre	Shrubbery	Litter undisturbed	Shrubs
7	Vlakvaag	Public	Ecozone	Small	Non-park	The Hague Centre	Shrubbery	Litter undisturbed	Shrubs
8	Vlakvaag	Public	Ecozone	Small	Street tree	The Hague Centre	Trees	Litter removed	Trees on sealed surface
9	Vlakvaag	Public	Ecozone	Small	Street tree	The Hague Centre	Trees	Litter removed	Trees on sealed surface
10	Vlakvaag	Public	Non-ecozone	Medium	Park	The Hague Centre	Grass	Litter removed	Unfertilized grass
11	Vlakvaag	Private	Ecozone	Large	Park	The Hague Centre	Trees	Litter undisturbed	Private
12	Vlakvaag	Private	Ecozone	Large	Urban forest	Scheven-ingen	Trees	Litter undisturbed	Private
13	Vlakvaag	Public	Ecozone	Large	Urban forest	Scheven-ingen	Trees	Litter undisturbed	Natural forest
14	Vlakvaag	Public	Ecozone	Large	Urban forest	Scheven-ingen	Trees	Litter undisturbed	Natural forest
15	Vlakvaag	Public	Ecozone	Large	Urban forest	Scheven-ingen	Trees	Litter undisturbed	Natural forest
16	Duinvaag	Public	Non-ecozone	Small	Street tree	Scheven-ingen	Grass	Litter removed	Fertilized grass
17	Duinvaag	Public	Ecozone	Medium	Street tree	Scheven-ingen	Trees	Litter removed	Trees on unsealed surface
18	Duinvaag	Private	Non-ecozone	Small	Non-park	Scheven-ingen	Shrubbery	Litter removed	Private
19	Duinvaag	Public	Ecozone	Large	Park	Scheven-ingen	Grass	Litter undisturbed	Unfertilized grass
20	Duinvaag	Public	Non-ecozone	Medium	Non-park	Scheven-ingen	Shrubbery	Litter undisturbed	Shrubs
21	Duinvaag	Private	Non-ecozone	Medium	Non-park	Scheven-ingen	Shrubbery	Litter undisturbed	Private
22	Duinvaag	Public	Non-ecozone	Medium	Park	Scheven-ingen	Trees	Litter undisturbed	Trees on unsealed surface
23	Duinvaag	Public	Non-ecozone	Medium	Park	Scheven-ingen	Grass	Litter removed	Fertilized grass
24	Duinvaag	Public	Ecozone	Medium	Park	Scheven-ingen	Grass	Litter undisturbed	Dune thickets
25	Duinvaag	Public	Non-ecozone	Medium	Non-park	Scheven-ingen	Grass	Litter undisturbed	Dune thickets

4.8 Estimating soil C storage

The green surface area map of The Hague was transformed into a C density map based on the laboratory findings of the soil samples using ArcGIS (based on the method of Richter et al., 2020). The total soil C storage was computed by multiplying the surface areas of each greenspace type with the corresponding soil C density.

5. Results

5.1 Classification of the investigated urban soils

An overview of sample plots with their corresponding soil classification is provided in Table 3. The soil classification was multi-faceted and included the soil's texture class, degree of acidity or basicity, contamination levels, size, shape, surroundings, land ownership and value from the ecological, social, historical and aesthetical perspective.

Table 3. Soil classification of each sample plot.

Sample plot	Greenspace description	Urban soil classification
1	Playground in between buildings	Sandy loam, slightly acidic, low to high contamination by heavy metals (Bhagirath, 2019 & 2020), approximately 900 m^2, with a shape of two adjacent rectangles, flat, surrounded by buildings, publicly owned but privately managed, insignificant from the historical and ecological perspective, but socially and aesthetically valuable.
2	Two street trees (in poor condition) on small plot of grass	Loamy sand, neutral, low contamination by heavy metals and PAHs (Bhagirath, 2019 & 2020), approximately 20 m^2 and with a rectangular shape, flat, adjacent to open car park and pavement, publicly owned, insignificant from the historical and social perspective, with low ecologic and aesthetic value.
3	Church surrounded by grass with chestnut trees	Loamy sand, neutral, no data on contamination levels, approximately 0.4 ha, with a rectangular shape, mildly hilly, surrounded by buildings on 2 sides and roads on the other two sides, publicly owned. The church itself has a high historical value, but the grass it is surrounded by appears to be only of social value. Combined, the greenspace has high aesthetic value but is of limited ecological value.
4	Pond adjacent to a strip of trees on grass	Sandy loam, neutral, slightly contaminated with heavy metals and mineral oils (Ensing, 2017), approximately 0.2 ha, with an elongated rectangular shape, flat, surrounded by an unpaved path on one side and the main road on the other side, publicly owned. The pond has high historical value and combined, the pond and the greenspace are socially, aesthetically, and ecologically valuable.
5	Horse chestnut tree (planted in 1880)	Loamy sand, neutral, no data on contamination levels, approximately 20 m^2, with a round shape, in the middle of an open square, flat, surrounded by buildings and roads, publicly owned, historically, socially and aesthetically valuable, with limited ecological value.
6	Palace garden	Sandy loam, moderately acidic, slight contamination of the topsoil led to soil replacement in the playground area (Hopman, 2007), but no data on the contamination levels of the remaining soil, approximately 1 ha, with a rectangular shape, flat, surrounded by roads of three sides and stables with greenery on the other side, publicly owned, historically, aesthetically, socially and ecologically valuable.
7	Shrubbery on the roadside (recently planted (between 2018 and 2020)	Sandy loam, slightly acidic, slightly contaminated by heavy metals (Haring, 2018), approximately 300 m^2, in a triangular shape, flat, next to a pond and the main road, publicly owned, insignificant from the historical and social perspective, but somewhat ecologically and aesthetically valuable.
8	Row of 12 street trees	Sandy loam, neutral, no data on contamination levels, 12 rectangular patches of approximately 5 m^2, flat, next to a pond and the main road, publicly owned,

		insignificant from the historical or social perspectives, with some ecological and aesthetic value.
9	Monument surrounded by 36 horse chestnut trees on plots of grass	Silt clay loam, moderately acidic, no data on contamination levels, 4 rectangles of 500 m^2, flat, surrounding the monument with a road in the middle, publicly owned, with high historical, ecological, aesthetical value, and somewhat socially valuable.
10	Park with pond in the middle	Sandy loam, neutral, the soil was slightly contaminated with heavy metals and PAHs before construction (Gemeente Den Haag, 1993). The deeper soil (below 1.5 m) was regarded as uncontaminated and the report advised to keep it separate from the other soil to allow for unrestricted reuse of the material (Hoomweg, 1999). More recently, the slight contamination of heavy metals (Zn, Hg, Pb) was confirmed by an investigation of soil adjacent to the park (Naussauplein) (Pires Gaspar-Goetheer, 2016; Rodenburg, 2019). Currently, the Western part of the park is classified as 'slightly contaminated' while there is no data for the Eastern part of the park (Van der Made, 2016). Oval shape of approximately 1 ha, steep decline towards the pond, surrounded by buildings, publicly owned. The buildings have some historical value but the green itself not so much although it is used for ceremonial purposes sometimes. The park has low ecological value but is socially and aesthetically valuable.
11	Plot of trees with shrubs within the premises of the Jewish cemetery	Sandy loam, strongly acidic, adjacent to the cemetery elevated levels of heavy metals (Hg, Pb, Cu) have been detected (Gaspar-Goetheer, 2016) and adjacent to the cemetery there is also a large plot of strongly contaminated soil (Van der Made, 2016), but no data on contamination levels of the cemetery itself were found. Approximately 1.6 ha and an irregular-shaped polygon, flat, surrounded by forest on two sides and roads on the other two, privately owned, ecologically, socially, aesthetically and historically valuable.
12	Private park/ forest (since the 15^{th}/16^{th} century)	Sandy loam, extremely acidic, no data on contamination levels, approximately 27 ha with a square shape, mildly hilly, surrounded by roads and forests, privately owned, ecologically, socially, aesthetically and historically valuable.
13	Urban forest, since 1100-1400 but many trees replaced mid 20^{th} century	Sandy loam, very strongly acidic, no data on contamination levels, approximately 111 ha (including sample plots 14 & 15) with a rectangular shape, hilly, surrounded by roads and forest, publicly owned, with limited historical value, but ecologically, socially and aesthetically valuable.
14	Urban forest, since 1100-1400 but many trees replaced mid 20^{th} century	Sandy loam, slightly acidic, the soil directly next to the bike lanes contained slightly elevated levels of heavy metals (Riemens, 2018), but no data on contamination levels of the remaining soil, approximately 111 ha (including sample plots 13 & 15) with a rectangular shape, hilly, surrounded by roads and forest, publicly owned, with limited historical value, but ecologically, socially and aesthetically valuable.
15	Urban forest, since 1100-1400 but many trees replaced mid 20^{th} century	Sandy loam, strongly acidic, no data on contamination levels, approximately 111 ha (including sample plots 13 & 14) with a rectangular shape, very steep decline towards the lake, surrounded by roads and forest, publicly owned, with limited historical value, but ecologically, socially and aesthetically valuable.
16	Large roundabout with trees on grass	Loamy sand, slightly acidic, the subsoil consists of a debris-containing layer mixed with sand which is slightly contaminated with Pb (van den Heuvel, 2016), no data on the contamination levels of the topsoil, approximately 300 m^2, circular-shaped, flat, surrounded by roads, publicly owned, insignificant from the historical and social perspective, with limited ecological and aesthetic value.
17	Street trees on strips of grass	Loamy sand, neutral, not-to-slightly contaminated by heavy metals (Smit, 2009), approximately 0.2 ha, narrow-rectangularly shaped, flat, surrounded by roads on all sides, publicly owned, insignificant from the historical and social perspective, but

		aesthetically and ecologically valuable.
18	Plot of shrubs on pavement	Sandy loam, neutral, the topsoil is not contaminated but the subsoil is slightly contaminated by heavy metals (van der Bijl, 2013), approximately 0.1 ha, triangularly shaped, flat, surrounded by buildings on 2 sides and a pavement on the other side, privately owned, insignificant from the historical and social perspective, with limited aesthetic and ecological value.
19	Park on top of a hill	Sandy loam, slightly acidic, no data on contamination levels, approximately 8 ha, irregularly shaped polygon, hilly, surrounded by roads and buildings, historically, aesthetically and ecologically valuable, but of limited social value due to its neglected management.
20	Plot of shrubs on pavement	Sandy loam, slightly acidic, no data on contamination levels, three rectangular plots of approximately 0.1 ha, flat, surrounded by buildings, publicly owned, insignificant from the social and historical perspective, with limited aesthetic and ecological value.
21	Plot of trees with shrubbery in between buildings	Silty loam, slightly acidic, slight contamination by heavy metals has been detected around the greenspace (not measured inside the greenspace) (Smit, 2015), rectangular plot of 300 m^2, flat, surrounded by buildings, privately owned, insignificant from the historic, social and ecological perspective, with some aesthetic value.
22	Shrubs and trees surrounding a paved playground	Loamy sand, neutral, not contaminated (van der Bijl, 2011), but much rubbish detected in and on the soil, 2 rectangular strips of 300 m^2 each, flat, surrounding the paved playground with roads on the other sides, publicly owned, insignificant from the historic perspective, with limited aesthetical, ecological, and social value.
23	Playground on field of grass with a couple of young, newly planted trees	Silt clay loam, neutral, suspected to be contaminated with heavy metals and PAHs but this suspicion has not been confirmed by lab analysis (Bouw, 2006), rectangular shape of 0.13 ha, flat, surrounded by buildings on 3 sides and a road on the other side, publicly owned, insignificant from the historical perspective, with limited ecological and aesthetic value, but socially valuable.
24	Playground in dunes	Sand, neutral, no data on contamination levels, circle of approximately 0.2 ha, mildly hilly, surrounded by roads, publicly owned, insignificant from the historical perspective, but ecologically, aesthetically and socially valuable.
25	Dune thickets	Sand, moderately alkaline, no data on contamination levels, rectangle of approximately 200 m^2, hilly, surrounded by roads, publicly owned, insignificant from the historical and social perspective, but aesthetically and ecologically valuable.

5.2 Urban soil properties

The mean clay content, determined by hand analysis, was 8.3% (± 1.68%). Clay content was especially large in greenspaces that consisted of alien topsoil (e.g. sample plots 9 and 23). The remaining samples contained low levels of clay and were classified as sand, loamy sand or sandy loam (Table 3, Fig. 5).

The mean dry bulk density of the soil was 0.99 g cm^{-3} (± 0.03 g cm^{-3}). The bulk density was especially low in the urban forest (sample plot 11-15). In the dunes, the highest bulk densities were measured (sample plots 24 & 25). The bulk density also varied locally, i.e. within a sample plot, revealing the heterogeneity of urban soils even within the same greenspace (Fig. 5).

The water-holding capacity of the soil ranged between 19% and 37% related to the dry weight of the soil. The water-holding capacity was consistently high in the forested area in the middle of the transect and significantly lower in the dune area. However, lower and higher water-holding capacities were also detected in several other greenspaces (Fig. 5).

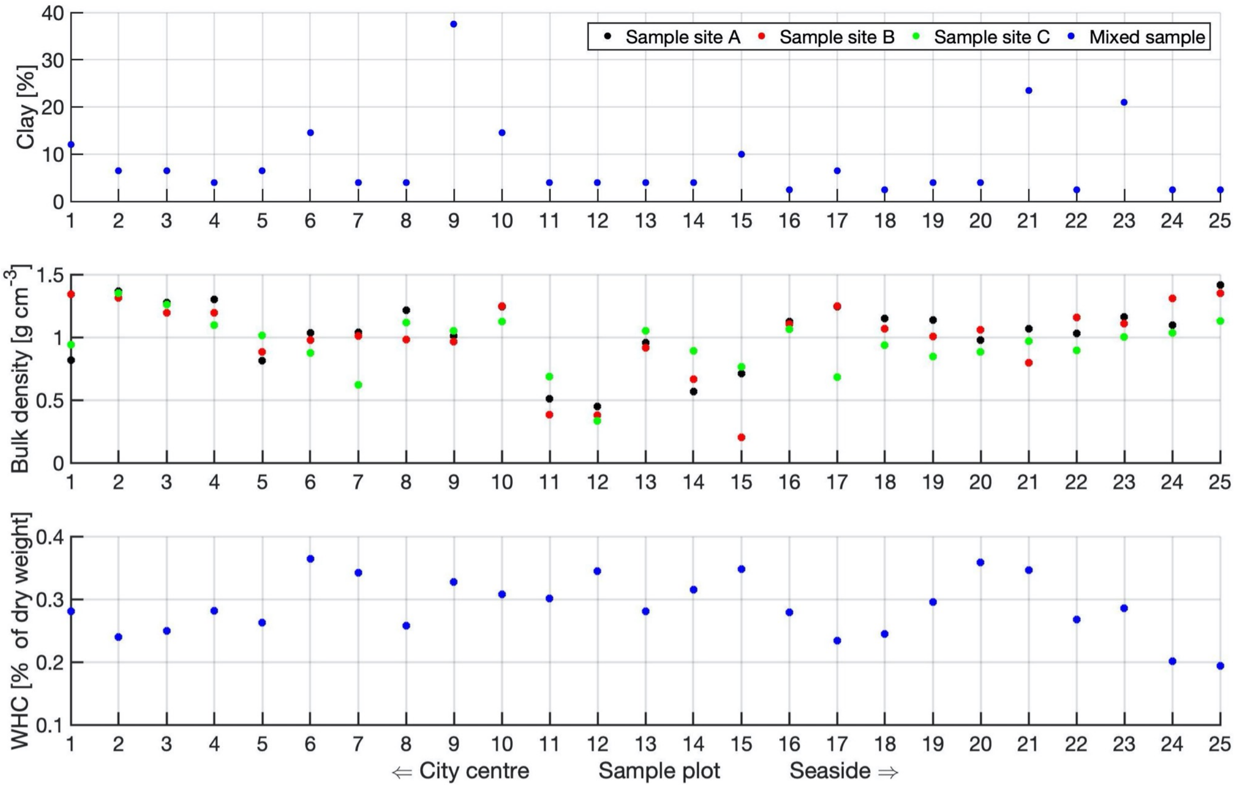

Fig. 5. Clay content, bulk density and water-holding capacity (WHC) along the transect.

The mean SOC content was determined to be 2.92% (± 0.36%) with large variations along the transect (Fig. 6). High SOC levels were detected in the mid-section of the city centre (sample plots 5, 6 & 7), but the suburban area also contained greenspaces with high SOC levels (sample plot 21). Relatively low SOC levels were measured in the urban forest (sample plots 10-15). The lowest SOC levels were detected in the dunes (sample plots 24 & 25).

