



**T.R.
ONDOKUZ MAYIS UNIVERSITY
INSTITUTE OF GRADUATE STUDIES
DEPARTMENT OF SOIL SCIENCE AND PLANT NUTRITION**

**SOIL ORGANIC CARBON STOCKS IN SELECTED AREAS OF
KRAKOW**

Master's Thesis

Swagata CHOWDHURY

Supervisor

Prof. Dr. Michał Gąsiorek

II. Supervisor

Prof. Dr. Orhan DENGİZ

SAMSUN

2022

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SAMSUN

2022

ACCEPTANCE AND APPROVAL OF THESIS

The study entitled “SOIL ORGANIC CARBON STOCKS IN SELECTED AREAS OF KRAKOW” prepared by **Swagata CHOWDHURY**, and supervised by **Prof. Dr. Michał Gąsiorek** and **Prof. Dr. Orhan DENGİZ** , was found successful and unanimously accepted by committee members as Master Thesis, following the examination on the date 19.8.2022 .

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This thesis has been approved by the committee members that already stated above and determined by the Institute Executive Board.

APPROVAL

.../.../...

Prof. Dr. Ali BOLAT
Head of Institute of Graduate Studies

DECLARATION OF COMPLIANCE WITH SCIENTIFIC ETHIC

I hereby declare and undertake that I complied with scientific ethics and academic rules in all stages of my Master's Thesis, that I have referred to each quotation that I use directly or indirectly in the study, and that the works I have used consist of those shown in the sources, that it was written in accordance with the institute writing guide and that the situations stated in the article 3, section 9 of the Regulation for TÜBİTAK Research and Publication Ethics Board were not violated.

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ÖZET

KRAKOW'UN SEÇİLMİŞ BÖLGELERİNDE TOPRAK ORGANİK KARBON STOKLARI

Swagata CHOWDHURY

Ondokuz Mayıs Üniversitesi

Lisansüstü Eğitim Enstitüsü

Toprak Bilimi Ve Bitki Besleme Ana Bilim Dalı

Yüksek Lisans, Ağustos /2022

Danışman I: Prof. Dr. Michał GASIOREK

Danışman II: Prof. Dr. Orhan DENGİZ

Karasal sistemlerdeki en büyük organik karbon kaynağı, karbon döngüsü için de çok önemli olan toprakta bulunur. Kentleşmenin küresel nüfus üzerinde önemli bir etkisi vardır, ancak toprak karbonunun dağılımı ve depolanması üzerindeki etkileri biraz belirsizdir. Bu çalışmanın temel amacı, incelenen topraktaki karbon içeriğini etkileyen faktörleri belirleyerek Krakow'un merkezi bölgelerindeki toprak organik karbon içeriğini ve stoklarını tahmin etmektir. Çalışma Krakow'un orta kesiminde gerçekleştirildi. Toprak örnekleri 0-20 cm derinlikten toplanmıştır. Toprak karbon içeriği $13.67 \text{ g} \cdot \text{kg}^{-1}$ ile $41.48 \text{ g} \cdot \text{kg}^{-1}$ arasındaydı ve en yüksek içerik çalışma alanının orta kısmında rapor edildi. Ortalama toprak karbon stoğu $6.78 \text{ kg} \cdot \text{m}^{-2}$ olarak bildirilmiş ve bu sonuç diğer illere göre yüksek çıkmıştır. Karbon sekestrasyonu için çalışılan toprağın yüksek bir potansiyeli olduğunu göstermektedir.

Anahtar Kelimeler: Toprak organik karbonu (SOC), Kütle yoğunluğu, Kentleşme

ABSTRACT

SOIL ORGANIC CARBON STOCKS IN SELECTED AREAS OF KRAKOW

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Master, August/2022
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The largest source of organic carbon in terrestrial systems is found in soil, which is also crucial to the carbon cycle. Urbanization has a significant impact on the global population, but its impacts on the distribution and storage of soil carbon are a little unclear. The main purpose of this study was to estimate the soil organic carbon content and stocks in central areas of Krakow by determining the factors that affect the carbon content in the studied soil. The study was carried out in central part of Krakow. Soil samples were collected at 0-20 cm depth. The content of soil carbon was from $13.67 \text{ g} \cdot \text{kg}^{-1}$ to $41.48 \text{ g} \cdot \text{kg}^{-1}$ and the highest content was reported in the central part of study area. The average of soil carbon stock was reported $6.78 \text{ kg} \cdot \text{m}^{-2}$ and this result was high compared to other cities. It suggests a high potential of studied soil for carbon sequestration.

Keywords: Soil organic carbon (SOC), Bulk density, Urbanization

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Swagata CHOWDHURY

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SYMBOLS AND ABBREVIATIONS

CO ₂	: Carbon dioxide
DDT	: Dichloro-diphenyl-trichloroethane
GHG's	: Greenhouse gases
GIS	: Geographical Information System
GPS	: Global Positioning System
PAHs	: Polycyclic aromatic hydrocarbons
PCB's	: Polychlorinated biphenyl's
PCDD	: Polychlorinated dibenzo-p-dioxine
SIC	: Soil Inorganic Carbon
SOC	: Soil Organic Carbon
TOC	: Total Organic Carbon

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1 INTRODUCTION

Terrestrial ecosystems play an important role in the global carbon cycle, serving as both carbon stores and carbon sources. Soil organic carbon (SOC) is the most abundant carbon source in terrestrial ecosystems, accounting for around 2000 PG C. Carbon sequestration is a well-known function of soil ecosystems. According to the worldwide several studies, land use and land use change is identified as one of the most important factors that influence carbon stocks; and urbanization is currently one of the most common modes of land-use change. As a result, it is critical to comprehend the impact of urban soils to regional SOC supplies as urbanization has a variety of effects on SOC stocks and trigger pathways that can either increase SOC formation or decrease SOC loss. However, many studies focus on assessing and mapping SOC for natural and agricultural regions, urban areas are generally overlooked from these regional carbon assessments (Vasenev et al., 2013). According to Canedoli et al. (2020) and Edmondson et al. (2012) most of the studies focus on the significant impact of urbanization on soil organic carbon (SOC) reserves whereas current estimates of SOC levels in urban soils range is minimal.

Several factors affect organic carbon cycling and accumulation in soils. SOC is known to be intimately dependent on the surrounding parameters such as clay particles, pH, bulk density, total soil nitrogen content, and land use changes. Anthropogenic sources such as land use / land cover paving, human settlement, and landscape management have clear influence on pedogenic dynamics, causing SOC stocks to increase geographically and temporally across urban timeframes. Overall urban patterns influence soil microbial biomass and communities, and also the dispersal of heat and pollution, all of which have an indirect impact on the organic carbon in surface soils (Liu et al., 2018).

Regional bioclimatic variables, as well as land use / land cover structure; influence the heterogeneity of SOC in and between cities. According to a study of over 100 cities, reported that urban soils at higher elevations has the ability to hold SOC due to delayed mineralization impeded by low temperatures. Because of more rapid mineralization and a constrained carbon intake with biomass, SOC stocks in dryland cities in the United States were much lower than in humid cities (Dvornikov et al., 2021).

The shift of natural to regulated ecosystems makes the lands extremely vulnerable to soil degradation cycles, resulting in soil carbon depletion and the emission of carbon dioxide (CO₂) and other greenhouse gases (GHGs) into the environment. As existing approaches imply that there is still a critical necessity to discover ways for regulating atmospheric CO₂ levels so the importance of carbon storage provided by soil as an important factor to climate change regulation cannot be ignored. There are indeed significant research shortfalls which limit our overall understanding of the consequences of urban development on soil, and that in fact greatly limits our ability to simulate and forecast their chemical-physical attributes, with serious implications for suitable land use planning and management (Canedoli et al., 2020).

Purpose of the study

Former study in Krakow mainly focused on heavy metal pollution in soil for Example in Planty park (Gąsiorek et al., 2017), micro morphological and physico-chemical analysis of cultural layers in anthropogenically transformed soils (Mazurek et al., 2016) along with seasonal variability of microbial biomass phosphorus (Gąsiorek & Halecki, 2022) in urban soil in Krakow but no study regarding directly to estimation of organic carbon stocks.

This study aimed to provide insight of soil organic carbon content and stocks in selected areas of Krakow, Poland that due to its high level of urbanization provides an excellent test case.

Objective

1. Estimation of soil organic carbon content and stocks in central areas of Krakow.
2. An attempt to determine the factors affecting the amount of carbon in the studied soils.
3. A comparison of the carbon stocks in the study region with other urban areas across the world.

2 LITERATURE REVIEW

2.1 Urban soils

Urban soils known sometimes as anthropogenic soils is considered where the human influence is greater and natural characteristics have frequently receded. In varied environments, such as parks, gardens, roadsides, and turf areas, urban soils sustain a diverse variety of recreational plants. Though it is referred that urbanization has many benefits (healthcare, sanitation, and transportation), this process converts the natural landscape posing a great threat to ecosystem and human health. The most visible difference in urban and natural soil is the structural change caused by urban soil usage resulting soil hardening which limits to reduce pollution, hydrological cycling, energy balance and increase in organic polychlorinated dibenzo-p-dioxine (PCDD), polychlorinated biphenyl's (PCBs), polycyclic aromatic hydrocarbons (PAHs), dichloro-diphenyl-trichloroethane (DDT) and inorganic pollutants (for example, heavy metals like Cd, Cr, Ni, Pb, Cu, Zn). In addition to this, it reduce the available moisture in soil, waterlogging caused of poor soil infiltration, and impact on soil microbial diversity (De Kimpe & Morel, 2000; Fabietti et al., 2010; Saha et al., 2017).

Urban parks are critical natural resources in cities and significant factors of carbon sequestration systems. Urban soils are under the mistaken impression that their quality is so poor that their contribution to carbon storage is minimal. The majority of studies on carbon sequestration in urban areas, on the other hand, have largely centred on total net generation by urban plants, overlooking the role of the soil segment. Unfortunately, limited work has been conducted to estimate SOC stocks in urban areas (Canedoli et al., 2020).

2.2 Pollution sources of urban soils

Urban soils have higher pH values, coarser texture, and higher bulk density; their mineralogical composition has changed slightly, and they are abundant in carbonates and iron oxides. The carbon content of urban soils, notably those in industrial areas, rises as a result of organic contaminants (Anta et al., 2011).

It is critical to change the mix and content of organic matter in urban soils. It is heavily influenced by the history of a certain metropolitan area as well as the maintenance of the urban landscape. Change in properties is governed by the degree

of soil contamination and also by landscape gardening, which involves planting exotic vegetation in streets and parks, altering the nutrition cycle and the composition of microbial population (Alberti & Marzluff, 2004).

First of all, as organic contaminants enter the environment, the content of organic matter increases. They arrive on urban soil as both fine airborne particles and garbage. The primary airborne fallouts include coal dust, soot, and other by products of incomplete combustion of solid and liquid fuels. Organic waste contains food waste, sewage sediments, and plastic (Pickett et al., 2008).

Secondly, urban soils have high carbon as a result of slowing mineralization of plant residue due to heavy metal contamination and lastly, the productivity of vegetation in cities is increasing as a result of rising temperatures, high levels of carbon dioxide in the air, and the preservation of green spaces. When compared to nearby native soils, all of these conditions support the accumulation of organic matter in urban soils. As a result, urban soils are reasonably regarded as carbon pool accumulation areas (Vodyanitskii, 2015).

2.3 Soil carbon dynamics

According to Lal et al. (2015), SOC is dynamic in general because of its high reactivity, energy source for all microbes and other biota in the soil, also it is typically removed by erosional processes due to its light weight and proximity to the soil surface. As a result, the SOC pool has a dynamic balance with its surroundings. Its magnitude and rate of change are determined by the balance between input (from root, deposition by water run-on or windblown sediments, compost, animal residues, cover crops) and output (oxidation, erosion, leaching) of biomass. The extent of change in SOC pool caused by natural or anthropogenic sources is determined by the interplay between input and losses. Carbon sequestration occurs when $\text{input} > \text{output}$ and degradation happens when $\text{input} < \text{output}$. Recently soil organic pool got attention by reducing loss and increasing input through proper land use management. Conservation agriculture or no-till farming in combination with mulching and cover cropping, holistic nutrient management involving the careful use of compost and chemical fertilizers, agroforestry, and other site-specific methods can help establish a positive SOC budget. All of these recommended management practices (RMPs) involve trade-offs (hidden costs) that must be critically and honestly analysed in the context of the site.

Current findings of Clara et al., (2017) on soil C dynamics and its impact on the global carbon cycle has already been partly motivated by a growing awareness of:

1. The role of small level availability to SOC for microbial carbon turnover that expanded more than a depth of approximately 20 cm
2. Connection between soil microorganisms and soil properties in relation to the carbon cycle along with other biogeochemical cycles
3. Impact of plant variety in growing soil microorganism activity and carbon sequestration.

2.4 Soil organic matter (SOM)

SOM refers to organic ingredients in soil that are in different stages of decomposition, like tissues from dead plants and animals, particles less than 2 mm in size, and soil microorganisms. SOM turnover is critical to the operation of soil ecosystems and global warming. It is essential for soil structure stabilization, nutrient availability, and water-retention capacity maintenance, making it a significant indication not just of agricultural production but also of environmental robustness. SOM breakdown releases additional mineral nutrients, allowing them access for crop production, also ensuring food security (van der Wal & de Boer, 2017).

Gougoulias et al. (2014) reported that SOM can be classified into various pools based on the time required for complete decomposition and the resulting retention time of the products in the soil (turnover time), as shown below:

- Active pools have a turnover time of months or years;
- Passive pools have a turnover time of thousand years or even decades.

2.5 Soil carbon pools and characteristics

2.5.1 Soil organic carbon pool

The SOC pool comprises over than three times the amount of C found in atmospheric Carbon dioxide, namely 1325 Pg C in the upper 1 m and 3000 Pg C while deep soil layer estimates are considered (Clara et al., 2017; Montanarella Luca et al., 2015). Based on resistance, SOC pools can be dynamically divided into three different fractions (Table 2.1) (Clara et al., 2017; Montanarella Luca et al., 2015).

Based on resistance, SOC pools can be dynamically divided into three different fractions.

Table 2.1. Types of SOC pools (Clara et al., 2017; Montanarella Luca et al., 2015)

Fast Pool (liable or active pool)	Intermediate Pool	Slow Pool (refractory or stable pool)
Incorporation of organic carbon to the soil results in a substantial proportion of biomass that has been lost in 1-2 years	Consists of microbologically degraded organic carbon that is partly fixed on soil surfaces and/or safeguarded in aggregates having turnover durations ranging from 10-100 years.	A highly stabilized SOC that enters a stage of a very slow transition lasting 100-1000 years.

2.5.2 Soil inorganic carbon pool

In the top 1 m, the soil inorganic carbon (SIC) pool contains around 950 Pg C (Lal et al., 2015). Carbonate minerals are the most common SIC forms, and they are either taken from the soil parent material (primary, lithogenic) or generated during soil development (secondary, pedogenic). Intermediate carbonates are generated by the reaction of dilute carbonic acid with Ca^{2+} or Mg^{2+} carried in from the outside by dust, runoff, manure, ocean drift, and sediment. This procedure is a primary mechanism for SIC sequestration in arid and semiarid climates, however the function of SIC in CO_2 mitigation and sequestration methods has received little attention (Lal, 2008; Shi et al., 2017).

2.6 Enrichment of urban soil with organic carbon

2.6.1 Influence of urban gardening

Issues regarding soil fertility enhance the carbon pool in cities. This is especially visible in cities growing in difficult environments, such as the desert zone, as watering urban soils enhances the vegetative state compared to the poor natural vegetation. It emphasizes the importance of keeping a close eye of fresh soils emerging in urban areas on previously unproductive strata. Many countries place a high value on gardening (De Kimpe & Morel, 2000).

Heavy metal pollution of soil has an impact on the carbon cycle. The decomposition rate of metallized litter decreases, but its thickness rises significantly when compared to uncontaminated litter. The scenario of the Severonikel industrial complex (Kola region, Russia), that pollutes the surroundings with heavy metals (most notably nickel) and sulphur, demonstrates that soil aerobic metabolism is suppressed not only due to strong soil degradation but also due to direct gradual accumulation of heavy metals (Vodyanitskii, 2015).

2.6.2 Influence of climate change

At one side, vegetation is harmed by the high temperature of urban air, which is caused by heat emitted by asphalt in the summertime and residential homes and offices in the winter. Heat islands are created in cities as a result of this temperature impact. An increase in background temperatures is most visible early in the night, reaching 2–3°C. However, air and soil temperatures are less in parks and urban forests than in urban districts with a significant proportion of sealed soils. Lowering the temperature in parks and urban woods during the hot summer months enhances the ecological conditions for soil inhabitants. The oasis effect develops in cities established in deserts because the night temperature is greater and the day temperature is less than in the surrounding desert. This encourages vegetation growth in cities, which directly contributes to the expansion of the carbon pool in urban soil (Brazel et al., 2000; Oke, 1989).