The DOC value varied significantly along with the sample plots of the transact, but intra-plot variability was also observed (Fig. 6). Low DOC levels were observed in the dunes (sample plots 24 and 25), and higher DOC values were detected in the urban forest (sample plots 11-15), but also in the mid-section of the city centre (sample plots 6 & 7).

The pH value differed significantly along the transect (Fig. 6). The city centre soils had pH values ranging from moderately acidic to neutral, but once the forested area in the middle of the transect was reached, the pH strongly dropped to very to extremely acidic. In the suburban area, the pH increased again and finally became slightly to moderately alkaline in the dune area. Along the entire transect, the pH value ranged from extremely acidic (pH < 4.4) to moderately alkaline (pH > 7.9) with a mean pH of 6.39 (± 0.10).

The mean value of electrical conductivity (EC), representative of the number of charged solutes in the pore water, was 89 µS cm^{-1} (± 4.30 µS cm^{-1}). No clear pattern could be derived along the transect (Fig. 6). Sample plots 11, 12, and 13, the southern part of the urban forest, and sample plots 24 and 25, the dunes, contained the lowest EC values.

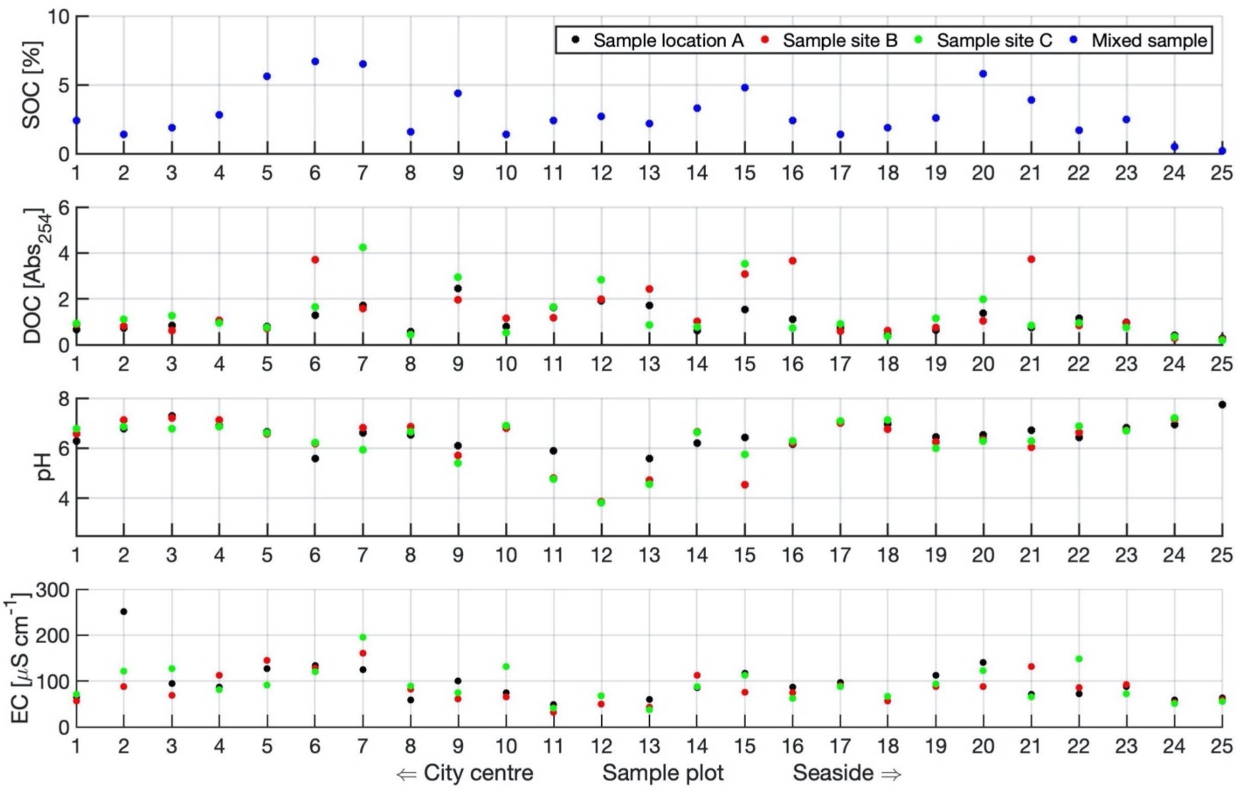

Fig. 6. SOC, DOC, electrical conductivity (EC) and pH along the transect.

Linear correlation analysis revealed a strong relationship between loss-on-ignition and SOC (R^2 = 0.77, Fig. 7). The slope of the regression function equals 0.4865 meaning that approximately 49% of the SOM consisted of SOC.

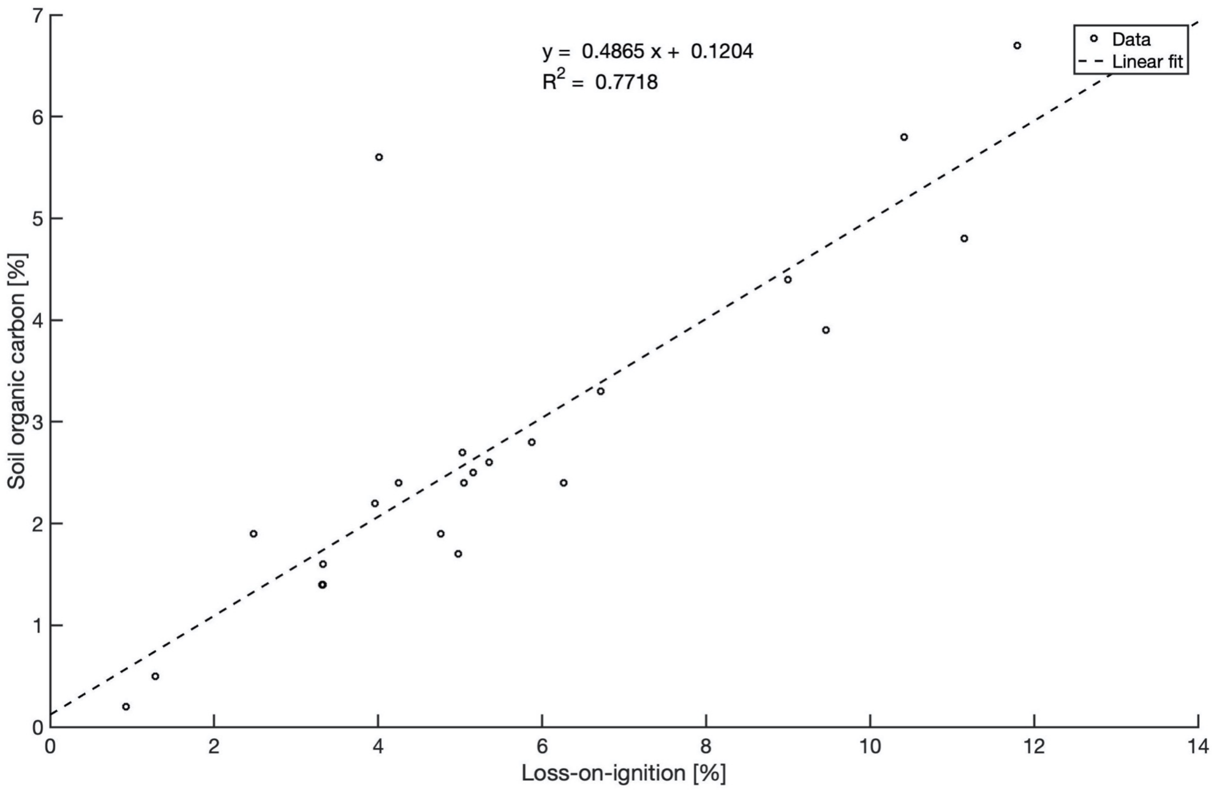

Fig. 7. The relationship between SOC and loss-on-ignition (LOI) in 25 urban soil samples.

Nutrient levels (N, P, S) were determined to be 0.20% (± 0.03%) N, 0.06% (± 0.01%) P and 0.06% (± 0.01%) S on average. These nutrient percentages translated to 1.93 kg N m^{-2} (± 0.23 kg N m^{-2}), 0.56 kg P m^{-2} (± 0.06 kg P m^{-2}) and 0.53 kg S m^{-2} (± 0.06 kg S m^{-2}) on average. The nutrient percentages resulted in a mean C:N:P:S ratio of 1:15:55:55 (Fig. 8).

In general, the C:N ratio of the soil was similar or higher than the C:N ratio of SOM (Fig. 8). Sample plots 10 and 21 formed clear exceptions with low C:N ratios of 9.3 and 9.1 respectively. A large variation in C:P ratios was detected along the transect. The C:P ratio was consistently high in the urban forest (sample plots 11-15), however, some greenspaces in the city centre also contained high C:P ratios (sample plots 5 & 7). Finally, the C:S ratio was lower than that of SOM in almost all sample plots. Only sample plots 5, 6, 7, 12 and 13 contained higher C:P ratios than SOM (Fig. 8). Raw data is presented in Appendix A and B.

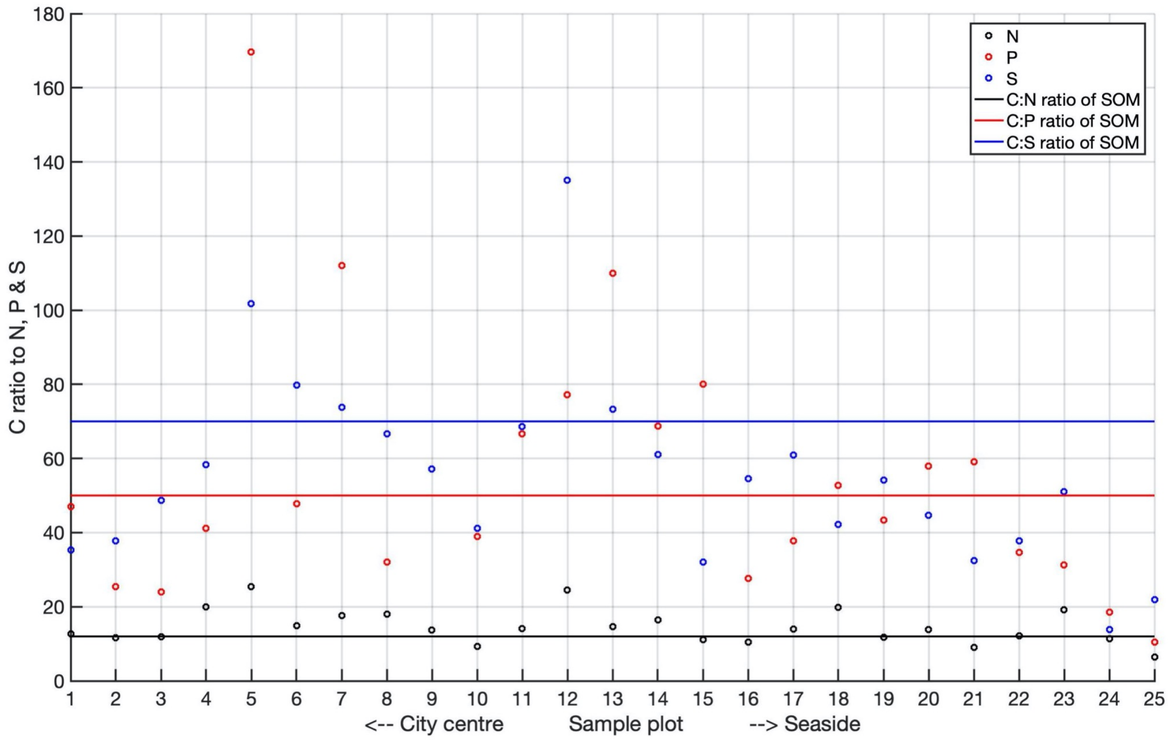

Fig. 8. C:N:P:S ratio of the sampled soil along the transect in relation to the C:N:P:S of SOM according to Kirby et al. (2011).

5.2.1 Interrelationships between soil properties

All measured soil parameters were correlated to inspect the interrelationships between the measured soil properties (Table 4). Strong correlations between SOC and N and S were detected (r_s = 0.81 for N, r_s = 0.82 for S). The association of SOC with P was only moderate in strength (r_s = 0.52), but the C:P ratio was considered strong (r_s = 0.72). Moreover, a strong association between SOC and the water-holding capacity of the soil was detected (r_s = 0.81). SOC levels were negatively correlated with the C mineralization expressed as the amount of C mineralized per SOC (r_s = -0.82) and positively with the potential C mineralization of the upper 30 cm of soil (r_s = 0.77).

The loss-on-ignition values strongly correlated with the DOC values (r_s = 0.74). The remaining strong correlations of LOI and the other soil properties were similar to that of SOC. Additionally, the DOC values strongly correlated with the water-holding capacity of the soil (r_s = 0.70). For the inorganic fraction of soil C, a different pattern was observed. SIC strongly correlated with $CaCO_3$ levels (r_s = 0.80, Fig. 9) and no other strong correlations were observed.

The pH value was strongly associated with $CaCO_3$ levels, indicating the liming effect of $CaCO_3$ (r_s = 0.84). Moreover, the pH was negatively correlated to potential C mineralization (r_s = -0.76). No significantly strong correlations between EC and other soil properties were detected.

Nitrogen levels were strongly correlated with S levels (r_s = 0.82), but not with P. Additionally, a strong association between N and the water-holding capacity of the soil was observed (r_s = 0.77). Furthermore, N appeared to have a negative effect on the C mineralization expressed as mg C per g SOC (r_s = -0.71). The C:P ratio was strongly associated with the potential C mineralization of the upper 30 cm of soil (r_s = 0.83). Lastly, the water-holding capacity of the soil was also strongly correlated with the potential C mineralization of the upper 30 cm of soil (r_s = 0.75).

Table 4. Spearman correlation *r* of the soil C fractions, soil-quality characteristics and mineralization rates. Italic numbers indicate significant correlations ($p < 0.05$) and bold numbers indicate strong correlations ($r_s \geq 0.70$). (TC: total soil carbon, SOC: soil organic carbon, SIC: soil inorganic carbon, LOI: loss-on-ignition, pH, EC: electrical conductivity, TN: total nitrogen, P: phosphorus, S: sulphur, C:N ratio, C:P ratio, C:S ratio, WHC: water-holding capacity, BD: bulk density, Clay: clay fraction, C_{min}/SOC: C mineralization [mg C/ g SOC], C_{min}/m^2: potential C mineralization of the upper 30 cm of soil [mg C/ m^2 soil]).

	TC	TC_d	SOC	SIC	LOI	DOC	pH	EC	TN	P	S	C:N	C:P	C:S	$CaCO_3$	WHC	BD	Clay	C_{min}/SOC	C_{min}/m^2
TC	-		***0.99***	-0.30	***0.83***	*0.63*	*-0.54*	*-0.47*	***0.83***	*0.56*	***0.82***	0.34	*0.67*	*0.42*	*-0.48*	***0.78***	*-0.52*	0.38	***-0.82***	***0.75***
TC_d		-	***0.79***	-0.18	***0.65***	*0.37*	-0.17	*0.62*	***0.72***	*0.68*	***0.77***	0.22	*0.34*	*0.26*	*-0.22*	*0.48*	0.01	*0.42*	***-0.75***	*0.41*
SOC			-	*-0.41*	***0.81***	*0.61*	*-0.58*	*0.42*	***0.82***	*0.52*	***0.81***	0.37	***0.72***	*0.44*	*-0.54*	***0.81***	*-0.55*	0.36	***-0.82***	***0.77***
SIC				-	-0.21	*-0.26*	*0.58*	0.13	-0.38	-0.10	-0.20	-0.14	*-0.41*	-0.24	***0.80***	*-0.46*	*0.33*	-0.30	*0.30*	*-0.37*
LOI					-	***0.74***	*-0.57*	*0.46*	***0.81***	*0.67*	***0.74***	0.07	*0.46*	*0.27*	*-0.44*	***0.78***	*-0.45*	*0.35*	***-0.73***	0.65
DOC						-	0.11	0.23	*0.61*	*0.40*	*0.40*	0.10	*0.51*	*0.35*	*-0.61*	***0.70***	*-0.48*	*0.31*	*-0.56*	*0.61*
pH							-	0.10	*-0.57*	-0.17	*-0.29*	-0.17	*-0.64*	*-0.45*	***0.84***	*-0.68*	*-0.65*	-0.18	*0.47*	***-0.76***
EC								-	*0.44*	*0.48*	*0.49*	0.06	0.10	0.12	0.05	*0.26*	0.00	*0.32*	*-0.37*	0.23
TN									-	*0.60*	***0.82***	-0.12	*0.55*	0.17	*-0.56*	***0.77***	*-0.41*	*0.44*	***-0.71***	*0.62*
P										-	*0.63*	-0.07	-0.11	-0.00	-0.21	*0.47*	0.06	*0.40*	*-0.54*	0.16
S											-	0.03	*0.45*	-0.09	-0.24	*0.63*	*-0.30*	*0.42*	*-0.66*	*0.50*
C:N												-	*-0.45*	***0.74***	-0.10	0.11	*0.31*	*-0.31*	*-0.36*	*-0.33*
C:P													-	*0.52*	*-0.53*	*0.64*	***-0.71***	0.19	*-0.52*	***0.83***
C:S														-	*-0.43*	0.28	*-0.38*	0.04	*-0.42*	*0.48*
$CaCO_3$															-	*-0.64*	*-0.50*	-0.07	*0.45*	*-0.57*
WHC																-	*-0.56*	*0.43*	*-0.60*	***0.75***
BD																	-	-0.07	*0.29*	-0.05
Clay																		-	-0.24	*0.33*
C_{min}/SOC																			-	*-0.41*
C_{min}/m^2																				-