2.7 Depletion of urban soil with organic matter

The diversity in organic matter composition is influenced by the development of the metropolitan area in numerous ways. One of the causes of organic matter loss is heavy compaction of urban soils. In the United States, a basic classification of urban soils by development stages was proposed; nevertheless, it appears inadequate for describing soil development in all cities and towns, notably in commercial European and Asian countries. This classification divides soil into two groups based on the stage of urban construction. The very first group has a major detrimental impact during the initial stage of building, when soils are heavily mixed in order to modify the soil profile and remove the humus horizon. This group's soils lose organic matter. The soils of the second group arise at a later stage of urban development as a result of long-term processes such as urban aerial fallout, fertilizer

and pesticide introduction, water regime control, and so on. Systematizing soil evolution processes in old industrial cities is significantly more complex, partly due to the wide variety of pollutants, which can be of both organic and inorganic origin and might have opposing effects. Heavy machinery is employed in road and building construction, which breaks soil aggregates, compacts the particle package, and reduces porosity. Soil compaction inhibits microbial activity and reduces microbial biomass. The loss of humus horizons during territory planning and construction reduces urban soil fertility dramatically. Surface scalping can bury humus up to 3 m deep. Soils on steep slopes experienced the greatest humus loss. Another critical issue is the removal of leaves from city parks. This measure could be the reason for the decrease in organic content in urban soils (Vodyanitskii, 2015).

2.8 SOC management for climate change mitigation and adaptation

Dealing with climate change represents an attempt to slow, halt, or reverse climate change by management techniques, changes in behaviour, and technical advances that minimize GHG emissions. CO₂ is one of the most common GHGs emitted by humankind in the modern age. Because of their carbon storage capacity, soils serve an important in lowering CO₂ emissions with suitable preventative mitigation methods. The advantages of such mitigating activities are typically global and long-term (Kane, 2015; Oakes, 2009).

Adaptation to climate change, on the other contrary, applies to measures to increase perseverance of extraordinary climatic events and conditions. It entails anticipating climate change and its negative consequences and attempting to regulate them through suitable steps that reduce the related risks and negative repercussions. Briefly expressed, they are behaviours that aid human and natural systems in adapting to climate change (Jarraud & Steiner, 2012).

Adaptation and mitigation methods can provide solutions to climate change that can be linked to sustainable development agenda. On a micro level, they are not always regarded complementary; they can be substitutable, competitive/conflicting, or independent of one another. Some climate change adaptation strategies, such as enhanced fertilization and irrigation, have a high energy requirement and may thus lead to even increased CO₂ pollution. However, adaptation may never be a fine

replacement for mitigation because the latter is usually required to avert even larger changes in the climate system (Clara et al., 2017).

4. MATERIALS AND METHODS

3.1 Study area and field works

The research reported here was carried out in Krakow, a city in southern Poland (Figure 3.1). Krakow is one of Poland's largest cities, with a population of almost one million people. The typical urban landscapes of central and eastern Europe are characterized by rapidly increasing car traffic and industrial expansion (Jasek et al., 2014). The driest season is winter, with roughly 30 mm of precipitation per month; the rainiest months are May and August, with around 80 mm per month on average (Jasek-Kamińska et al., 2020). Brown earths and alluvial soils formed on loamy sands, boulder loam, and loess-like sediments are the most common natural soils in the study area (Komornicki 1974). However, recent urbanization causes deterioration of the environment (Jasek et al., 2014). Therefore, most of these soils are classified as anthropogenic soils.

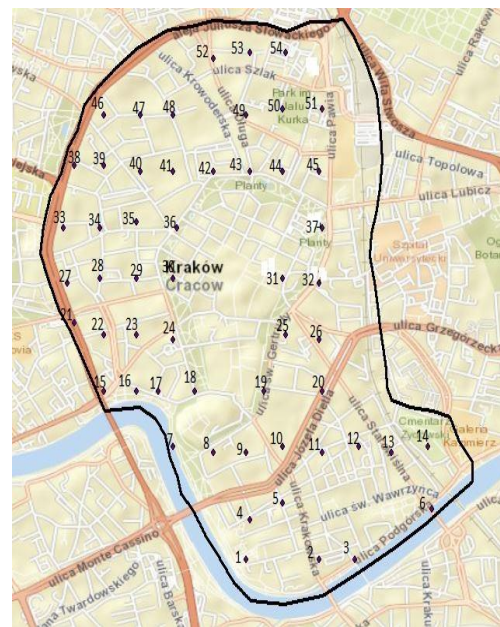


Figure 3.1. Map of Poland (worldmaps.com) Figure 3.2. Map of study points

In autumn and spring of 2021 and 2022, field research was carried out. Based on Geographical Positioning System methodologies (GPS), a total of 54 study points were randomly allocated (Figure 3.2). The precise localization of the study points is shown in Table 3.1.

Table 3.1. Geographical information system points of collected samples

Sample point	Latitude (N)	Longitude (E)
1	50°02'49"	19°56'18"
2	50°02'50"	19°56'37"
3	50°02'50"	19°56'50"
4	50°02'57"	19°56'20"
5	50°03'00"	19°56'31"
6	50°03'01"	19°57'09"
7	50°03'10"	19°55'59"
8	50°05'29"	19°93'55"
9	50°05'21"	19°93'87"
10	50°05'57"	19°94'41"
11	15°05'28"	19°94'41"
12	50°05'28"	19°94'41"
13	50°05'26"	19°94'89"
14	50°05'21"	19°95'41"
15	50°03'31"	19°55'71"
16	50°03'33"	19°55'90"
17	50°03'33"	19°55'97"
18	50°03'37"	19°56'07"
19	50°03'34"	19°56'40"
20	50°03'33"	19°56'68"
21	50°03'33"	19°55'34"
22	50°03'30"	19°55'42"
23	50°03'30"	19°55'49"
24	50°03'50"	19°56'02"
25	50°03'52"	19°56'45"
26	50°03'26"	19°56'42"
27	50°03'39"	19°55'29"
28	50°03'40"	19°55'39"
29	50°03'50"	19°55'49"
30	50°03'67"	19°55'94"
31	50°03'69"	19°56'51"
32	50°03'65"	19°56'61"
33	50°06'40"	19°92'47"
34	50°06'53"	19°92'81"
35	50°03'50"	19°55'49"
36	50°06'35"	19°93'34"
37	50°03'82"	19°56'66"
38	50°06'69"	19°92'60"
39	50°06'79"	19°92'69"
40	50°06'64"	19°93'06"
41	50°06'57"	19°93'34"
42	50°06'60"	19°93'56"
43	50°03'95"	19°56'33"
44	50°03'93"	19°56'45"
45	50°06'70"	19°94'27"
46	50°07'02"	19°92'76"
47	50°06'86"	19°93'07"
48	50°07'06"	19°93'17"
49	50°06'89"	19°93'92"
50	50°06'95"	19°94'15"
51	50°06'95"	19°94'36"
52	50°07'18"	19°93'63"
53	50°07'22"	19°93'79"
54	50°07'11"	19°94'26"

One representative sample was made up of 10 individual samples collected within a square plot with 1 m sides (four samples at the corners and six within the squares). Individual soil samples were then properly mixed together to prepare a representative sample of each study point.

Individual soil samples were taken using special sampler (Figure 3.3) from the 0–20 cm surface layer at each study site (Figure 3.4) and collected in plastic bag (Figure 3.5).



Figure 3.3. Collection of soil material using special sampler



Figure 3.4. Soil samples collection at 0-20 cm depth



Figure 3.5. Drying of collected soil samples at room temperature

Undistributed soil was taken into 100 cm³ metal cylinders (Figure 3.6) to determine its bulk density.



Figure 3.6. Undistributed soil sample in metal cylinder

3.2 Laboratory analysis

Distributed soil samples were dried at room temperature before sieving through a certified polypropylene sieve (2.0 mm mesh) (Gąsiorek et al., 2017).

The following analyses were performed in the soil material prepared in this way:

- content of total organic carbon (TOC) using the Tiurin's method modified by Oleksynowa (Lityński et al., 1976),

- soil texture using the Bouyoucos aerometric method, modified by Casagrande and Prószyński according to PN-R-04032 (Polish Standard, 1998), soil textural class was calculated using USDA (United States Department of Agriculture) (<https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey>),

- pH was measured potentiometrically in a 1:2.5 (w/v) suspension of distilled water and $1 \text{ mol} \cdot \text{dm}^{-3}$ KCl (Lityński et al., 1976) using a standard combination electrode and a CPI-551 Elmetron pH meter,

- CaCO_3 content was determined by the Scheibler method (Lityński et al., 1976),

- soil bulk density was determined from oven dried undisturbed cores as mass per volume, soil was dried at 105°C (Mocek & Drzymała 2010).

According to estimated soil bulk density the soil mass of 1 m^2 at the depth of 0-20 cm were calculated to estimate soil carbon stocks.

Statistical analysis was performed by using Statistica 12 program and presented maps were prepared by using Arc GIS software.

5. RESULTS

4.1 Soil texture

Due to the similarity of textural composition in studied area found during the field work, analysis was done in in half of the samples or (in every second sample). The tested soils were characterized by the highest content of sand fractions, 58.7% on average, among which the fractions 0.5-0.25 mm and 0.25-0.1 mm were predominant (Figure 4.1). The silt content averaged 35.8% and clay 5.5% (Figure 4.2).

According to USDA soil texture classification the majority of studied soil was classified as sandy loam, and only few of them as silt loam (Figure 4.3). For the graphical presentation of the soil texture, the program on the following website was used

<https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey>.

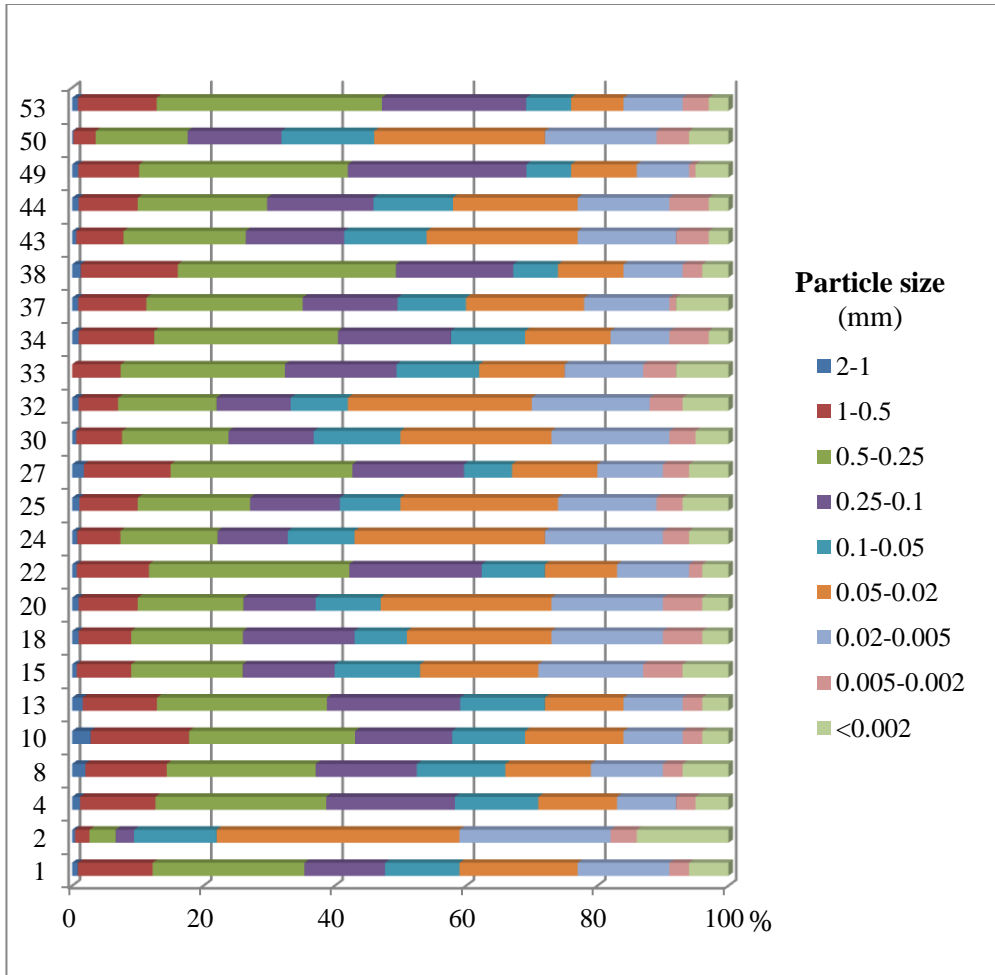


Figure 4.1. Soil texture classification in the studied soil [%]

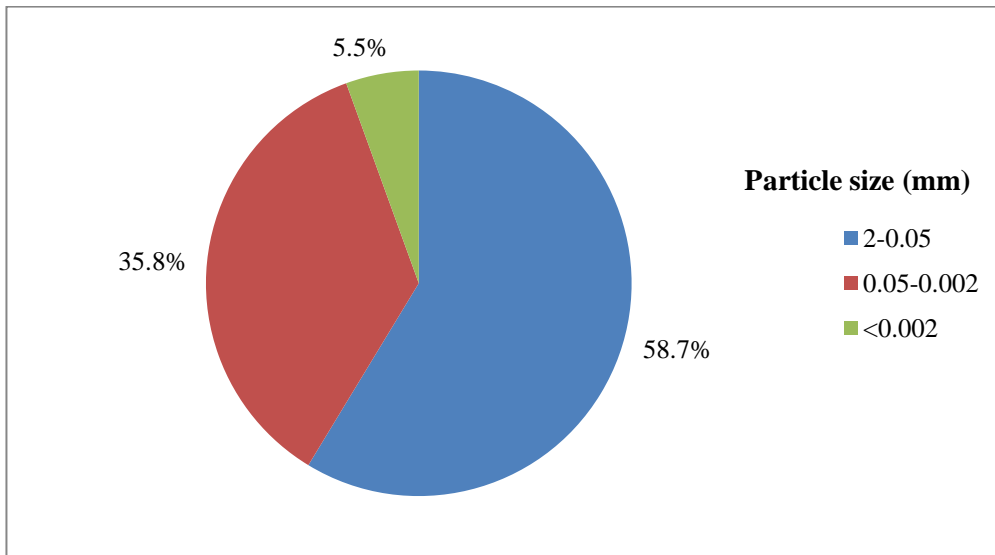


Figure 4.2. Average content of sand, silt and clay in the studied soil

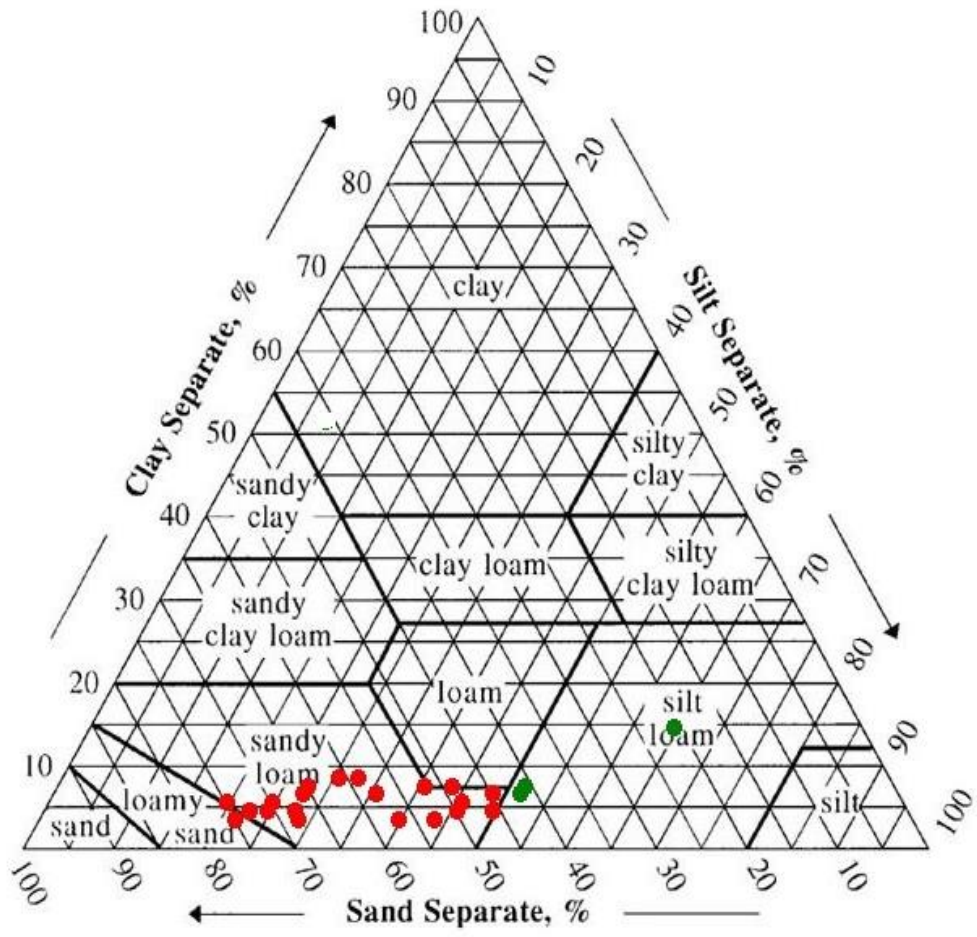


Figure 4.3. Soil texture classification [from USDA soil texture calculator]

4.2 Soil pH

The pH value measured in water suspension in the studied soils ranged from 6.7 to 7.7 (Tabel 4.1), and in most of soils it was significantly above 7.0. The soils in the central and north-eastern parts of the study area were characterised by lower pH values compared to other study points (Figure 4.4).