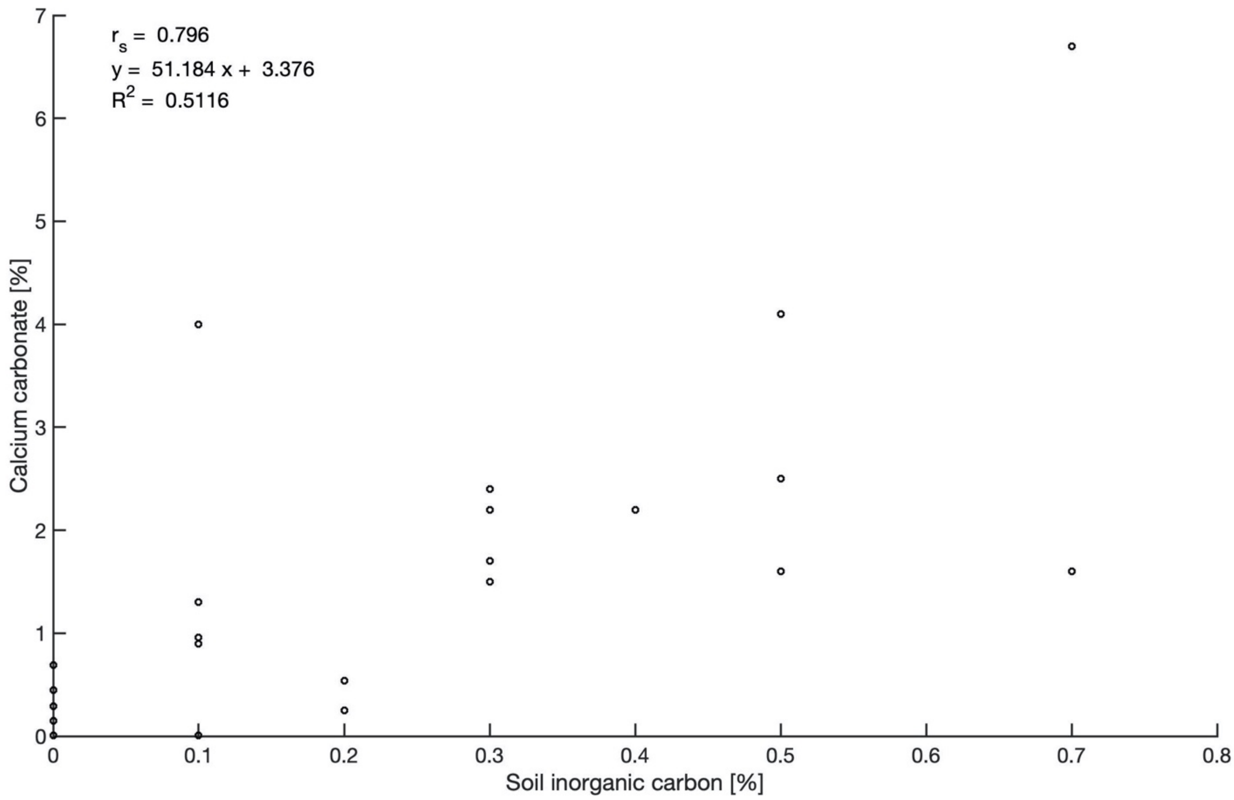

Fig. 9. The relationship between SIC and $CaCO_3$ in 25 urban soil samples.

5.3 Soil C densities, degradability and storage

The mean C content of the upper 30 cm of the soil of the evaluated greenspaces of The Hague was 3.13 % (± 0.35%, Appendix B). Combined with the bulk density, these C concentrations resulted in a mean C density of 88.2 t/ha (± 0.56 t/ha) of which 89% (± 0.36%) was contributed by SOC and 11% (± 0.05%) by SIC, all related to the upper 30 cm of soil. SIC contribution to TC was especially large in the dune areas, whilst SOC dominated the total C values for the remainder of the samples. A large variation in soil C densities was observed in the 25 sample plots (Fig. 10). The highest soil C densities were found in sample plots 5, 6, 7, and 20. Plots 7 and 20 consisted of patches of shrubs on the pavement, plot 5 of an old chestnut tree and plot 6 of shrubbery in the palace gardens. The lowest C densities were found in plots 24 and 25: the dunes (Fig. 10). No clear spatial trend was observed.

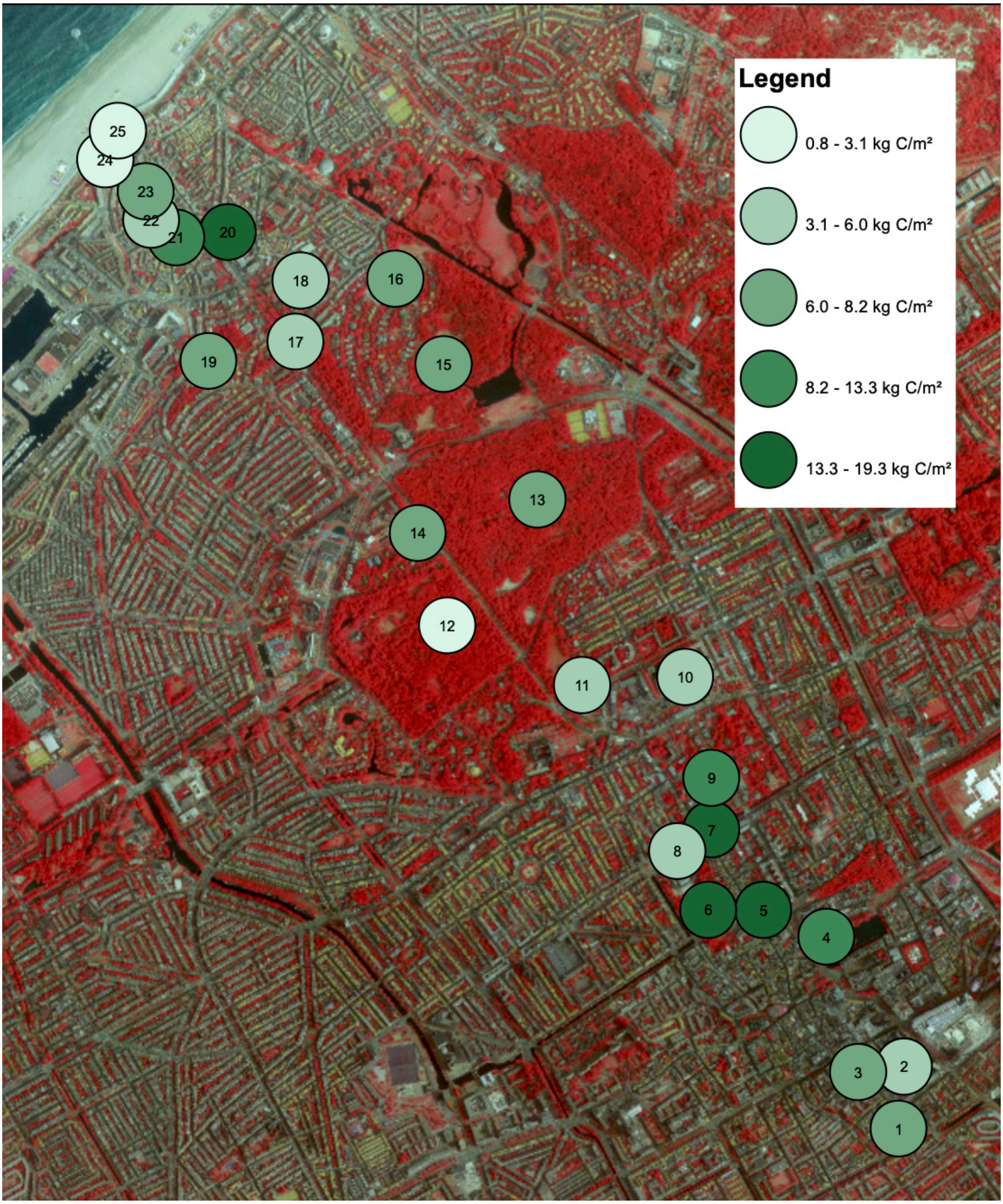

Fig. 10. Total carbon densities of the upper 30 cm of soils of the sample plots from the city centre (sample plot 1) to the seaside (sample plot 25).

5.3.1 Soil C densities in different types of greenspaces

Dividing the sample plots by vegetation class revealed that soils beneath shrubbery contained significantly higher C densities than those beneath trees or herbaceous vegetation (Fig. 11A, Kruskal-Wallis One-way ANOVA, Chi-sq: 17.18, $p < 0.01$). DOC values were significantly higher in soils beneath shrubbery and trees than herbaceous vegetation (Kruskal-Wallis One-way ANOVA, Chi-sq: 10.45, $p < 0.01$). Moreover, the N, P and S densities were also higher in soils beneath shrubs (Kruskal-Wallis One-way ANOVA, Chi-sq: 16.96, $p < 0.01$ for N, Kruskal-Wallis One-way ANOVA, Chi-sq: 11.04, $p < 0.01$ for P, Kruskal-Wallis One-way ANOVA, Chi-sq: 21.10, $p < 0.01$ for S). However, the P densities in soils beneath shrubs were only higher than soils beneath trees, and not than soils beneath grasses. The C:P ratio was lower in soils beneath grasses than soils beneath trees and shrubs (Kruskal-Wallis One-way ANOVA, Chi-sq: 9.49, $p < 0.01$). The C:N and C:S ratios did not significantly differ between the vegetation classes.

The soils in greenspaces that were publicly owned contained significantly higher C densities than the greenspaces that were privately owned (Fig. 11C, Wilcoxon rank sum test: 2444, $p < 0.05$), and the greenspaces located in the city centre contained higher C densities than those located in the suburban Scheveningen (Fig. 11D, Wilcoxon rank sum test: 1463, $p < 0.05$). Moreover, the more urbanized city centre contained higher EC values than the more suburban district (Fig. 11, Kruskal-Wallis One-way ANOVA, Chi-sq: 3.9, $p < 0.05$).

For the soil types, the soils classified as ‘Beekeerd’ soils held significantly higher C densities than those classified as ‘Meerveen’, ‘Vlakvaag’ and ‘Duinvaag’. However, C densities in ‘Meerveen’, ‘Vlakvaag’ and ‘Duinvaag’ soils did not significantly differ from each other (Fig. 11B, Kruskal-Wallis One-way ANOVA, Chi-sq: 15.82, $p < 0.01$). Additionally, ‘Beekeerd’ soils exposed higher EC values than ‘Vlakvaag’ and ‘Duinvaag’ soils (Kruskal-Wallis One-way ANOVA, Chi-sq: 8.99, $p < 0.05$). Dividing the greenspace by status of ‘Ecozone’, land use, size of the greenspace or litter management did not result in any significant differences in C densities (Fig. 11E, 11F, 11G, 11H).

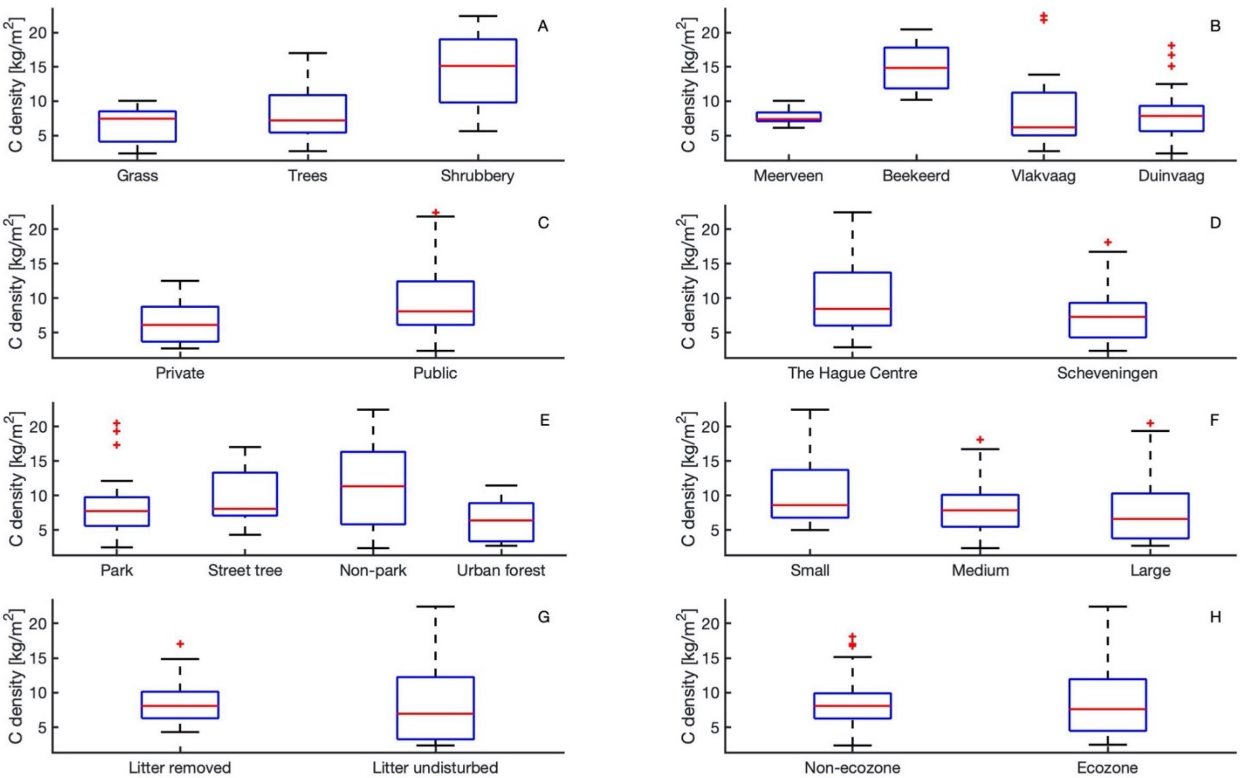

Fig. 11. Boxplots of the total C densities in the upper 30 cm of soil in different greenspace types. The red line represents the median, the box marks the first and third quartile and the whiskers indicate the largest and smallest data points excluding outliers. The red plus sign represents outliers. Subplot A compares the different vegetation classes. Subplot B compares the different soil types. Subplot C compares different land ownership. Subplot D compares the different districts. Subplot E analyses different land uses. Subplot F analyses different greenspace sizes. Subplot G analyses different plant litter management. Subplot H analyses the influence of the status of ‘Ecozone’. Only the categories in subplots A, B, C and D differ significantly (statistics in text).

The municipality of The Hague divided its greenspace management based on landscape and land cover (van Droesberg, 2017). When comparing the management packages (and simultaneously the land cover classes), it was detected that soils beneath shrubs contained significantly higher soil SOC densities than most other classes, except fertilized grass and trees on sealed surfaces (Fig. 12). Interestingly, the soil beneath trees placed on unsealed surfaces contained higher SIC densities than the soil beneath trees placed on sealed surfaces (Fig. 12).