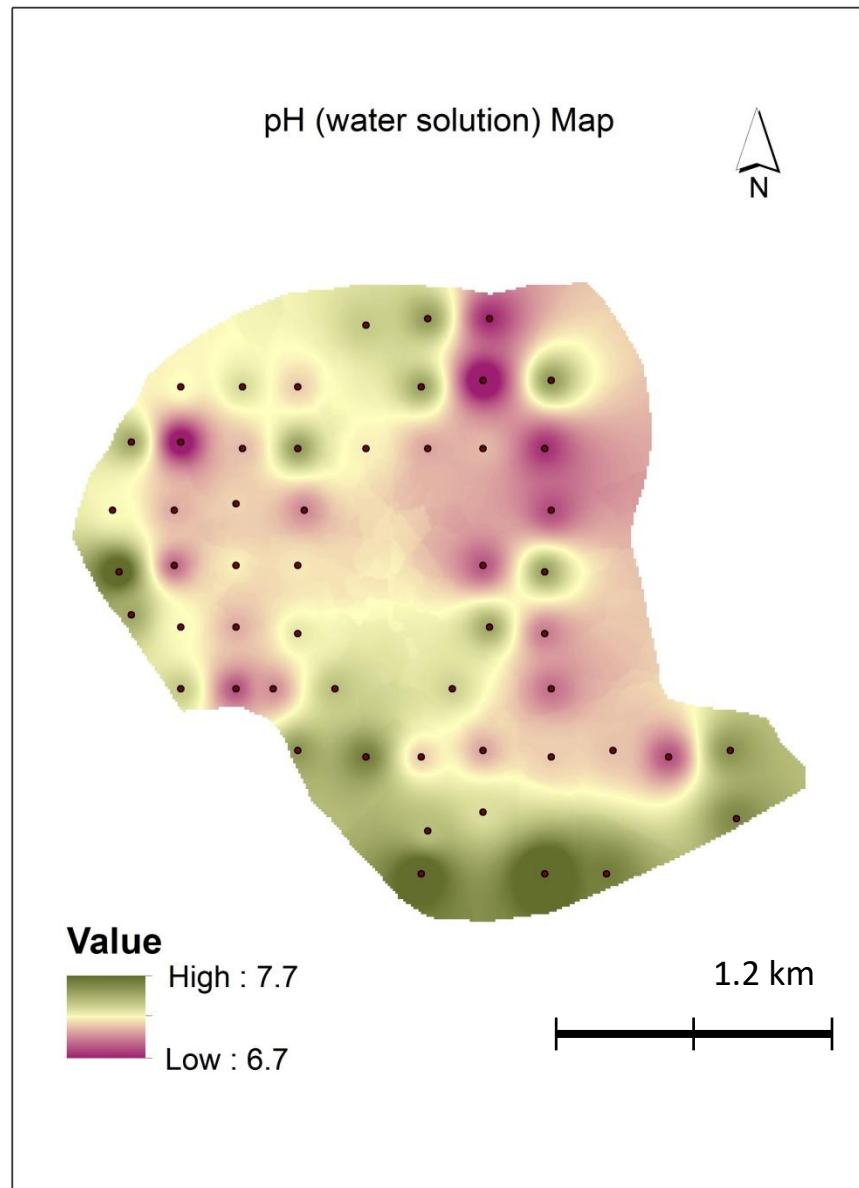


Figure 4.4. The pH value (water suspension) in the studied soil

The pH value measured in KCl suspension in the studied soils was lower like pH value in water suspension and ranged from 5.93 to 7.41 and in most of soils it was significantly above 6.0 (Table. 4.7.1). Especially the soil of north part of study area was characterized by lower pH values measured in KCl (Figure 4.5).

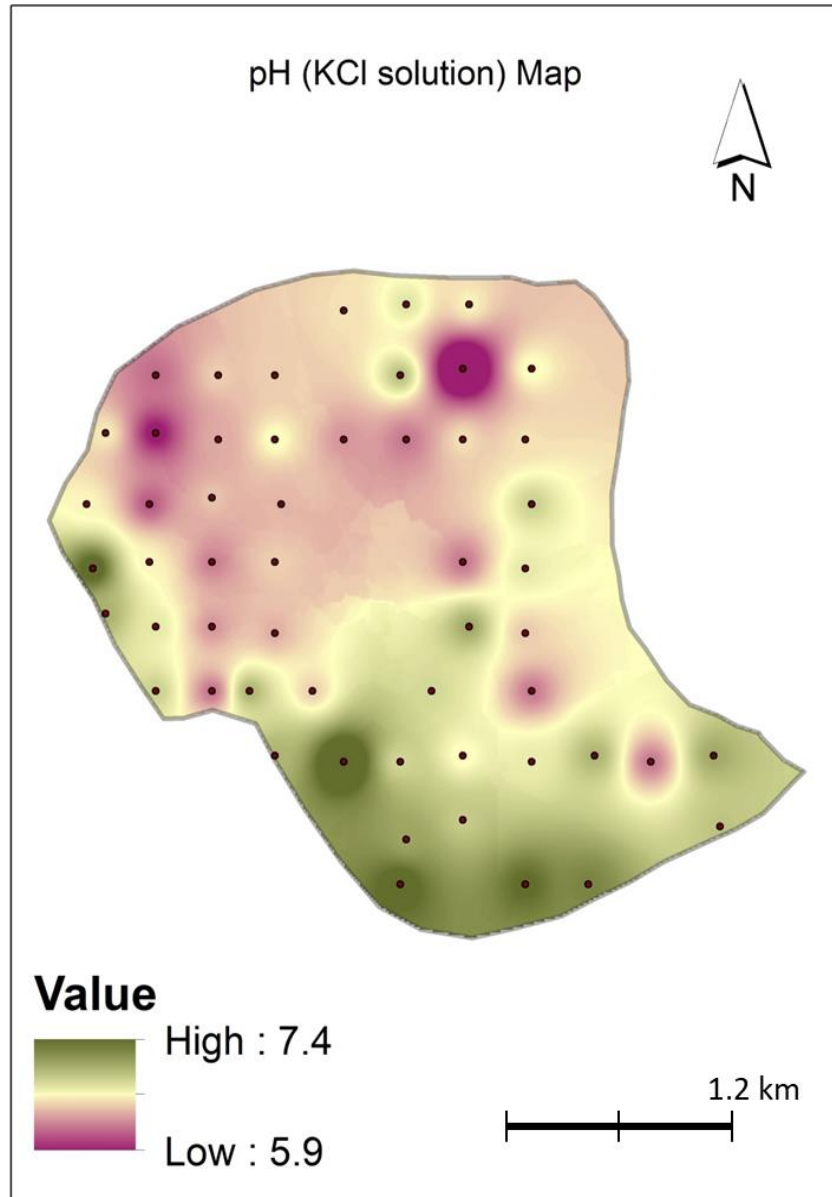


Figure 4.5. The pH value (KCl) in the studied soil

4.3 Content of CaCO₃

The highest content of CaCO₃ in studied soil was 5.5%, but there were also soils some study points without calcium carbonate (Figure 4.6). Average CaCO₃ content was 2.0% (Table 4.1). Highest values were reported in the south-west part of study area.

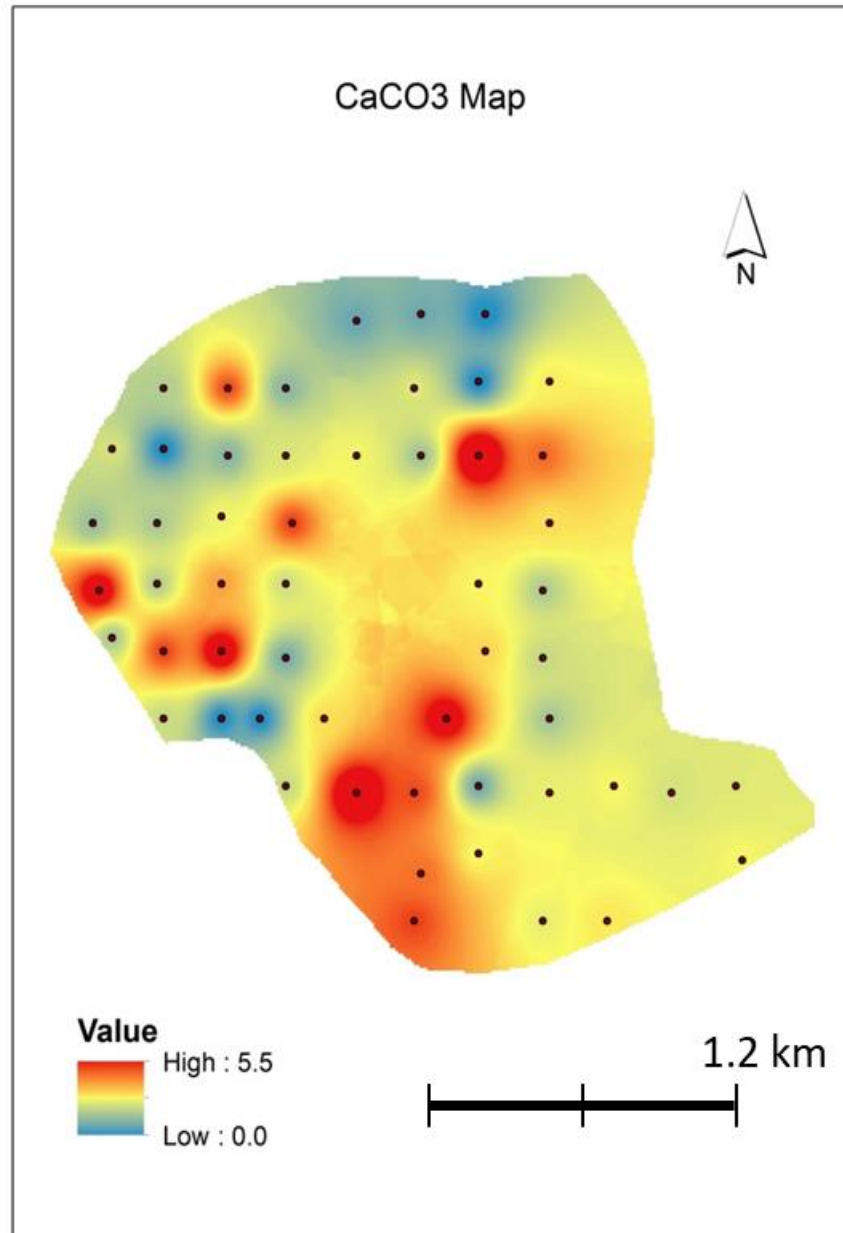


Figure 4.6. Content of CaCO₃ (%) in studied soil

4.4 Soil organic carbon

Figure 4.7 shows the soil organic carbon content in the study area. The content of soil organic carbon in studied soil ranged from $13.6 \text{ g} \cdot \text{kg}^{-1}$ to $41.4 \text{ g} \cdot \text{kg}^{-1}$. Average carbon content was found $26.92 \text{ g} \cdot \text{kg}^{-1}$ (Table 4.7.1). Carbon content was higher in the central and northern part of the sampling area occupied by parks (Figure 4.7).

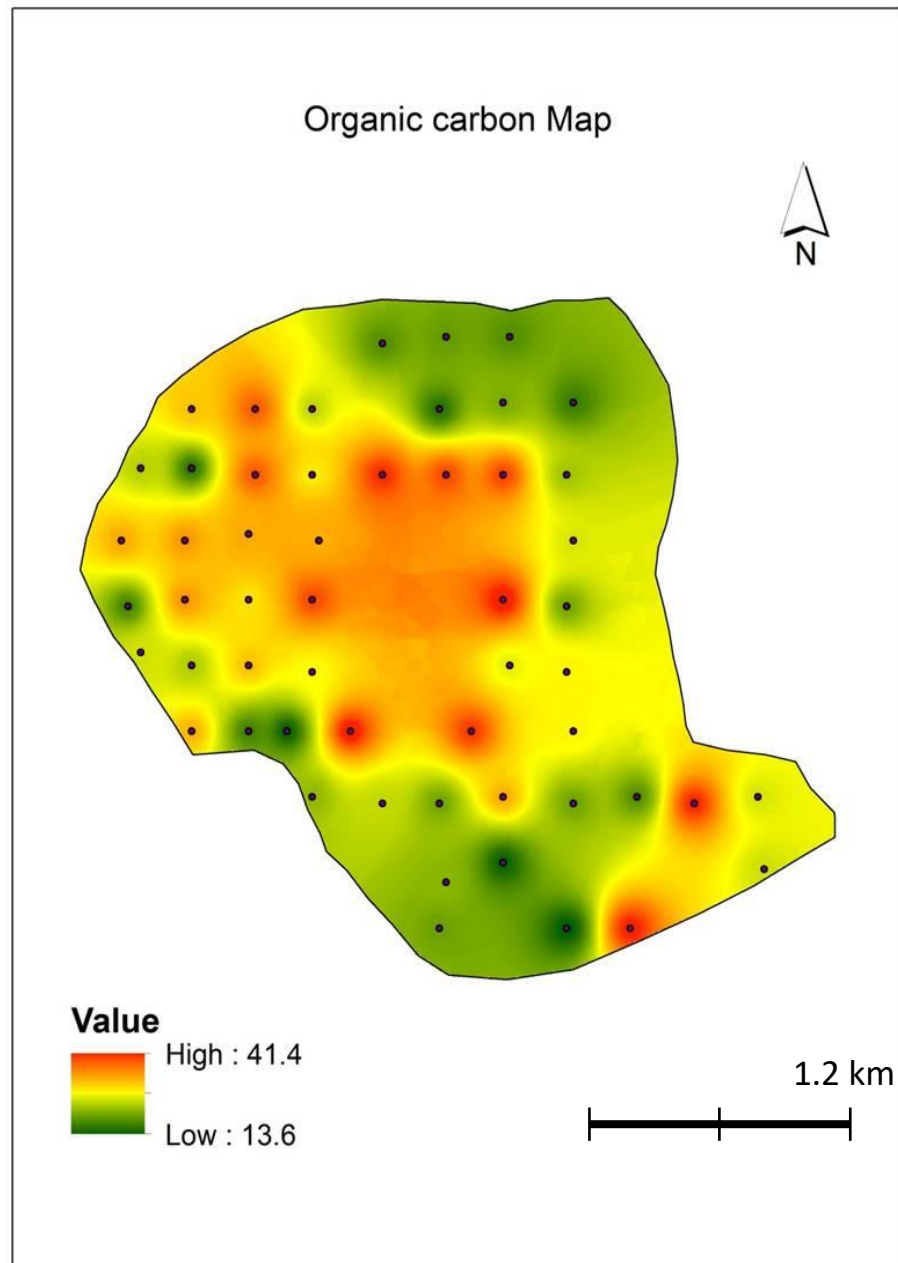


Figure 4.7. Content of soil organic carbon ($\text{g} \cdot \text{kg}^{-1}$) in studied soil

4.5 Bulk density

Regarding the soil bulk density, the studied soil presented an average of $1.25 \text{ g} \cdot \text{cm}^{-3}$ while the maximum value was $1.5 \text{ g} \cdot \text{cm}^{-3}$ and the minimum $1.0 \text{ g} \cdot \text{cm}^{-3}$ respectively (Figure 4.8). Lowest bulk density was observed in the north-eastern side of the study area where organic carbon content is higher (Table 4. 1).