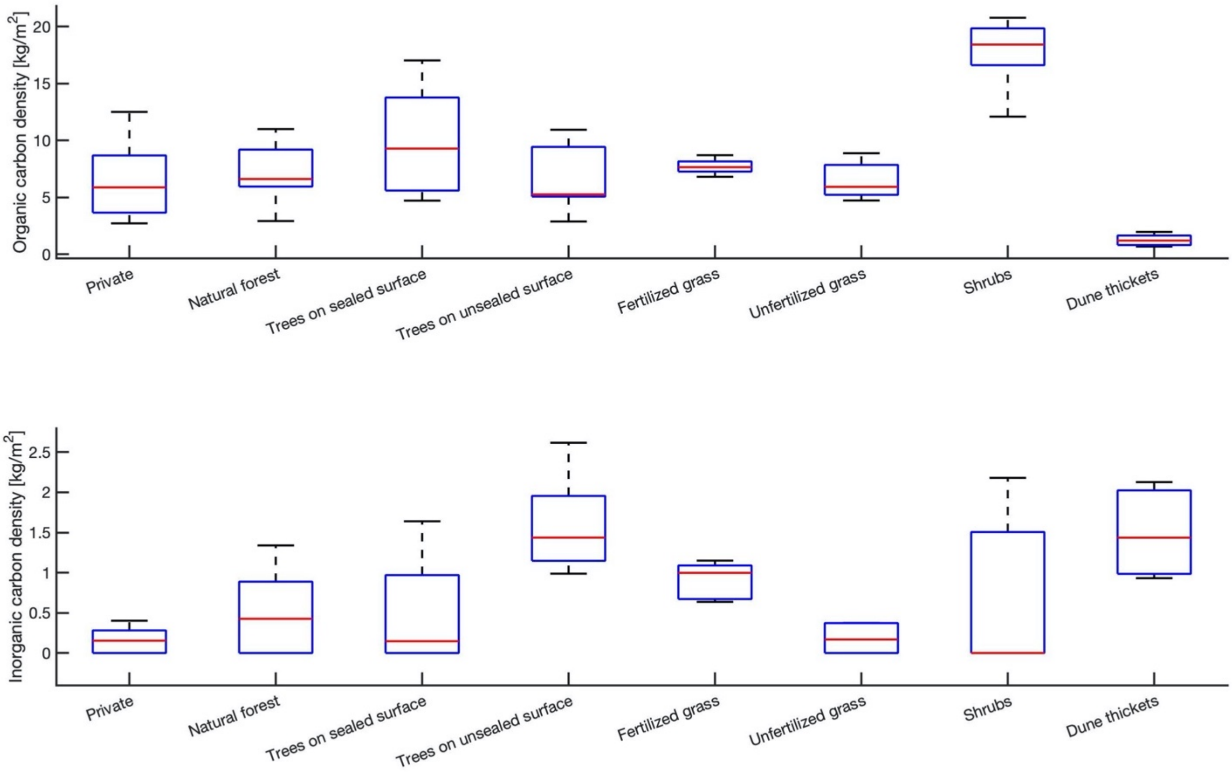

Fig. 12. Organic (upper plot) and inorganic (lower plot) C densities in the upper 30 cm of soil for the different management classes. The red line represents the median, the box marks the first and third quartile and the whiskers indicate the largest and smallest data points excluding outliers.

Although C densities did not significantly differ between greenspaces that were classified as ‘Ecozones’ or ‘non-Ecozone’ DOC levels in the soil of greenspaces that were classified as Ecozones were higher than those in non-Ecozones (Wilcoxon rank sum test: 1715, $p < 0.05$). Moreover, a lower pH was detected in soils of greenspaces classified as ‘Ecozones’ compared to soils of greenspaces classified as ‘Non-ecozone’ (Wilcoxon rank sum test: 1183, $p < 0.01$ for pH). Lastly, bulk density was lower in greenspaces classified as ‘Ecozone’ than ‘Non-ecozone’.

Even though no significant difference in C densities was detected between greenspaces with and without litter management, litter management did have a pronounced effect on other soil properties. Higher DOC and loss-on-ignition levels were detected in greenspaces where plant litter was relatively undisturbed (Fig. 13A & 13B, Wilcoxon rank sum test: 1704, $p < 0.05$ for DOC, Wilcoxon rank sum test: 1692, $p < 0.05$ for loss-on-ignition). Additionally, pH values were lower in greenspaces where it was assumed the plant litter was left undisturbed compared to the greenspaces where the plant litter was removed (Fig. 13C, Wilcoxon rank sum test: 1169, $p < 0.01$). Lastly, soils with undisturbed plant litter contained a higher water-holding capacity than those where litter was removed (Fig. 13D, Wilcoxon rank sum test: 208, $p < 0.05$).

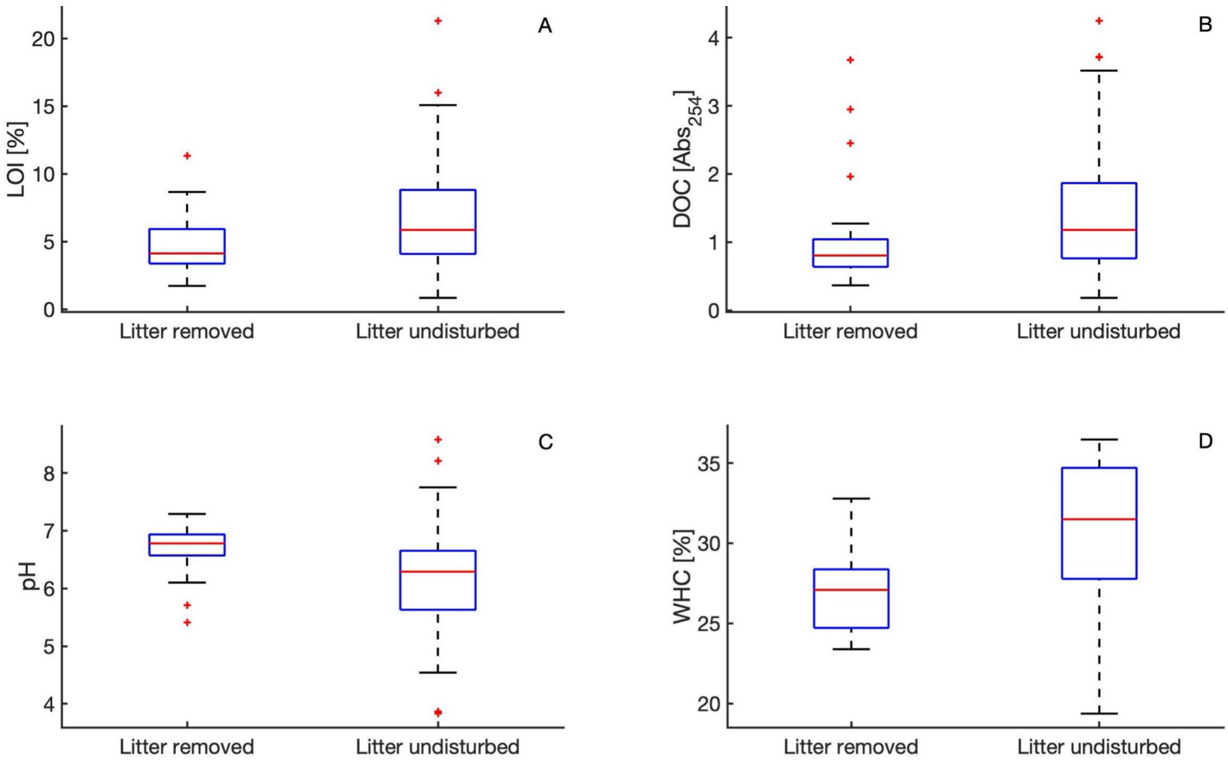

Fig. 13. Boxplots of loss-on-ignition (LOI, subplot A), DOC (subplot B), pH (subplot C) and the water-holding capacity (WHC) of the soil (subplot D) in dependency of litter management. The red line represents the median, the box marks the first and third quartile and the whiskers indicate the largest and smallest data points excluding outliers. The red plus sign represents outliers.

5.3.2 Degradability of urban soil organic matter

The mean mineralization of SOC in respect to SOC content was 17.9 mg C/g SOC (± 2.16 mg C/g SOC) and the mean cumulative amount of C mineralized after a 6-week incubation period was 37.4 mg C/100 g soil (± 2.05 mg C/100 g soil). The potential C mineralization of the upper 30 cm of soil was established at 127.5 mg C m^{-2} (± 10.6 mg C m^{-2}). The mineralization over time was linear for all soil samples (Fig. 14, R^2 = 0.98 - 1.00).

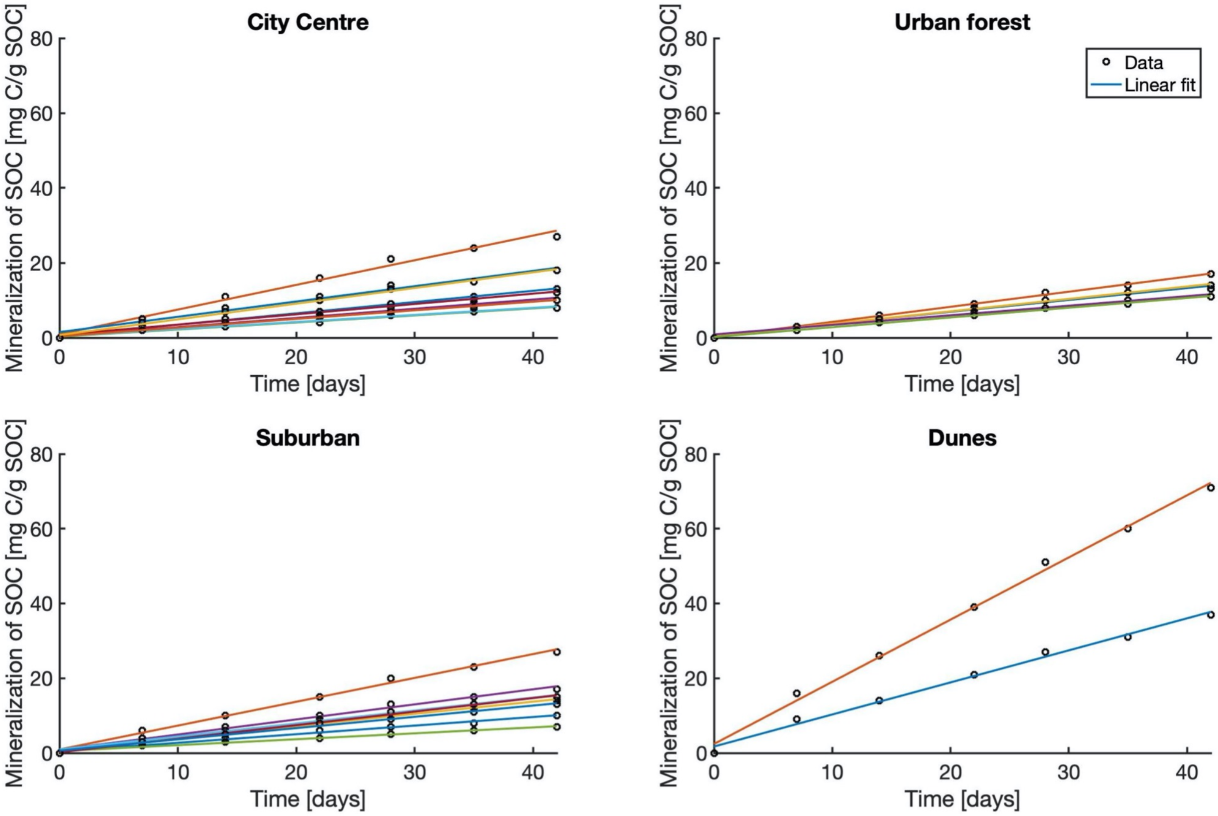

Fig. 14. Cumulative mineralization of SOC to CO_2 evolution along the transect from the city centre (upper left), to the urban forest (upper right), to the suburban area (lower left) to the dune area (lower right). The points represent replica Z (Fig. 15). The data points and fit for replica Y were similar.

The mineralization rate of SOC in relation to the SOC content of the soil [mg C/ g SOC] was significantly higher in the dunes (sample points 24 & 25) than in the city centre, urban forest and suburban area (Fig. 15, Kruskal-Wallis One-way ANOVA, Chi-sq: 12.18, $p < 0.01$). However, the potential C mineralization, expressed as the amount of C released from the upper 30 cm of soil, was lowest in the dunes and highest in the urban forest. No difference was detected between the potential C mineralization of greenspaces located in the city centre or suburban area (Kruskal-Wallis One-way ANOVA, Chi-sq: 20.24, $p < 0.01$).

The degradation of SOM was independent of greenspace management, but the potential C mineralization was higher in soils where plant litter was relatively undisturbed than in soils where plant litter was removed regularly (Wilcoxon rank sum test: 821, $p < 0.01$). The C mineralization normalized to SOC was lower in soils beneath shrubs than soils beneath grasses, but not than trees (Kruskal-Wallis One-way ANOVA< Chi-sq: 7.12, $p < 0.05$). Moreover, the potential C mineralization of the upper 30 cm of soil was lower in soils beneath herbaceous vegetation than soils beneath trees and shrubs (Kruskal-Wallis One-way ANOVA< Chi-sq: 14.7, $p < 0.01$).

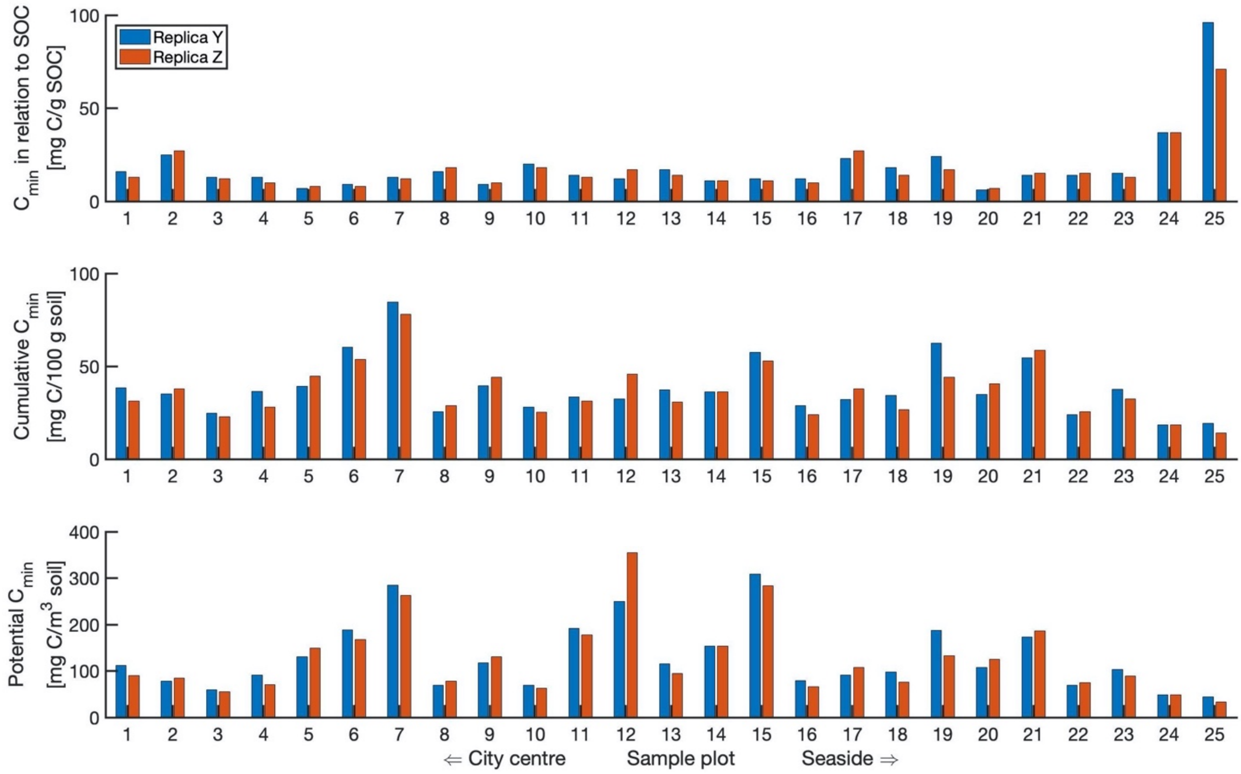

Fig. 15. C mineralization in relation to SOC (upper), cumulative C mineralization (middle) and potential C mineralization of the upper 30 cm of soil (lower) under laboratory conditions in 25 urban soil samples after 6 weeks of incubation.

The C and N contents of the soil strongly correlated with the mineralization of SOC (Table 4). Additionally, a strong association of the potential C mineralization with the pH and the water-holding capacity of the soil was detected (r_s = -0.76 for pH & r_s = 0.75 for WHC). Furthermore, a strong correlation between the potential C mineralization and the C:P ratio of the soil was found (r_s = 0.83). The correlations of the potential C mineralization with the C:N and C:S ratios was only weak (Table 4). Lastly, a moderate association between potential C mineralization and DOC levels was observed (r_s = 0.61).

5.3.3 Soil carbon storage

The sample transect crossed the districts 'The Hague Centre' and 'Scheveningen' which cover a combined area of ~20.8 km^2 (~25% of the entire municipality of The Hague). Based on the green maps of the Netherlands, 7.6 km^2 (~37%) of these districts were covered by greens, of which 52% was covered by herbaceous vegetation (< 1 m), 13% by shrubs (< 2.5 m) and 35% by trees (> 2.5 m) (Fig. 16 & 17).

It was estimated that the upper 30 cm of soil in The Hague that is covered by greenspaces has the potential to store 18.8 kt of C (± 0.63 kt C for herbaceous vegetation, ± 0.45 kt C for shrubs, ± 0.55 kt C for trees, Fig 17). This potential is dependent on several variables (vegetation, land ownership, urbanization, soil type) of which only the vegetation class was considered.