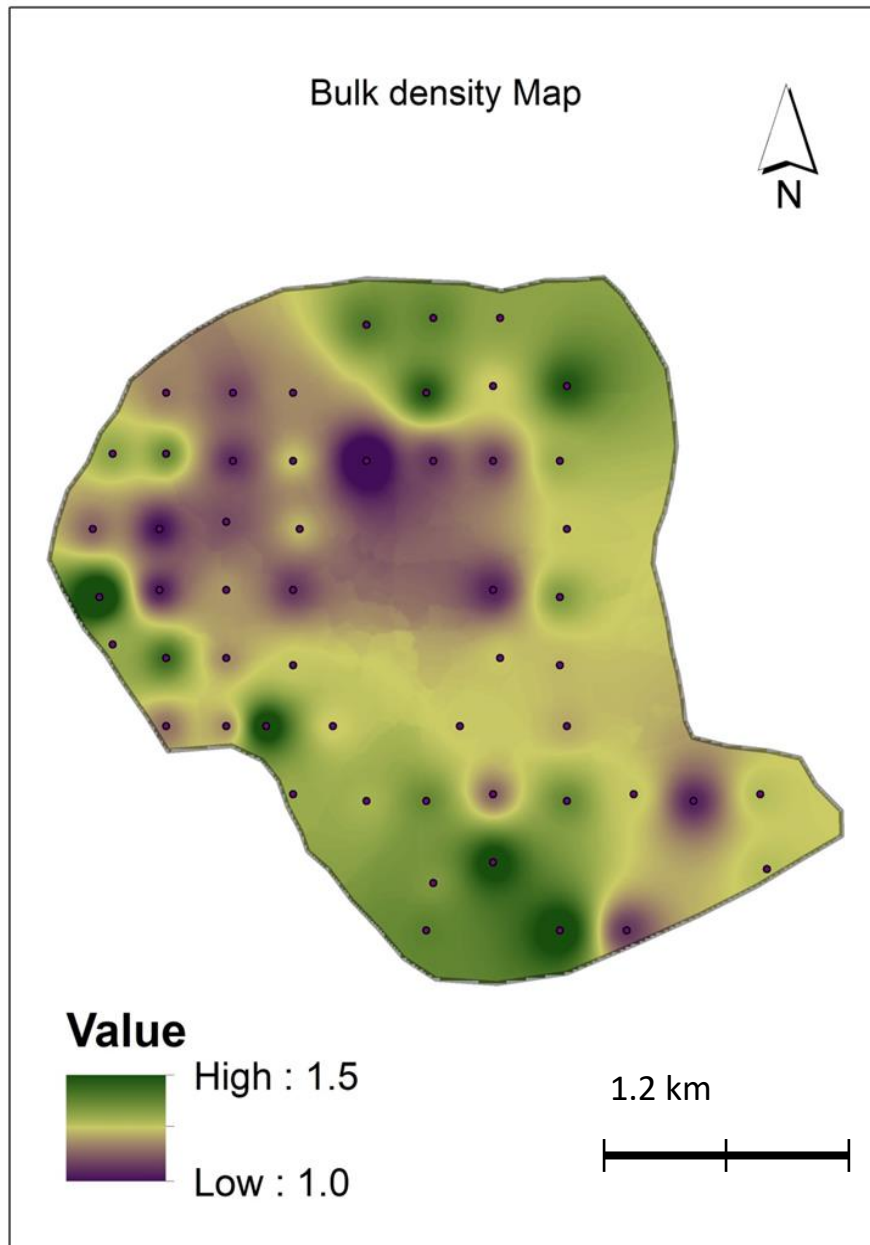


Figure 4.8. Bulk density ($\text{g} \cdot \text{cm}^{-3}$) of studied soil

4.6 Soil organic carbon stocks

Figure 4.9 shows the total organic carbon stocks in all studied soils. The maximum value was found $10.6 \text{ kg} \cdot \text{m}^{-2}$ and the minimum was $4.05 \text{ kg} \cdot \text{m}^{-2}$. The average of total carbon stock in all studied soil samples was $6.78 \text{ kg} \cdot \text{m}^{-2}$ (Table 4.1). Especially in the central part of study area organic carbon stocks were higher.

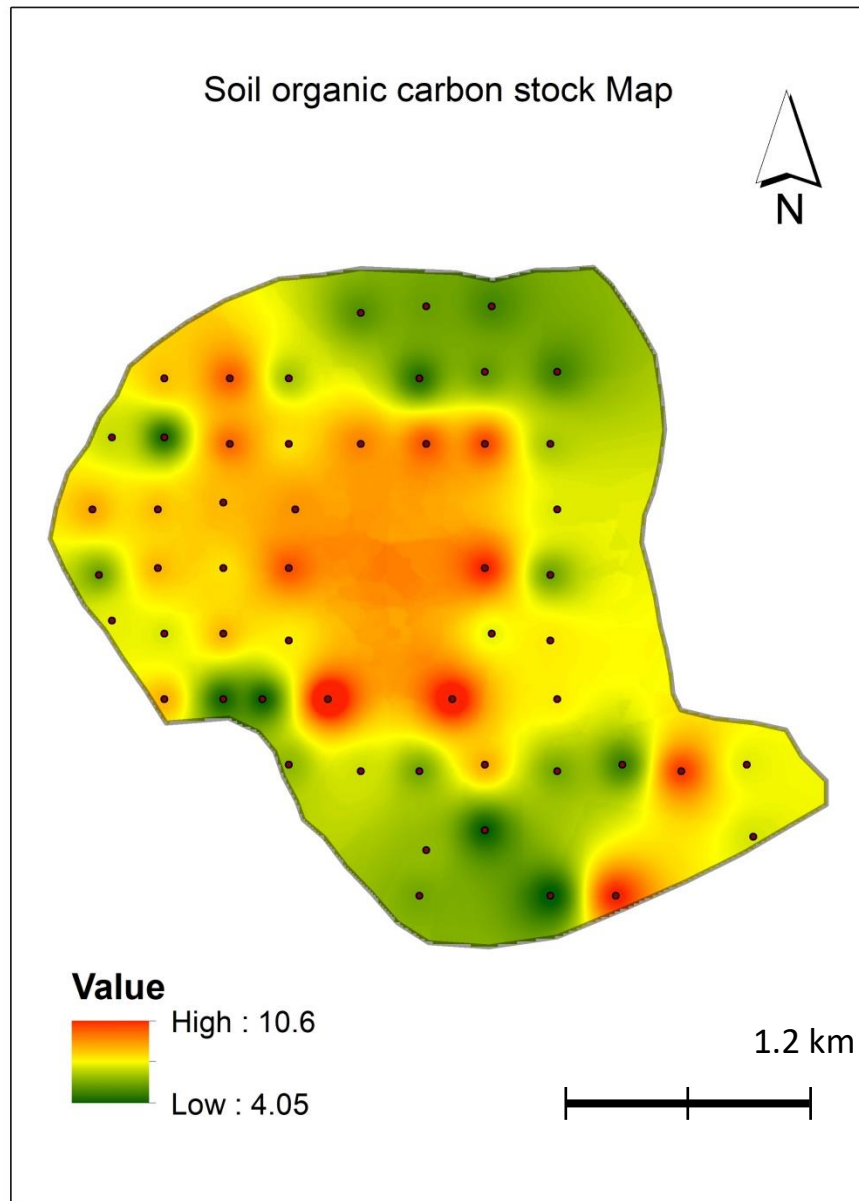


Figure 4.9. Total soil organic carbon stocks ($\text{kg} \cdot \text{m}^{-2}$)

4.7 Statistical analysis

The results were analysed by descriptive statistics. Mean, median, maximum, minimum, range and standard deviation were calculated for the soil properties regarding texture, pH (water and KCl), bulk density, CaCO₃, soil organic carbon and total organic carbon stocks (Table 4.1).

Table 4.1. Basic descriptive statistics of the study results

Parameters	Texture (mm)			pH (water)	pH (KCl)	Bulk density (g · cm ⁻³)	CaCO ₃ (%)	SOC (g · kg ⁻¹)	Soil organic carbon stocks (kg · m ⁻²)
	Sand	Silt	Clay						
Minimum	22	19	3	6.70	5.43	1.0	0.0	13.67	4.05
Maximum	76	64	14	7.74	7.41	1.55	5.5	41.48	10.62
Range	54	45	11	1.04	1.98	0.55	5.5	27.81	6.57
Mean	58.7	35.8	5.5	7.20	6.76	1.29	2.0	26.92	6.78
Median	59.5	33.5	5	7.19	6.74	1.28	6.85	25.33	6.58
SD	13.38	12.03	2.41	0.23	0.24	0.10	1.37	8.34	1.70

Spearman's rank correlation coefficients among the analysed soil properties were calculated (Table 4.2). There were strong statistically significant relationships between soil organic carbon (SOC), SOC stocks and bulk density.

Table 4.2. The value of Spearman's rank correlation coefficient among the soil properties

Soil properties	SOC	SOC stocks	Sand	Silt	Clay	Bulk density	CaCO ₃	pH (H ₂ O)	pH(KCl)
SOC	-	0.991***	-0.099	0.165	-0.384	-0.882***	0.185	-0.176	-0.395**
SOC stocks	-	-	-0.126	-0.187	-0.357	-0.832***	0.198	-0.180	-0.401**
Sand	-	-	-	-0.989***	-0.436*	0.007	0.158	0.062	0.174
Silt	-	-	-	-	0.346	-0.078	-0.208	-0.122	-0.270
Clay	-	-	-	-	-	0.353	0.142	0.320	0.543**
Bulk density	-	-	-	-	-	-	-0.131	0.159	0.353**
CaCO₃	-	-	-	-	-	-	-	0.316*	0.358**
pH (H₂O)	-	-	-	-	-	-	-	-	0.686***
pH(KCl)	-	-	-	-	-	-	-	-	-

Levels of significance:

***p<0.001, **p<0.01, *p<0.05

5. DISCUSSION

Content of soil organic carbon (SOC) depends on many factors like vegetation cover, water conditions, temperature etc. In case of urban area SOC content is modified by several anthropogenic factors (combustion, household wastes, traffic, construction works) which also influence on other soil properties (for example texture, pH, bulk density). As a result content of SOC differs within and among cities (Gąsiorek & Halecki, 2022; Jasek et al., 2014; Lorenz & Lal, 2009; Vodyanitskii, 2015).

In terms of texture, studied soil had highest content of sand 0.5-0.25 mm and 0.25-0.1 mm sub-fractions. Therefore, an average content of sand (58.7%), silt (35.8%) and clay (5.6%) were reported. Hence, soil in the studied area was classified as sandy loam texture class. Nevertheless, the percentage of sand was lower compared to the findings mentioned by Kane (2015) and Scharenbroch et al. (2005) which reporting 75% of sand particles in Moscow city. Another study by Greinert et al. (2013) reported dominance of sand and sandy loam soil in old town square and Vineyard Park of Zielona Góra city (western Poland). Indeed, the reason beyond the highest content of sand in studied soils, might be the presence of stone in urban soils due to the transportation and use of artificial materials like concrete and masonry bricks which somehow may increasing the presence of sand and stone rather than silt and clay (Yang & Zhang, 2015). During the field studies we found fragments of bricks, limestone, plastic, charcoal in the soil and that could be one of the reasons of sandy texture in study area.

The analysed soil reaction was mostly neutral to alkaline. The highest pH was 7.7 and the lowest 6.7 (water suspension). This result could be sustained with the result obtained by Kazlauskaitė-Jadzevičė et al. (2014) with pH greater than 7.0 in the city of Vilnius (Lithuania) and pH range of 7.4-8.6 in Siena municipality area of central Italy (Yang & Zhang, 2015). The reason behind city soils having a higher pH which has already been observed and mentioned by various authors, might be explained through the presence of construction waste such as bricks, which can raise the pH (Alexandrovskaya & Alexandrovskiy, 2000; Biasioli et al., 2006; Jim, 1998). Moreover, alkaline reactions were seen in soil samples taken from the Mall in Washington, DC, which contained infill materials made of building rubble (Short et

al., 1986). Soil pH in KCl was found in the range of 5.9-7.4 which is supported by Greinert et al. (2013) who reported pH value in this solution between 6.8 and 7.1 in Zielona Góra.

Despite the fact that alkalization of urban soils has a number of drawbacks associated to the introduction of plants that need acidic soil it provides several benefits too. By stabilizing many pollutants (particularly lead), which are in this case less moveable in the soil and are not absorbed by plants, it boosts the soils resistance to acidification brought on by "acid rain" and the possibility of stabilizing numerous pollutants (Greinert et al., 2013).

The highest content of CaCO_3 (5.5%) which correspond to $6.65 \text{ g} \cdot \text{kg}^{-1}$ mineral carbon or contributed 14.6% of mineral carbon in total carbon content (organic + inorganic) was found in pH greater than 7.0. According to Shi et al. (2017), high Ca^{2+} provides alkaline condition leading to a positive relationship between soil organic and inorganic carbon content. However, in our study no such correlations were found (Table 4.2). Different components of household trash discovered in urban arable soils throughout fieldwork, including eggshells, animal bones, batteries, charcoal, and ashes, serve as sources of such carbonate substances (Asabere et al., 2018).

The highest accumulation of organic carbon was mostly found in surface layer as shown in many studies (Faber et al., 2012; Lal et al., 2015; Liu et al., 2018; Lorenz & Lal, 2015; Stockmann et al., 2013) and that is the reason to collect soil samples from 0 to 20 cm depth. In the studied soil, the average content of soil carbon was found $26.92 \text{ g} \cdot \text{kg}^{-1}$ with the highest of $41.5 \text{ g} \cdot \text{kg}^{-1}$ and the lowest of $13.67 \text{ g} \cdot \text{kg}^{-1}$. Current and past land use has an effect on organic carbon content. The highest content was found in the central and northern part of the study area. The content of SOC in studied soils is higher compared with the results founded by Gaberšek & Gosar (2018) in the urbanized town of Maribor, a city of Slovenia ($33.0 \text{ g} \cdot \text{kg}^{-1}$). Furthermore, our results could be supported by several researches done in Singapore, USA and Italy. In Singapore, the roadside soil has presented concentrations from 0.33 to $53.2 \text{ g} \cdot \text{kg}^{-1}$ at depth of 0-30 cm. While the content of SOC in soils derived from urban areas in the USA demonstrated contents ranged from 8-23 $\text{g} \cdot \text{kg}^{-1}$, and lastly in Torino (Italy) at 0-30 cm soil depth, content of 3-48 $\text{g} \cdot \text{kg}^{-1}$ was reported (Biasioli et al., 2006; Ghosh et al., 2016; Golubiewski, 2006).

The highest content of SOC founded in studied soils derived from urban areas might be related with lawn maintenance, which often involves water and nutrient inputs to optimize grass growth as mentioned by Pouyat et al. (2006).

Bulk density is an important soil parameter generally affected by land use management, soil texture, water content and root penetration factors (Erdal Sakin, 2012). Average soil bulk density $1.29 \text{ g} \cdot \text{cm}^{-3}$ was noticed in the studied soil which is a little lower than the study reported by Scharenbroch et al. (2005) who reported bulk density $1.39 \text{ g} \cdot \text{cm}^{-3}$ in the urban street and parks of Moscow. Bulk density has an inverse relationship with soil organic carbon. According to the statistical analysis of our result (Table 4.2) a strong correlation was noticed between bulk density and organic carbon which is supported by the study of Dobson et al. (2021), having low bulk density ($0.92 \text{ g} \cdot \text{cm}^{-3}$) and high soil organic carbon concentration ($58.2 \text{ mg} \cdot \text{g}^{-1}$). It means if bulk density was found higher in the study points having low organic carbon content and vice versa.

In our study the average of soil organic carbon stock was $6.78 \text{ kg} \cdot \text{m}^{-2}$ at 0-20 cm depth. According to result presented in Table 5.1 the average of our result is three times higher than the organic carbon stock found in Hamburg, Germany ($2.9 \text{ kg} \cdot \text{m}^{-2}$) at 0-30 cm depth and almost similar with Milan ($6.9 \text{ kg} \cdot \text{m}^{-2}$), Italy at 0-40 cm depth respectively. However, the other studies reported in the table 5.1 in different soil depth were higher than our study.

Hence comparing the results of other studies in different soil depth of 0-100 cm it was noticed that the range of SOC stock was reported in the range of 1.1-42.5 $\text{kg} \cdot \text{m}^{-2}$ whereas our result was in the range of 4.05 - 10.05 $\text{kg} \cdot \text{m}^{-2}$ in 0-20 cm soil depth. According to our research, it could say that urban soils must be carefully managed to capture increased carbon and lessen climate change, strengthening the sustainability and resiliency of cities (Zhang et al., 2022).

Table 5.1. SOC stock in urban areas (Canedoli et al., 2020)

Area	Depth (cm)	Organic carbon stock (kg · m ⁻²)
Milan (Italy)	0-40	6.9
Hamburg (Germany)	0-30	2.9
Ruhr area (Germany)	0-30	11.1-16.4
Singapore	0-100	1.1-42.5
Ohio (USA)	0-100	16.3-21.1
Urumqi, Xinjiang (China)	0-80	8.1
Baltimore and New York (USA)	0-100	8.2

6. CONCLUSION

1. The investigated soils were dominated by sand fractions (on average 58.7%) followed by silt (35.75%) and clay (5.54%) that influenced the majority of soils to be sandy soils.

2. Most of the soils were characterized by neutral to alkaline reaction. It is influenced by the presence of CaCO_3 in almost all studied soil.

3. Most of the soils average content of organic carbon was $26.92 \text{ g} \cdot \text{kg}^{-1}$ where the highest was $41.48 \text{ g} \cdot \text{kg}^{-1}$ and the lowest was $13.67 \text{ g} \cdot \text{kg}^{-1}$. The highest content of organic carbon was found in the most anthropogenic transformed part of study areas (historical centre of Krakow).

4. The estimated soil bulk density in 0-20cm depth was similar or lower compared to other cities and the average value was $1.29 \text{ g} \cdot \text{cm}^{-3}$.

5. In the studied soils at 0-20cm depth average carbon stocks was reported $6.78 \text{ kg} \cdot \text{m}^{-2}$. Highest carbon stock was found $10.6 \text{ kg} \cdot \text{m}^{-2}$ and the lowest $4.05 \text{ kg} \cdot \text{m}^{-2}$. In studied area carbon stock was high compared to other cities of world. It shows the high potential of Krakow for carbon sequestration which is particularly important to combat climate change and reducing the amount of carbon dioxide.

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Publications

1. Chowdhury, S., Gasiorek, M. & Dengiz, O. (2021). Overview of heavy metal contamination in urban soil and impact on human health. International Soil Science Symposium on "Soil Science & Plant Nutrition" Samsun, Turkey.

Won Awards, Incentives and Scholarships

1. Erasmus Mundus scholarship to study Erasmus Mundus Joint Master Degree in Soil Science (2020-2022)