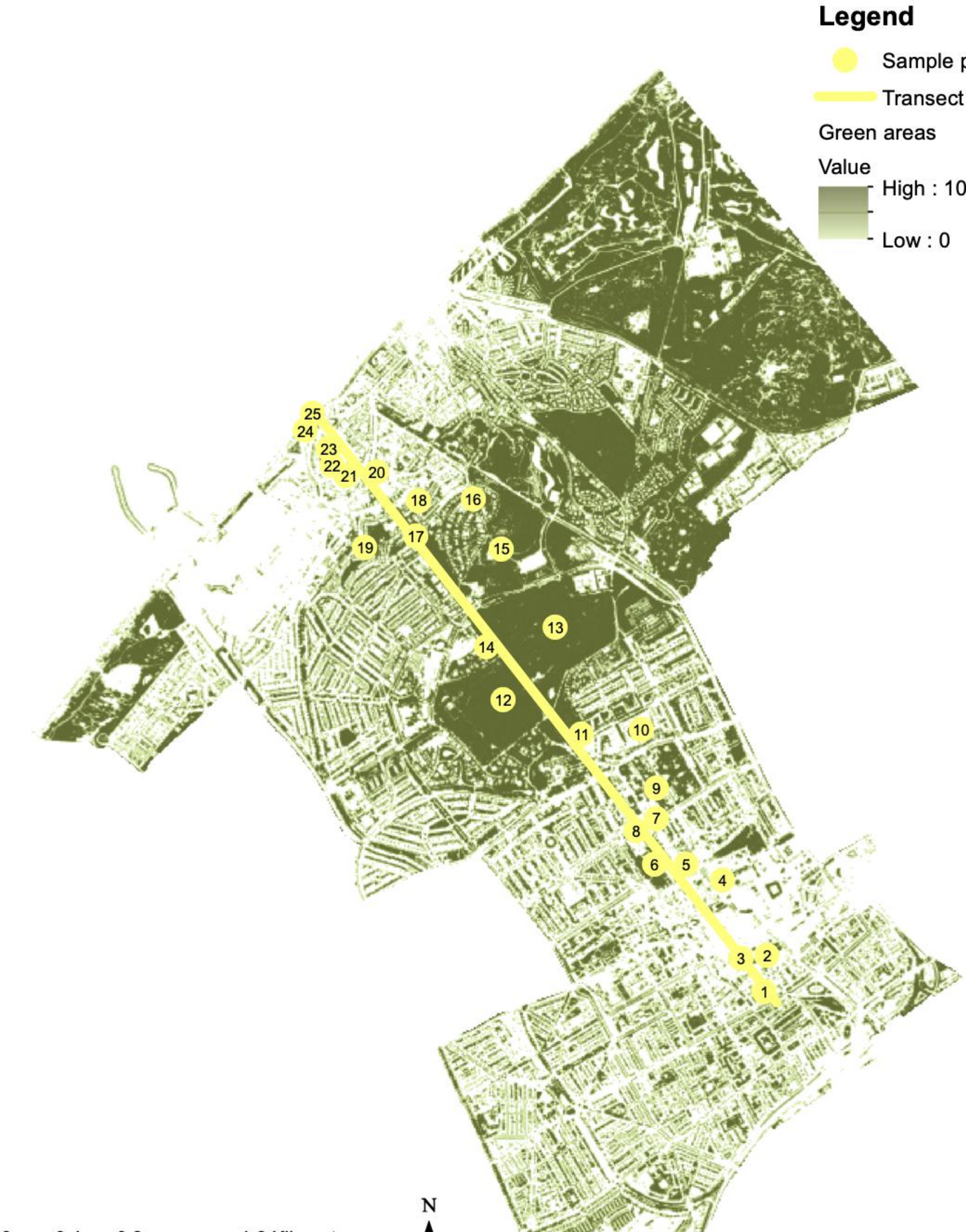

Fig. 16. Green surface area map of The Hague's districts 'Centre' and 'Scheveningen' (based on RIVM, 2017).

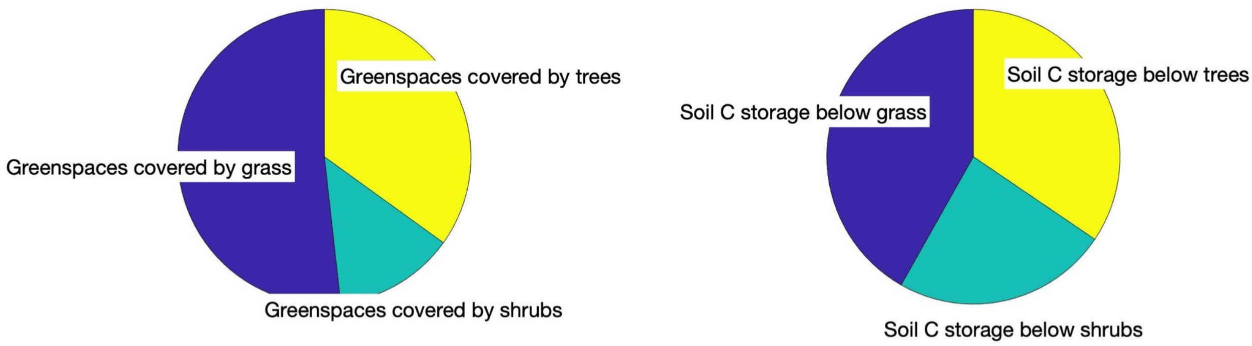

Fig. 17. Distribution of vegetation coverage (left) and estimated C storage in The Hague (right) of the tree vegetation classes: grass, shrubs and trees.

6. Discussion

This study aimed to quantify the soil C storage in The Hague in dependency of its land use, vegetation and soil type, land ownership, urbanization extent, management practises, greenspace size, and status of 'Ecozone'. This more holistic approach, as opposed to soil C modelling based on land use and/or soil type only, helped to better understand the C storage potential of urban soils.

Using the mean C densities of the vegetation classes led to a total C storage of 18.8 kt in districts Scheveningen and the city centre of The Hague of which 7.86 kt C was stored beneath herbaceous vegetation (± 0.63 kt C), 4.46 kt was stored beneath shrubs (± 0.45 kt C) and 6.48 kt C was stored beneath trees (± 0.51 kt C). The total soil C storage in those districts roughly equalled 1% of the annual greenhouse gas (GHG) emissions of the entire municipality of The Hague (GHG data provided by J. Noordhoek, pers. com., 14/09/2020).

This study detected a mean soil C density of 8.8 kg C m^{-2} of which 8.2 kg C m^{-2} was SOC in the upper 30 cm of soil in the 25 sampled greenspaces in The Hague. For the urban C storage studies performed in the same Köppen-Gauger climate classification, namely Cfb, Beesley et al. (2012) detected a total C density of 1.0 to 5.0 kg C m^{-2} in the upper 15 cm of soil in Liverpool, U.K., Edmondson et al. (2012) reported a SOC density of 14.4 kg C m^{-2} in the upper 21 cm of soil in Leicester, U.K., Cambou et al. (2018) estimated a SOC density of 9.9 kg C m^{-2} in the upper 30 cm of soil in Paris, France, and Weissert et al. (2016) reported a SOC density between 9.3 and 16.4 kg C m^{-2} in the upper 30 cm of soil in Auckland, New Zealand. Data were in the same order of magnitude, however, the sample depths between the studies differed significantly, which make them not directly comparable.

6.1 High soil C densities beneath shrubs

The amount of SOM is balanced between the ability of decomposers to access SOM and the protection of SOM from decomposition by the soil minerals, which means that SOM is composed of organic fragments of various sizes and in various stages of decay (Lehmann & Kleber, 2015). This concept opposed the idea that humification processes create recalcitrant humic substances that comprise the greater part of SOM (Lehmann & Kleber, 2015). The balancing act between decomposition and protection from decomposition may be disturbed in urban environments leading to either an accumulation or reduction of SOM stocks.

Shrubs and their management appeared to have a positive effect on the accumulation of soil C in urban environments. The impacts of vegetation itself and management practices could not be reliably distinguished in the data. Planting shrubs and managing the system as prescribed by the greenspace management system of the Municipality of The Hague (van Droesbergen, 2017) will lead to the further development of soil, rhizosphere and soil biota which will then lead to an accumulation of SOM.

Shrubs outperformed trees and herbaceous vegetation considering soil C accumulation. Although, stating that shrub plant litter and root functioning are of higher quality to form SOM is too simplistic. It is rather the environmental, abiotic and biotic factors of the soil and vegetation that created conditions that resulted in SOM accumulation (Lehmann & Kleber, 2015). One important abiotic factor was the increased nutrient concentrations of soils beneath shrubs (N, P, S, Fig. 8). Moreover, it appeared that the SOM in soils beneath shrubs was more stable against mineralization under laboratory conditions than grasses, but not than trees. However, the potential C mineralization of the upper 30 cm of soil beneath shrubs was higher than that of soil beneath grasses, which is likely due to the higher SOM and DOC content of the soil beneath shrubs. Texture class did not impact C densities beneath shrubs as shrubs on soils of different texture classes all contained higher soil C levels.

6.2 Relatively low C densities in the acidified urban forest

The urban forest in the middle of the transect (sample plot 11-15) contained relatively low C densities of 6.0 kg C m^2 (± 0.76 kg C m^2) compared to the other sampled greenspaces, which may be because the urban forest soil was strongly acidified (with a mean pH of 5.2, with locally extremely acidic conditions of 3.8, Fig. 5 & 10). When soil acidifies, the soil microbial community shifts from a balance between soil bacteria and fungi to a fungal-dominated soil, which changes the way organic matter is decomposed (Rousk et al., 2009). A fungal-dominated soil is characterized by slow nutrient cycling and a high capacity to retain nutrients (de Vries et al., 2006). The shift from bacteria and fungi to mostly fungi may thus lead to a decrease in C mineralization (Francini et al., 2018).

The relatively low C densities in the urban forest may be explained by the C dynamics of the soil. The potential C mineralization in the urban forest was 1.9-4.8 times higher than in the remaining greenspaces suggesting that the conditions in the urban forest were more favourable for the mineralization of SOC (Fig. 15). This notion was also observed in the data of the soil-quality characteristics as higher pH values, C:P ratios and DOC levels were detected in the urban forest (Fig. 6 & 8) and pH, C:P and DOC significantly correlated with the mineralization of SOC (Table 4). The influence of P on C mineralization in urban forests was also investigated by Chen et al. (2014) who observed higher C mineralization under P enrichment in organic matter in urban sites. What caused the relatively high P levels in the urban forest of The Hague is unclear as the forest is not managed with fertilizers. Whether it is the efficient cycling of P through plant litter decomposition, pet waste pollution or plant-symbiotic fungi that thrive in acidic soils requires further investigation.

These findings are in line with Kim and Yoo (2020) who measured a lower respiration rate in the roadside tree system than in urban forests, although they measured respiration in the field using the chamber method, making the results not directly comparable. They added that it may be more difficult for soil microorganisms to mineralize organic materials in roadside soils than in urban forests because roadside soils may be more susceptible to urban pollutants which are likely inhibiting microbial activity.

6.3 Low C densities in the dunes

In the dunes, low C densities were measured (Fig. 10). The mean soil organic C content of the dune samples (0.35% SOC) was comparable to the values reported in similar dune vegetation in the region (0.44%, de Vries, 1993). The dunes are a relatively young ecosystem consisting of soil with a coarse texture and a low water-holding capacity, which makes the chemical and physical protection of SOM from decomposition minimal. Dune systems are valuable for multiple reasons (e.g. coastal protection, water purification), however, from the perspective of soil C storage they are less relevant.

6.4 Soil C densities in different types of greenspaces

C densities of the upper 30 cm of soil differed significantly in the following urban greenspace categories: vegetation class, soil type, land ownership and urbanization extent. No differences in C densities were detected for the categories land use, 'Ecozone', litter management, and size of the greenspace (Fig. 11).

6.4.1 Soil C densities: soil types

This study did not classify the substrate type, as only the upper 30 cm of soil was sampled. Instead, it was hypothesized that the national soil map of the Netherlands (1:50,000-10,000) could be extrapolated over the urban area of The Hague (Fig. 2). It was hypothesized that the more developed 'Beekeerd' soil would contain higher soil C densities than the less developed 'Vlakvaag' and 'Duinvaag' soil. Additionally, it was hypothesized that the peaty 'Meerveen' soils would contain the highest soil C densities. It was found that this hypothesis was only partially held as only the 'Beekeerd' soil contained significantly higher soil C densities than the other soil types (Fig. 11).

The rejected hypothesis may result from the fact that urban soils are often constructed. Especially in greenspaces that were used as playgrounds, it was clearly visible that the topsoil consisted of alien soil with a different texture and colour. Over time, mixing may occur, which was observed at some of the older sites. However, at some of the younger or recently redecorated greenspaces, the external top layer did not visibly mix yet, which implied minimal influence of the original substrate. These findings have implications for soil C modelling as the extrapolation of soil maps over urban areas may not be the most appropriate approach to estimate soil C stocks. It also has significance for soil C stock estimations as the buried horizon, i.e. the former topsoil, or peaty subsoils of the 'Meerveen' soils may contain significant amounts of C.

The mean organic C content of the sampled greenspaces (2.9%) exceeds the mean C content in Dutch grasslands, croplands, and nature for all soil types except the peaty 'Meerveen' (Table 5), which is in line with Lindén et al. (2020), Edmondson et al. (2014) and Cambou et al. (2018) who reported higher SOC levels in urban ecosystems than in adjacent agricultural grasslands, croplands or upland forest soils. The lower SOC content in agricultural soil may reflect the long-term effect of agricultural practices, such as ploughing, application of chemical fertilizers and crop removal, on SOC content and soil quality (Edmondson et al., 2014; Lal, 2009)

For urban soils, Lof et al. (2017) assumed a soil C stock of 0.9 times the soil C stock of the respective soil type, which is based on the widely held assumption that urban soils are SOC impoverished due to anthropogenic influences. However, most of the urban soils of greenspaces in The Hague were relatively undisturbed, i.e. vegetation was predominantly permanent, SOC stocks are sufficient for soil functioning (> 1.5%, Lal, 2016a), and soil compaction was limited and thereby did not restrict root growth. For the urban greenspaces in The Hague, the assumption therefore resulted in an underestimation of current C stocks, which was especially apparent for the soil type 'Kalkhoudende zandgronden' (Table 5). In the city centre where peaty soils were expected, the applied sampling method could not confirm whether this was the case (sample plots 1, 2, & 3). 'Meerveen' soils consist of mineral topsoil on top of a nutrient-rich peat layer (~ 60 cm deep). As only the upper 30 cm of soil was sampled, the soil type could not be confirmed. Although, it is likely that SOC content in the upper 30 cm of the mineral layer of 'Meerveen' soil does not accurately reflect the C content of the entire soil profile.

Table 5. Modelled SOC densities in the Netherlands (upper 30 cm) versus measured SOC densities in The Hague (upper 30 cm).

Soil type	Mean SOC density in the Netherlands (Conijn & Lesschen, 2015)	SOM (Conijn & Lesschen, 2015)	SOC [%] *Conijn & Lesschen (2015) assume that 50% of SOM is SOC according to Pribyl et al. (2010)	Assumed SOC density in urban areas in the Netherlands (Lof et al., 2017 based on Conijn & Lesschen, 2015)	Measured SOC densities in The Hague	Measured SOC in The Hague
Veengronden	191 t SOC/ha	Grassland: 24.9 Cropland: 21.4 Nature: 42.5	Grassland: 12.5 Cropland: 10.7 Nature: 21.3	172 t SOC/ha	149 t SOC/ha (n = 9)	1.9%
Eerdgronden	82 t SOC/ha	Grassland: 4.3 Cropland: 4.2 Nature: 4.9	Grassland: 2.2 Cropland: 2.1 Nature: 2.5	74 t SOC/ha	70 t SOC/ha (n = 9)	5.0%
Kalkloze zandgronden	75 t SOC/ha	Grassland: 4.4 Cropland: 4.2 Nature: 3.1	Grassland: 2.2 Cropland: 2.1 Nature: 1.6	67 t SOC/ha	77 t SOC/ha (n = 27)	3.3%
Kalkhoudende zandgronden	52 t SOC/ha	Grassland: 2.8 Cropland: 2.3 Nature: 2.2	Grassland: 1.4 Cropland: 1.2 Nature: 1.1	47 t SOC/ha	67 t SOC/ha (n = 30)	2.3%

6.4.2 Soil C densities: vegetation

This study detected that upper soil beneath shrubs in urban greenspaces accumulates soil C to a greater extent than the soil beneath trees and herbaceous dominated vegetation (Fig. 11), which is not in line with the pattern commonly observed in non-urban ecosystems where usually the soil C densities are highest in woodlands (Bell et al., 2011). However, this pattern is consistent with Lindén et al. (2020) who also reported higher C densities beneath shrubbery than beneath trees and herbaceous vegetation in the urban soils of Helsinki, Finland. Although, Lindén et al. (2020) could not distinguish whether the different soil C stocks were the result of management (mulching in the case of shrubs) or the vegetation itself. Edmondson et al. (2014) on the other hand hypothesized higher soil C densities beneath trees than grassland but detected no difference in land cover in the urban soils of Leicester, the U.K. These findings contrasted the widespread idea of tree planting to increase the provision of urban ecosystem services, although increasing tree cover may have a positive effect on aboveground C storage (Edmondson et al., 2014; Davies et al., 2011).

6.4.3 Soil C densities: urbanization extent

Larger C densities were detected in the city centre than in the suburbs of The Hague (Fig. 11); A mean C density of 44 kg C m^{-2} was measured in the city centre of The Hague and a mean C density of 31 kg C m^{-2} was detected in Scheveningen. This pattern differed for several urban soil studies, for example in Berlin the suburbs contained higher C densities than the city centre (Richter et al., 2020), but in Paris, the city centre contained higher soil C densities than the suburbs (Cambou et al., 2018). For Berlin, higher soil C densities in the suburbs were likely the result of management effects in the large domestic gardens that are typical for the suburbs of Berlin (Richter et al., 2020). In Paris, the higher soil C densities are explained by the substrate origin; City Centre greenspaces were constructed with soil rich in SOM and suburban greenspaces were constructed with soils poorer in

SOM (Cambou et al., 2018). This historic origin was also likely the case for The Hague in combination with the fact that the original substrate was also poorer in the suburbs of The Hague.

6.4.4 Soil C densities: land ownership

This study detected higher soil C densities in the soils of publicly owned greenspaces than in those of privately-owned greenspaces (Fig. 11), which is not in line with Edmondson et al. (2014), Rawlins et al. (2008) and Pouyat et al. (2009). These studies detected higher SOC concentrations in gardens than non-domestic greenspaces and explained this difference by stating that domestic gardens are likely supplemented with organic materials by their owners. However, this study did not include domestic gardens. The distinction between private and public was made based on whether the greenspace managed by the municipality of The Hague or not. Private greenspaces in this study entailed privately managed parks, communal gardens managed by the building committee, cemeteries, and gardens of retirement homes. The difference in C densities of publicly and privately owned greenspaces is nonetheless likely a management effect, which was especially apparent in the urban forest. The part of the urban forest that was privately managed contained considerably lower soil C densities than the part that was publicly managed (sample plot 12 vs. sample plot 13-15, Fig. 10). The active management of the municipality described by Van Droesberg (2017) resulting in larger soil C stocks than the passive, private management (private management provided by E. Evers, pers. com., 09/03/2021).

6.4.5 Soil C densities: greenspace management

This study detected no pronounced differences in SOC storage under different urban greenspace management practices (Fig. 11 & 12). The management category shrubs contained significantly higher soil C densities than the other management packages (Fig. 12). However, whether this difference was the effect of management of the vegetation itself could not be reliable distinguished from the data (Fig. 11).

Furthermore, investigating the effect of urban greenspace management on SOC storage was complicated because urban greenspace management packages may have reverse effects on soil C stocks, which is for example observed in the maintenance of lawns that incorporate fertilization, but also the removal of grass clippings. These reverse effects make it difficult to predict the responses in soil C (Lindén et al., 2020).

When simplifying management practices to litter management only, similar C densities were detected in soils that were depleted of plant litter and soils that were naturally augmented with plant litter. Litter management did have a pronounced effect on LOI, DOC, pH, and the water-holding capacity of the soil (Fig. 13). Moreover, potential C mineralization was higher in soils that were naturally augmented with plant litter than those that were depleted of plant litter (section 5.3.2). The latter implies that perhaps the fresh plant litter input is readily mineralized by the microbial community and thereby does not lead to an increase in SOC accumulation.

Lastly, higher SIC densities were detected in soils beneath trees on unsealed surfaces than in soil beneath sealed surfaces. This difference is likely not a management effect, but the result of unintended anthropogenic inputs. The trees on unsealed surfaces were predominantly rows of trees places on strips of grass along main roads. The dust inputs of e.g. construction work and roads may have increased SIC levels in those plots.

6.4.6 Land use

For the greenspaces in The Hague, the category land use was not a good predictor for soil C storage as no different C densities were detected in the soil of urban forests, street trees, parks and non-parks. These four categories held a wide range of soil types, vegetation and land-ownership which appeared to be more influential than their land use.

6.4.7 Soil C densities: greenspace size

The use of high spatial resolution GIS data at the scale of 10 x 10 m enabled the inclusion of small patches of green in the total soil C storage of The Hague. This inclusion proved to be significant as large greenspace only comprised 26% of the greenspaces in the districts of The Hague Centre and Scheveningen and the measured C densities in the medium and smaller greenspaces were comparable to those in larger greenspaces (Fig. 11).

6.4.8 Soil C densities: status of 'Ecozone'

The Hague classified several greenspaces as 'Ecozone', meaning they are part of the ecological main structure of The Hague, to indicate their importance for biodiversity (Den Haag Dataplatform, 2020). This study aimed to find out whether the status of 'Ecozone' was also a good predictor for soil C storage. No difference was found in soil C densities in the soils of greenspaces that were either classified as 'Ecozones' or 'Non-ecozones' (Fig. 11). However, the bulk density, DOC and pH of the soil differed significantly between 'Ecozones' and 'Non-ecozones' (section 5.3.1). As these parameters also significantly correlated with C densities (Table 4), it suggested that greenspaces that are classified as 'Ecozones' potentially have a higher C storage capacity. Nonetheless, why these factors combined did not result in higher soil C densities remains unclear.

6.5 C:N:P:S ratio

The urban soils of The Hague have a mean C:N:P:S ratio of 1:15:55:55 and a moderate to strong correlation between C, N, P, and S (Fig. 8), which meant that these nutrients could form a limiting factor in C sequestration. SOM smaller than 4 mm is believed to have a nearly constant C:N:P:S ratio of 1:12:50:70, which suggests that at these nutrient proportions, humification occurs most effectively (Kirby et al., 2011). This humification optimum suggests that for each tonne of sequestered soil C, the soil approximately co-locks 80, 20 and 14 kg of N, P, and S (Kirby et al., 2011). Moreover, a higher C:N:P:S ratio than the humification optimum may result in C and nutrient losses to the atmosphere after organic amendments aimed at increasing the SOM stock. This loss is due to the positive priming effect, which is caused by the response of soil microbes to the fresh organic inputs (e.g. co-metabolism, microbial mining, Kirby et al., 2014). The lower C:N:S ratio in the urban soils of The Hague postulates that opportunities exist through increased input of these nutrients in the form of fertilizers to improve C sequestration rates (Kirby et al., 2013; Kirby et al., 2016).

6.6 Soil C dynamics

Investigating why some SOM persists for a long time and other SOM degrades readily will help to predict SOM stock's response to climate change (Schmidt et al., 2011; Wan et al., 2020). To gain insights into the C dynamics of urban soils, aerobic soil C mineralization was measured over time and mineralization normalized to SOC was used as a representative of the degradability of urban SOM. For SOM to contribute to long-term C storage, it is not required to build 'stable' SOM pools, instead, SOC is regarded as always in flux, not as a stagnant pool (Janzen, 2015; Lehmann & Kleber, 2015). The dynamic soil C stock can be enlarged by either increasing the C inflows or by decreasing the C outflows (Janzen, 2015). In this study, initial measurements took place to assess the latter: the mineralization of SOC under laboratory conditions.

As soil respiration is strongly dependent on temperature, moisture status and compaction, large differences in mineralization rates may occur within urban areas due to the urban heat island effect (Pickett et al., 2011) and use of the urban greenspace (e.g. soil compaction due to human trampling, Kim & Yoo, 2020). Since the conditions during incubation were more favourable than those in the fields, the measured respiration rates likely exceed in situ rates and therefore did not represent true C emissions from the investigated sample plots. Although the respiration values may be overestimated, the experimental design allowed for comparison between the urban soils samples (Saviozzi et al., 2014).

The mineralization rate of SOM differed along the transect (Fig. 15), which suggested different C availability for the decomposer organisms during the incubation period (Lehman & Kleber, 2015; Saviozzi et al., 2014). The highest mineralization rates normalized to SOC were found in the sandy dunes (Fig. 15). However, when translated to potential C mineralization, expressed as the amount of C released by the upper 30 cm of soil, the dunes emitted the lowest amount of C, whilst the urban forest in the middle of the transect emitted the highest amount of C (Fig. 15, section 6.2).

The high degradability of SOC in the dunes may be explained by the coarse texture of the soil. The sandy texture affects SOM decomposition through smaller particle surface areas, higher porosity, and lower water holding capacity (Barré et al., 2014). Decomposition in sandier soils may therefore be faster than in finer textured soils where aerobic C mineralization may be inhibited lower oxygen concentrations and chemical and physical stabilization of SOM by soil minerals (Barré et al., 2014). The influence of texture was also observed by Zacháry et al. (2018) who reported faster SOC turnover rates for sandier than finer-textured soils.

The degradability of SOM significantly correlated with the C and N contents of the soil (Table 4). The significance positive correlation between the C mineralization and SOC and N were confirmed by Ahn et al. (2009) and Zacháry et al. (2018). Conversely, the C:N ratio of the soil only weakly correlated with the C mineralization (Table 4), which is in line with Zacháry et al. (2018) who state that the C:N ratio is likely a less good indicator for the recalcitrant C pools.

Furthermore, the effect of litter management on the potential C mineralization was pronounced even though the soils did not contain significantly different C densities (Fig. 11). After 6 weeks of incubation, the analysis quantified a potential C mineralization of 90 mg C/ m^2 (± 3.4 mg C/ m^2) for the soils depleted from plant litter and 162 mg C/ m^2 (± 12 mg C/ m^2) soil for the soils augmented with plant litter, suggesting that urban soils that are naturally augmented with plant litter possess a higher SOC turnover rate. Just like in the urban forest, the greenspaces where plant litter was naturally augmented contained lower pH values, higher DOC values and higher water-holding capacities (Fig. 13), which may all lead to increased SOC turnover.

The moderate association between DOC and the mineralization of SOC ($r_s = 0.61$) may confirm the pathway of the breakdown of SOM into smaller, water-soluble compounds which then become accessible for decomposer organisms (Lehmann & Kleber, 2015). DOC levels are also a good indicator of microbial C availability. In general, a high correlation between microbial biomass C with DOC is reported (Zack et al., 1990 in Jones et al., 2006). The association between DOC and the mineralization of SOC may therefore also reflect the difference in highly microbial active soils and lower microbial active soils.

No pronounced acceleration of mineralization was detected during the first incubation interval, as for example Saviozzi et al. (2014) observed, instead, respiratory C release was linear over time (Fig. 14). However, this absence of an initial acceleration may have also resulted from the longer measurement intervals (weekly versus daily). Additionally, the impact of aeration and the consequent water loss followed by the supplementation of water was assessed in the experimental design. In the final analysis, neither the aeration nor the rewatering afterwards seemed to impact the mineralization rate. Therefore, it was not further included in the data analysis.

6.7 Implications for urban planners

This case study yielded several findings which are relevant from a practical point of view. When planning and managing urban greenspace for soil C storage, shrubs are preferred over trees and herbaceous vegetation. Moreover, the supplementation of N, P and S to reach ratios to approximate the optimal humification ratios are recommended. When accounting for the co-benefits of increasing soil C stocks, improving the N, P and S availability may become economically and environmentally sensible (Kirby et al., 2011).

Furthermore, to close the difference in soil C storage between privately and publicly owned greenspace, it is advised to adopt the management practices of the municipality of The Hague. Although careful comparison of management practices per specific case is recommended. Lastly, urban soil C storage is similar in smaller greenspaces than in larger ones. The smaller greenspaces should therefore not be neglected in urban planning for soil C sequestration.

6.8 Implications for measuring C densities

This study detected several methodological implications of which the heterogeneity of urban soils, the determination of SOC, SIC, DOC and clay content are further discussed. Urban soil characteristics are highly heterogeneous, which was observed in the large variations between samples plots, but also in the variability in properties in sample sites. The data also exposed multiple variables that influence soil C stocks, which called for multivariate statistics. However, the small sample size of 75 did not allow for that.

The strong association between SOC and loss-on-ignition ($R^2 = 0.77$) in combination with the 0.49% conversion factor of SOM to SOC made loss-on-ignition a robust method to calculate urban soil C stocks. The factor of almost 2 is in line with Pribyl (2010) who challenged the conventional factor of 1.724 and discovered that the assumption that 58% of SOM consists of SOC is too high. Instead, a factor of 2 would be more accurate in almost all cases (Pribyl, 2010). Nonetheless, the conventional conversion factor was applied in several urban soil studies.

Determination of SIC is often approached by measuring $CaCO_3$ levels, which also is applied in urban soil studies (e.g. Saviozzi et al., 2013). In our study, SIC was strongly, but not perfectly correlated to $CaCO_3$ ($r_s = 0.80$) which may be because SIC predominantly but not entirely constituted of $CaCO_3$. This imperfect association may also be of methodological origin. SOC and total C concentrations were determined by Agrolab (Deventer, the Netherlands) and SIC was believed to be the difference between the two. However, for some samples, a higher SOC than total C was reported, which revealed the shortcoming of this methodology. Moreover, $CaCO_3$ (also determined by Agrolab) was reported in g kg^{-1} dry weight in two significant figures, which resulted in order of precision higher when translated to dry weight percentage. Alternatively, total C levels can be determined using a CN elemental analyser. To distinguish between SIC and SOC, the same procedure can be repeated if first SIC is drained from the samples by adding hydrogen chloride (HCl, 5.7 M; 10 ml HCl to 2.5 g soil (Edmondson et al., 2012; Rawlins et al., 2008)).

DOC levels were assessed with a proxy: the absorbance at 254 nm. However, no calibration data was available to translate the Abs to DOC concentrations. The Abs data allowed for comparison of DOC levels along the transect, but it was not possible to assess the contribution of DOC to total SOC levels.

Lastly, clay content was determined by hand, which had clear limitations. For example, to translate the texture class to clay percentage the average clay content of the respective texture class was used, leading to large margins of error. To acquire more precise clay levels, organic materials first need to be removed, after which the sieving test can follow.

6.9 Research opportunities

This study evaluated urban soil C stocks to assess what their role could be in climate mitigation. However, to go from current soil stocks to annual C fluxes to reveal whether the urban soil acts as a C source or sink, further research is required. By establishing potential annual soil sequestration and/or emission rates, it can be established whether urban soils can achieve negative emissions.

This study found that urban soil C stocks are underestimated, which potentially also is the case for urban soil sequestration rates that are currently applied in C modelling studies. Continuous monitoring over time will help to better understand urban soil C dynamics to gain insights into SOC turnover and seasonal or longer C dynamics.

A total of 25 greenspaces were included in this study. However, urban soils are characterized by their high heterogeneity, which was also perceived in the large variations in C densities in The Hague. To contribute to natural soil C inventories, it is recommended to expand the sampling campaign to other Dutch cities of various urbanization patterns, soil types and greenspace management. Expanding the sampling campaign will also contribute to the development of a reliable set of parameters to estimate urban soil C stocks in temperate climates.

The focus of this study was on soil C stocks. Although C stocks in soils are three times higher than C stocks in vegetation, the assessment of the C levels of the vegetation is nonetheless valuable as it will contribute to the understanding of feedback loops between C stored in soils and vegetation (Hayat et al., 2017 in Richter et al., 2020). Additionally, including sealed surfaces and the subsoil in the sampling campaign will add to the complete overview of how much C is stored in the city (Cambou et al., 2018; Vasenev & Kuzyakov, 2018). Subsoils may contain more C because of their greater depths, but also because former topsoils may have been buried in subsoils during the construction of the greenspace (Zhu et al., 2017). Surface sealing is considered one of the major threats to soil functioning, but the lack of oxygen supply may also protect the SOC from further decomposition (Churkina, 2012).

7. Conclusion

This study drafted the first urban soil C balance in the Netherlands. The use of high spatial resolution GIS data with a scale of 10 x 10 m enabled the inclusion of small patches in the total soil C storage of The Hague, which proved to be significant as the smaller urban greenspaces, which are typical for dense urban centres, contained similar soil C density as the larger urban greenspaces, such as urban forests. The districts of The Hague Centre and Scheveningen had a soil C budget of 18.8 kt in the upper 30 cm of soil of which 7.86 kt C was stored beneath herbaceous vegetation (± 0.63 kt C), 4.46 kt was stored beneath shrubs (± 0.45 kt C) and 6.48 kt C was stored beneath trees (± 0.51 kt C).

It was detected that the upper 30 cm of the sampled urban soil from the urban greenspace of The Hague contained significant amounts of C. Along the transect, going from the city centre to the seaside, 25 urban greenspaces were sampled resulting in a mean C density of 88 t/ha, of which 82 t/ha was considered organic C. A high spatial variance in soil C stocks and other soil-quality parameters was detected. The soil C storage was dependent on the type of vegetation, urbanization extent and land ownership. It was hypothesized that national soil maps could be extrapolated over the urban area of The Hague. Additionally, it was hypothesized that land use would be a good predictor for urban soil C storage; it was believed that parks and urban forests would contain higher soil C stocks than other land uses. However, the hypothesized links between land use and soil type were not apparent in this case study, suggesting that processes driving soil C storage are controlled by different factors. Soil C storage in urban ecosystems is highly variable, which affects how generalizable these results are across other Dutch cities.

Although urban soil can be highly disturbed or altered by anthropogenic activities, the high C densities in The Hague suggested that its potential to store C appeared unaffected. The positive association between SOC levels and other soil-derived ecosystem services and the high SOC levels in urban ecosystems suggests that the urban ecosystem services have potentially been undervalued, which is especially apparent in the strong correlation between SOC and the water-holding capacity of the soil. It is therefore advised to acknowledge urban soils and their soil C stocks as a valuable resource in urban greenspace management as this recognition may lead to more resilient urban ecosystems.

8. Comments by the Municipality of The Hague

The civil servants that were present at the Resilient Cities Hub event on 7 July 2021 were especially interested in the future potential of enhancing urban soil C stocks. Moreover, they wondered how these results could be extrapolated to the other districts of The Hague and other cities in the province of Zuid-Holland. The generalisability of this study is difficult to guarantee as it consisted of a single case study. Therefore, the municipality of Leiden hopes that next thesis season a new student will pick up this subject. Leiden is currently operating a nudging campaign to encourage citizens to green their gardens. They are therefore also interested in how these efforts will translate into increased soil C storage. Furthermore, the management of urban greenspaces is currently adapting to focus more on biodiversity by e.g. an adapted mowing regime. This transition provides the opportunity to also include management specially focussed on protecting and enhancing soil C stocks.

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Appendix A: Raw data of parameters measured at Delft University of Technology

Table A1. Raw data of parameters measured at each sample site.

Sample plot	Sample site	pH	EC [µS/cm]	DOC [Abs_{254}]	LOI [%]	Bulk density [g/cm^3]
1	A	6.28	64	0.665	3.706688155	0.7632353673
1	B	6.57	57	0.884	6.065994863	0.2025678737
1	C	6.78	71	0.918	5.357848952	0.7108096749
2	A	6.78	251	0.736	3.914519672	1.061717299
2	B	7.12	88	0.806	3.428110506	1.103317905
2	C	6.86	121	1.104	2.604688439	1.125253095
3	A	7.29	95	0.848	4.04040404	0.6867419434
3	B	7.2	69	0.611	3.375274616	0.3831290297
3	C	6.78	127	1.273	6.866693516	0.510506804
4	A	6.91	87	1.026	5.367399485	0.9689647405
4	B	7.12	113	1.058	6.411024566	0.7958926314
4	C	6.86	81	0.959	5.852976428	1.06864077
5	A	6.65	127	0.801	4.225074038	0.8851132027
5	B	6.57	145	0.703	4.353821907	1.05829372
5	C	6.61	91	0.747	3.457182595	0.9776005579
6	A	5.59	134	1.296	9.182238296	1.0015435
6	B	6.19	128	2.921	15.08143977	1.10871499
6	C	6.23	120	1.656	11.12893523	1.16008319
7	A	6.61	125	1.713	8.021712907	0.8450497038
7	B	6.83	161	1.573	8.650039588	1.005934811
7	C	5.93	195	3.038	21.29721179	1.137277981
8	A	6.53	59	0.561	3.382029218	0.9372027635
8	B	6.87	82	0.429	2.909525707	1.06886331
8	C	6.66	89	0.427	3.700059043	1.151113211
9	A	6.1	100	2.183	6.97352825	0.6841745748
9	B	5.71	61	1.962	11.35450161	1.246093013
9	C	5.41	75	2.615	8.66811795	1.244825218
10	A	6.87	75	0.794	2.879269261	0.8955380334
10	B	6.79	65	1.146	3.383458647	1.157041985
10	C	6.91	132	0.53	3.704449366	1.03090031
11	A	5.89	49	1.628	4.885226604	1.260938387
11	B	4.81	32	1.179	4.082864039	1.194183444
11	C	4.77	41	1.653	3.773957716	1.278294949
12	A	3.87	50.4	1.915	4.430005907	0.8742657084
12	B	3.87	50.2	1.99	4.072308304	0.9769204204

12	C	3.83	67.8	2.55	6.5828845	1.033608379
13	A	5.59	60	1.719	5.290791599	1.013267044
13	B	4.73	43	2.176	4.824300179	0.8842067576
13	C	4.56	37	0.871	1.776198934	0.8124263355
14	A	6.21	86	0.615	8.83179446	1.129383906
14	B	6.66	112	1.018	5.437586823	1.349479845
14	C	6.63	88	0.766	5.867195243	1.418020384
15	A	6.42	117	1.541	10.05608974	1.034791938
15	B	4.54	76	2.816	8.785009067	1.307905998
15	C	5.75	112	2.883	14.60247703	1.094965759
16	A	6.17	87	1.107	5.429594272	1.053174376
16	B	6.21	74	2.92	6.327593112	0.9175396942
16	C	6.29	62	0.729	7.024214529	0.9565524204
17	A	7.04	97	0.751	3.193810752	1.350672262
17	B	7	90	0.593	2.234749346	1.312573594
17	C	7.08	88	0.896	4.562737643	1.366915876
18	A	6.96	57	0.427	1.735833998	0.3354965706
18	B	6.75	56	0.608	3.605047066	0.3798154148
18	C	7.12	67	0.366	2.101260756	0.450127643
19	A	6.46	112	0.629	4.398708636	0.9399903974
19	B	6.25	88	0.761	6.468253968	1.341463347
19	C	6	94	1.143	5.194029851	0.8158672047
20	A	6.54	140	1.373	12.28847703	0.8928561183
20	B	6.34	88	1.049	6.013847676	0.6676008043
20	C	6.29	123	2.001	12.94562836	0.56704058
21	A	6.71	71	0.752	5.941373205	1.097385554
21	B	6.04	131	2.847	15.98790323	1.196200913
21	C	6.29	66	0.841	6.450968644	1.301983611
22	A	6.42	72	1.151	5.931034483	0.6197181984
22	B	6.63	86	0.832	4.121648659	1.01035436
22	C	6.88	148	0.941	4.886386487	1.038296474
23	A	6.83	88	0.974	5.14867292	1.117964
23	B	6.71	92	0.947	6.006785073	0.981279657
23	C	6.7	72	0.749	4.330230676	1.213860888
24	A	6.95	59	0.418	1.515151515	1.050860033
24	B	7.17	53	0.274	1.103013591	0.965225742
24	C	7.21	51	0.355	1.234322118	1.008672988
25	A	7.75	63	0.278	0.9460547504	1.123912585
25	B	8.21	59	0.228	0.848313472	1.249596413
25	C	8.58	55	0.182	0.9722222222	1.242465018

Table A2. Raw data of parameters measured at each sample plot.

Sample plot	Clay content [%]	Moisture content [%]	WHC [%]
1	12	12.44993052	28.10746584
2	6.5	9.219621887	23.98888745
3	6.5	13.30725771	24.94760165
4	4	12.71980279	28.13364966
5	6.5	10.96302666	26.27213365
6	14.5	24.09759358	36.468272
7	4	18.80737881	34.2192691
8	4	10.18751046	25.79204178
9	37.5	18.98889252	32.78295778
10	14.5	16.22533311	30.80014099
11	4	10.63015563	30.15756148
12	4	18.66748812	34.44782761
13	4	13.44716276	28.10832991
14	4	16.17128463	31.49664471
15	10	20.59241904	34.81162955
16	2.5	11.8471232	27.90249129
17	6.5	10.59547572	23.39500807
18	2.5	8.501846316	24.4851978
19	4	14.84888305	29.5686751
20	4	19.48565776	35.88047074
21	23.5	18.23291762	34.66354202
22	2.5	11.63726666	26.78199584
23	21	13.66072973	28.60470673
24	2.5	5.981017837	20.0824852
25	2.5	4.309734513	19.37248129

Appendix B: Raw data of parameters measured at Agrolab

To evaluate the reliability of the soil analyses performed in a commercial laboratory (Agrolab, Deventer, the Netherlands), a replica of the sample from plot 1 was sent to Agrolab. For the C related parameters, no differences were detected. For the nutrients N, P, and S a slight difference of 17, 4 and 7% was detected respectively, which may also be the result of a slight variation of 4% in measured water content (Table B1).

Table B1. Comparison of results for two replicates of soil analyses performed on plot 1 soil by Agrolab

	Replica 1	Replica 2
Dry weight (DW) [%]	86.3	82.3
CaCO3 [kg/ kg DW]	13	13
Total C [%]	2.5	2.5
TOC [%]	2.4	2.4
N [mg/kg DW]	1900	2300
P [mg/kg DW]	510	530
S [mg/kg DW]	680	730

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Datum	10.06.2021
Relatienr	35004563
Opdrachtnr.	1048451

ANALYSERAPPORT

Opdracht **1048451   Bodem / Eluaat**

Opdrachtgever	35004563 TU DELFT CITG
Uw referentie	PO 2112021600 / C23B71
Opdrachtacceptatie	26.05.21

Geachte heer, mevrouw,

Hierbij zenden wij u de resultaten van het door u aangevraagde laboratoriumonderzoek.

Dit rapport mag alleen in zijn geheel worden gereproduceerd. Eventuele bijlagen zijn onderdeel van het rapport.

Indien u nog vragen heeft of aanvullende informatie wenst, verzoeken wij u om contact op te nemen met Klantenservice.

Wij vertrouwen erop u met de toegezonden informatie van dienst te zijn.

Met vriendelijke groet,

AL-West B.V. Jørgen Smit, Tel. +31/570788120

De parameters die in dit document worden vermeld, zijn geaccrediteerd volgens EN ISO/IEC 17025:2017. Alleen niet-geaccrediteerde parameters/resultaten zijn gemarkeerd met het symbool " *) ".

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Opdracht **1048451 Bodem / Eluaat**

Monsternr.	*Monstername*	*Monster beschrijving*
511519	onbekend	1
511520	onbekend	2
511521	onbekend	3
511522	onbekend	4
511523	onbekend	5

	Eenheid	**511519** 1	**511520** 2	**511521** 3	**511522** 4	**511523** 5
Algemene monstervoorbehandeling						
Kaakbreker malen		--	--	--	++	--
Droge stof	%	86,3	89,5	86,3	85,8	85,4
Klassiek Chemische Analyses						
Totaal stikstof (N)	mg/kg Ds	1900 x)	1200 x)	1600 x)	1400 x)	2200 x)
CaCO3-gehalte	g/kg Ds	13 *)	22 *)	17 *)	22 *)	2,9 *)
Nitraat (N)	mg/kg Ds	27	73	29	24	27
Nitriet (N)	mg/kg Ds	<5,0	<5,0	<5,0	<5,0	<5,0
Stikstof volgens Kjeldahl (N)	g/kg Ds	1,9 *)	1,1 *)	1,6 *)	1,4 *)	2,2 *)
Koolstof (totaal)	% Ds	2,5 *)	1,8 *)	2,2 *)	3,1 *)	5,6 *)
Totaal Organisch Koolstof (TOC)	% Ds	2,4	1,4	1,9	2,8	5,6
Voorbehandeling metalen analyse						
Koningswater ontsluiting		++	++	++	++	++
Metalen						
Fosfor [P]	mg/kg Ds	510	550	790	680	330
Zwavel, totaal [S]	mg/kg Ds	680 *)	370 *)	390 *)	480 *)	550 *)

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Opdracht **1048451 Bodem / Eluaat**

Monsternr.	*Monstername*	*Monster beschrijving*
511524	onbekend	6
511525	onbekend	7
511526	onbekend	8
511527	onbekend	9
511528	onbekend	10

	Eenheid	511524 (6)		511525 (7)		511526 (8)		511527 (9)		511528 (10)	
Algemene monstervoorbehandeling											
Kaakbreker malen		--		--		--		--		--	
Droge stof	%	71,3		77,8		87,5		71,4		84,7	
Klassiek Chemische Analyses											
Totaal stikstof (N)	mg/kg Ds	4500	x)	3700	x)	890	x)	3200	x)	1500	x)
CaCO3-gehalte	g/kg Ds	<0,10	*)	16	*)	9,0	*)	<0,10	*)	9,6	*)
Nitraat (N)	mg/kg Ds	31		46		26		22		14	
Nitriet (N)	mg/kg Ds	<5,0		<5,0		<5,0		<5,0		<5,0	
Stikstof volgens Kjeldahl (N)	g/kg Ds	4,5	*)	3,7	*)	0,87	*)	3,2	*)	1,5	*)
Koolstof (totaal)	% Ds	6,6	*)	7,2	*)	1,7	*)	4,4	*)	1,5	*)
Totaal Organisch Koolstof (TOC)	% Ds	6,7		6,5		1,6		4,4		1,4	
Voorbehandeling metalen analyse											
Koningswater ontsluiting		++		++		++		++		++	
Metalen											
Fosfor [P]	mg/kg Ds	1400		580		500		770		360	
Zwavel, totaal [S]	mg/kg Ds	840	*)	880	*)	240	*)	770	*)	340	*)

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Opdracht **1048451 Bodem / Eluaat**

Monsternr.	*Monstername*	*Monster beschrijving*
511529	onbekend	11
511530	onbekend	12
511531	onbekend	13
511532	onbekend	14
511533	onbekend	15

	Eenheid	**511529** 11	**511530** 12	**511531** 13	**511532** 14	**511533** 15
Algemene monstervoorbehandeling						
Kaakbreker malen		--	--	--	--	--
Droge stof	%	88,0	81,1	84,8	84,4	75,1
Klassiek Chemische Analyses						
Totaal stikstof (N)	mg/kg Ds	1700 x)	1100 x)	1500 x)	2000 x)	4300 x)
CaCO3-gehalte	g/kg Ds	<0,10 *)	<0,10 *)	<0,10 *)	25 *)	2,5 *)
Nitraat (N)	mg/kg Ds	15	<5,0	13	34	29
Nitriet (N)	mg/kg Ds	<5,0	<5,0	<5,0	<5,0	<5,0
Stikstof volgens Kjeldahl (N)	g/kg Ds	1,7 *)	1,1 *)	1,5 *)	2,0 *)	4,3 *)
Koolstof (totaal)	% Ds	2,5 *)	2,7 *)	2,2 *)	3,8 *)	5,0 *)
Totaal Organisch Koolstof (TOC)	% Ds	2,4	2,7	2,2	3,3	4,8
Voorbehandeling metalen analyse						
Koningswater ontsluiting		++	++	++	++	++
Metalen						
Fosfor [P]	mg/kg Ds	360	350	200	480	600
Zwavel, totaal [S]	mg/kg Ds	350 *)	200 *)	300 *)	540 *)	1500 *)

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Opdracht 1048451 Bodem / Eluaat

Monsternr.	*Monstername*	*Monster beschrijving*
511534	onbekend	16
511535	onbekend	17
511536	onbekend	18
511537	onbekend	19
511538	onbekend	20

	Eenheid	**511534** 16	**511535** 17	**511536** 18	**511537** 19	**511538** 20
Algemene monstervoorbehandeling						
Kaakbreker malen		--	--	--	--	--
Droge stof	%	**86,7**	**87,7**	**88,9**	**82,4**	**74,1**
Klassiek Chemische Analyses						
Totaal stikstof (N)	mg/kg Ds	**2300** x)	**1000** x)	**960** x)	**2200** x)	**4200** x)
CaCO3-gehalte	g/kg Ds	**5,4** *)	**67** *)	**40** *)	**1,5** *)	**4,5** *)
Nitraat (N)	mg/kg Ds	**30**	**30**	**15**	**47**	**51**
Nitriet (N)	mg/kg Ds	**<5,0**	**<5,0**	**<5,0**	**<5,0**	**<5,0**
Stikstof volgens Kjeldahl (N)	g/kg Ds	**2,3** *)	**0,99** *)	**0,94** *)	**2,2** *)	**4,2** *)
Koolstof (totaal)	% Ds	**2,6** *)	**2,1** *)	**2,0** *)	**2,6** *)	**5,7** *)
Totaal Organisch Koolstof (TOC)	% Ds	**2,5**	**1,4**	**1,9**	**2,6**	**5,8**
Voorbehandeling metalen analyse						
Koningswater ontsluiting		++	++	++	++	++
Metalen						
Fosfor [P]	mg/kg Ds	**870**	**370**	**360**	**600**	**1000**
Zwavel, totaal [S]	mg/kg Ds	**440** *)	**230** *)	**450** *)	**480** *)	**1300** *)

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Opdracht **1048451 Bodem / Eluaat**

Monsternr.	*Monstername*	*Monster beschrijving*
511539	onbekend	21
511540	onbekend	22
511541	onbekend	23
511542	onbekend	24
511543	onbekend	25

	Eenheid	511539 (21)	511540 (22)	511541 (23)	511542 (24)	511543 (25)
Algemene monstervoorbehandeling						
Kaakbreker malen		--	--	--	--	--
Droge stof	%	76,4	87,0	83,7	94,8	95,6
Klassiek Chemische Analyses						
Totaal stikstof (N)	mg/kg Ds	4300 x)	1400 x)	1300 x)	440 x)	310 x)
CaCO3-gehalte	g/kg Ds	6,9 *)	16 *)	15 *)	24 *)	41 *)
Nitraat (N)	mg/kg Ds	37	29	26	7,3	7,3
Nitriet (N)	mg/kg Ds	<5,0	<5,0	<5,0	<5,0	<5,0
Stikstof volgens Kjeldahl (N)	g/kg Ds	4,3 *)	1,4 *)	1,3 *)	0,43 *)	0,30 *)
Koolstof (totaal)	% Ds	3,9 *)	2,2 *)	2,8 *)	0,8 *)	0,7 *)
Totaal Organisch Koolstof (TOC)	% Ds	3,9	1,7	2,5	0,5	0,2
Voorbehandeling metalen analyse						
Koningswater ontsluiting		++	++	++	++	++
Metalen						
Fosfor [P]	mg/kg Ds	660	490	800	270	190
Zwavel, totaal [S]	mg/kg Ds	1200 *)	450 *)	490 *)	360 *)	91 *)

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Opdracht **1048451 Bodem / Eluaat**

Monsternr.	*Monstername*	*Monster beschrijving*
511544	onbekend	26

	Eenheid	511544 26	
Algemene monstervoorbehandeling			
Kaakbreker malen		--	
Droge stof	%	**82,6**	
Klassiek Chemische Analyses			
Totaal stikstof (N)	mg/kg Ds	**2300**	x)
CaCO3-gehalte	g/kg Ds	**13**	*)
Nitraat (N)	mg/kg Ds	**21**	
Nitriet (N)	mg/kg Ds	**<5,0**	
Stikstof volgens Kjeldahl (N)	g/kg Ds	**2,3**	*)
Koolstof (totaal)	% Ds	**2,5**	*)
Totaal Organisch Koolstof (TOC)	% Ds	**2,4**	
Voorbehandeling metalen analyse			
Koningswater ontsluiting		**++**	
Metalen			
Fosfor [P]	mg/kg Ds	**530**	
Zwavel, totaal [S]	mg/kg Ds	**730**	*)

x) Gehaltes beneden de rapportagegrens zijn niet mee inbegrepen.
Verklaring:"<" of n.a. betekent dat het gehalte van de component lager is dan de rapportagegrens.
De parameter-specifieke analytische meetonzekerheid en informatie over de berekeningsmethode zijn op aanvraag beschikbaar, indien de gerapporteerde resultaten boven de parameterspecifieke rapportagegrens liggen.

Begin van de analyses: 26.05.2021
Einde van de analyses: 10.06.2021

De resultaten hebben uitsluitend betrekking op de geanalyseerde monsters. In gevallen waarin het testlaboratorium niet verantwoordelijk was voor de bemonstering, gelden de gerapporteerde resultaten voor de monsters zoals zij zijn ontvangen. .

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Opdracht 1048451 Bodem / Eluaat

Toegepaste methoden

conform ISO 10694 (2008) *) **:** Koolstof (totaal)
conform ISO 10694 (2008) : Totaal Organisch Koolstof (TOC)
conform NEN 6961; NEN-EN 13657 (afval) : Koningswater ontsluiting
conform NEN 6966 *) **:** Zwavel, totaal [S]
conform NEN 6966 : Fosfor [P]
conform NEN-ISO 10693 *) **:** CaCO3-gehalte
conformNEN-EN12880; AS3000, AS3200; NEN-EN15934 : Droge stof
eigen methode *) **:** Stikstof volgens Kjeldahl (N)
eigen methode : Kaakbreker malen
eigen methode (meting conform NEN-ISO 15923-1) : Nitraat (N) Nitriet (N)
<Geen informatie> : Totaal stikstof (N)

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Bijlage bij Opdrachtnr. 1048451

CONSERVERING, CONSERVERINGSTERMIJN EN VERPAKKING

Er zijn verschillen met de richtlijnen geconstateerd die mogelijk de betrouwbaarheid van de resultaten van onderstaande monsters of analyses beïnvloeden.

511519	De monsternamedatum van het monster is onbekend.
511520	De monsternamedatum van het monster is onbekend.
511521	De monsternamedatum van het monster is onbekend.
511522	De monsternamedatum van het monster is onbekend.
511523	De monsternamedatum van het monster is onbekend.
511524	De monsternamedatum van het monster is onbekend.
511525	De monsternamedatum van het monster is onbekend.
511526	De monsternamedatum van het monster is onbekend.
511527	De monsternamedatum van het monster is onbekend.
511528	De monsternamedatum van het monster is onbekend.
511529	De monsternamedatum van het monster is onbekend.
511530	De monsternamedatum van het monster is onbekend.
511531	De monsternamedatum van het monster is onbekend.
511532	De monsternamedatum van het monster is onbekend.
511533	De monsternamedatum van het monster is onbekend.
511534	De monsternamedatum van het monster is onbekend.
511535	De monsternamedatum van het monster is onbekend.
511536	De monsternamedatum van het monster is onbekend.
511537	De monsternamedatum van het monster is onbekend.
511538	De monsternamedatum van het monster is onbekend.
511539	De monsternamedatum van het monster is onbekend.
511540	De monsternamedatum van het monster is onbekend.
511541	De monsternamedatum van het monster is onbekend.
511542	De monsternamedatum van het monster is onbekend.
511543	De monsternamedatum van het monster is onbekend.
511544	De monsternamedatum van het monster is onbekend.

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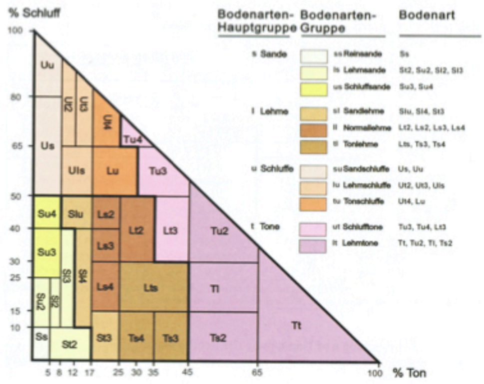
Appendix C: Clay fraction determination

KA5	FAO	Clay	Silt	Sand
Ss	S	0 -<5	0-< 10	85-<100
Sl2	LS or SL	5-<8	10-<25	67-<85
Sl3	SL	8-<12	10-<40	48-<82
Sl4	Sl or L	12-<17	10-<40	43-<78
Slu	L	8-<17	40-<50	33-<52
St2	S or LS or SL	5-<17	0-<10	73-<95
St3	SL or SCL	17-<25	0-<15	60-<83
Su2	mostly LS	0-<5	10-<25	70-<90
Su3	mostly SL	0-<8	25-<40	52- <75
Su4	SL	0-<8	40-<50	42-<60
Ls2	L	17-<25	40-<50	25-<43
Ls3	L	17-<25	30-<40	35-<53
Ls4	L or SL or SCL	17-<25	15-<30	45-<68
Lt2	L or CL	25-<35	30-<50	15-<45
Lt3	CL or SiCL or SiC or C	35-<45	30-<50	5-<35
Lts	SL or SCL or SC or C or CL or L	25-<45	15-<30	25-<60
Lu	SiL or SiCL or CL	17-<30	50-<65	5-<33
Uu	Si	0-<8	80-<100	0-<20
Uls	SiL	8-<17	50-<80	18-<42
Us	SiL	0-<8	50-<80	12-<50
Ut2	SiL or Si	8-<12	65-<92	0-<27
Ut3	SiL	12-<17	65-<88	0-<23
Ut4	SiL	17-<25	65-<83	0-<18
Tt	C	65-<100	0-<35	0-<35
Tl	C	45-<65	15-<30	5-<40
Tu2	C or SiC	45-<65	30-<55	0-<25
Tu3	SiC or SiCl	30-<45	50-<65	0-<20
Tu4	SiL or SiCL	25-<35	65-<75	0-<10
Ts2	C or SC	45-<65	0-<15	20-<55
Ts3	C or SC	35-<45	0-<15	40-<65
Ts4	SCL	25-<35	0-<15	50-<75
fS,fSms, fSgs				
mS, mSfs, mSgs				
gS				



German triangle

FAO triangle

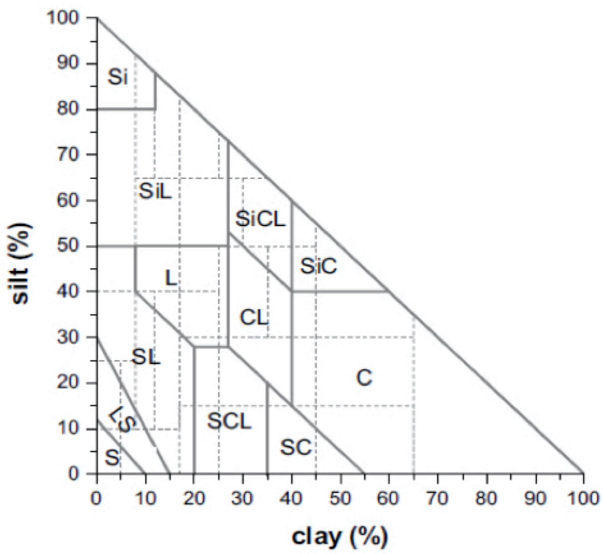


Fig. C1. Texture triangle according to the German soil texture classification KA5 (upper) and the FAO (lower).

Bestimmungsschlüssel für Bodenarten nach KA5

1. Formbarkeit/Ausrollbarkeit auf halbe Bleistiftdicke	2. Klebrigkeit	3. Körnigkeit und sonstige Merkmale	Bodenart
0 = nicht ausrollbar, zerbröckelt beim Versuch			
	0 = keine Klebrigkeit, Probe zerbricht sofort		
		ohne erkennbare Feinsubstanz	Ss
		sehr wenig Feinsubstanz	Su2
		deutlich Feinsubstanz, die auch in Fingerrillen haftet	Su3
		viel Feinsubstanz, die stark in Fingerrillen haftet	Su4
	1 = sehr geringe Klebrigkeit, Probe zerbricht sehr leicht		
		deutlich Feinsubstanz, die auch in Fingerrillen haftet	Su3
		viel Feinsubstanz, die stark in Fingerrillen haftet	Su4
1 = nicht ausrollbar, Probe reißt und zerbricht bei mehr als halber Bleistiftdicke			
	0 = keine Klebrigkeit, Probe zerbricht sofort		
		deutlich Feinsubstanz, die auch in Fingerrillen haftet	Su3
		viel Feinsubstanz, die stark in Fingerrillen haftet	Su4
		Sandkörner erkennbar, samtig-mehlige Feinsubstanz überwiegt	Us
		Sandkörner kaum erkennbar, fast nur samtig-mehlige Feinsubstanz	Uu
	1 = sehr geringe Klebrigkeit, Probe zerbricht sehr leicht		
		sehr wenig Feinsubstanz	Sl2
		Sandkörner erkennbar, samtig-mehlige Feinsubstanz überwiegt	Us
		Sandkörner kaum erkennbar, fast nur samtig-mehlige Feinsubstanz	Uu
	2 = geringe Klebrigkeit, Probe zerbricht leicht		
		sehr wenig Feinsubstanz	St2
		Feinsubstanz überwiegt	Uls
2 = schwer auszurollen, da die Probe starke Neigung zum Reißen und Brechen aufweist			
	0 = keine Klebrigkeit, Probe zerbricht sofort		
		deutlich Feinsubstanz, die auch in Fingerrillen haftet	Su3
		viel Feinsubstanz, die stark in Fingerrillen haftet	Su4
	1 = sehr geringe Klebrigkeit, Probe zerbricht sehr leicht		
		deutlich Feinsubstanz, die auch in Fingerrillen haftet	Su3
		viel Feinsubstanz, die stark in Fingerrillen haftet	Su4
		sehr wenig Feinsubstanz	Sl2
		Sandkörner kaum erkennbar, fast nur samtig-mehlige Feinsubstanz, matte Reibflächen	Ut2
	2 = geringe Klebrigkeit, Probe zerbricht leicht		
		sehr wenig Feinsubstanz	St2
		Feinsubstanz überwiegt	Uls
		Sandkörner nicht erkennbar, fast nur Feinsubstanz, matte Reibflächen	Ut3
3 = ausrollbar, Probe reißt nur schwach oder bricht			
	1 = sehr geringe Klebrigkeit, Probe zerbricht sehr leicht		
		viel, deutlich mehlige Feinsubstanz	Slu
	2 = geringe Klebrigkeit, Probe zerbricht leicht		
		wenig bis mäßig Feinsubstanz	Sl3
		sehr wenig Feinsubstanz	St2
		viel, deutlich mehlige Feinsubstanz	Slu
		mäßig bis viel Feinsubstanz, schwach glänzende Reibflächen	Sl4
		Feinsubstanz überwiegt	Uls
	3 = mittlere Klebrigkeit, Probe zerbricht wenig		
		Sandkörner deutlich erkennbar, mäßig viel, sehr klebrige Feinsubstanz	St3
		Sandkörner deutlich erkennbar, mäßig Feinsubstanz, schwach glänzende Reibflächen	Ls4
		Sandkörner deutlich erkennbar, viel Feinsubstanz, glänzende Reibflächen	Ls3
		Sandkörner deutlich erkennbar, viel, schwach mehlige Feinsubstanz	Ls2
		Sandkörner kaum erkennbar, sehr viel Feinsubstanz, matte bis schwach glänzende Reibflächen	Lu
		Sandkörner nicht erkennbar, nur schwach mehlige Feinsubstanz, matte bis schwach glänzende Reibflächen	Ut4
	4 = starke Klebrigkeit, Probe zerbricht kaum		
		Sandkörner kaum erkennbar, sehr viel Feinsubstanz, matte bis schwach glänzende Reibflächen	Lu
4= leicht ausrollbar, Probe reißt und bricht nicht			
	3 = mittlere Klebrigkeit, Probe zerbricht wenig		
		Sandkörner kaum erkennbar, sehr viel Feinsubstanz, matte bis schwach glänzende Reibflächen	Lu
	4 = starke Klebrigkeit, Probe zerbricht kaum		
		Sandkörner gut erkennbar, sehr viel Feinsubstanz, schwach raue, schwach glänzende Reibflächen	Lt2
		Sandkörner deutlich erkennbar, viel Feinsubstanz, sehr stark glänzende Reibflächen	Lts
		Sandkörner kaum erkennbar, sehr viel Feinsubstanz, matte bis schwach glänzende Reibflächen	Lu
		Sandkörner gut erkennbar, viel Feinsubstanz, raue, glänzende Reibflächen	Ts4
		Sandkörner nicht erkennbar, nur Feinsubstanz, raue, schwach glänzende Reibflächen	Tu4
	5 = sehr starke Klebrigkeit, Probe zerbricht nicht		
		Sandkörner deutlich erkennbar, viel Feinsubstanz, sehr stark glänzende Reibflächen	Lts
5 = sehr leicht auch dünner als halbe Bleistiftdicke ausrollbar			
	4 = starke Klebrigkeit, Probe zerbricht kaum		
		Sandkörner deutlich erkennbar, viel Feinsubstanz, sehr stark glänzende Reibflächen	Lts
		Sandkörner nicht erkennbar, nur Feinsubstanz, schwach raue, glänzende Reibflächen	Tu3
	5 = sehr starke Klebrigkeit, Probe zerbricht nicht		
		Sandkörner deutlich erkennbar, viel Feinsubstanz, sehr stark glänzende Reibflächen	Lts
		Sandkörner deutlich erkennbar, sehr viel Feinsubstanz, schwach raue, glänzende Reibflächen	Ts3
		Sandkörner schwach erkennbar, sehr viel Feinsubstanz, schwach raue, glänzende Reibflächen	Lt3
		wenig Sandkörner erkennbar, viel Feinsubstanz, stark glänzende Reibflächen	Ts2
		sehr wenig Sandkörner erkennbar, sehr viel Feinsubstanz, glänzende Reibflächen	Tl
		Sandkörner nicht erkennbar, nur Feinsubstanz, schwach raue, glänzende Reibflächen	Tu3
		Sandkörner nicht erkennbar, nur Feinsubstanz, schwach raue, glänzende Reibflächen	Tu2
		Sandkörner nicht erkennbar, nur Feinsubstanz, glatte, glänzende Reibflächen	Tt

Anmerkungen

1 bei St2 Bindigkeit nur bis 2 festgelegt, da sonst keine erkennbare Differenz zu Sl2 vorhanden
2 bei Uls Bindigkeit nur bei 2 festgelegt, da sonst keine erkennbare Differenz zu Us vorhanden
3 bei Tu2 Reibflächen nicht als schwach rau gekennzeichnet, da sonst kein Unterschied zu Tu3