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

EXPLORING SANDY SOILS IN KRAKOW: FROM PLEISTOCENE TERRACES TO ANTHROPOCENE GARDENS

Master's Thesis

Axel CERÓN-GONZÁLEZ

Supervisor
Prof. Dr. Orhan DENGİZ

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dr hab. inż. Michał GĄSIOREK

SAMSUN
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.ACCEPTANCE AND APPROVAL OF THE THESIS

The study entitled **“EXPLORING SANDY SOILS IN KRAKOW: FROM PLEISTOCENE TERRACES TO ANTHROPOCENE GARDENS”** prepared by **Axel CERÓN-GONZÁLEZ**, and supervised by **Prof. Dr. Orhan DENGİZ**, was found successful and unanimously accepted by committee members as Master thesis, following the examination on the date 21.8.2023.

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Member	Prof. Dr. Coşkun GÜLSER Ondokuz Mayıs University Department of Soil Science and Plant Nutrition	☒ Accept ☐ Reject

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

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Prof. Dr. Ahmet TABAK
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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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Yes ☐ (If it necessary, please add appendices.)

No ☒

23 / 08 / 2023
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DECLARATION OF THE THESIS STUDY ORIGINALITY REPORT

Thesis Title : EXPLORING SANDY SOILS IN KRAKOW: FROM PLEISTOCENE TERRACES TO ANTHROPOCENE GARDENS

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ÖZET

KRAKOW'DA KUMLU TOPRAKLARIN KEŞFİ: PLEISTOSEN TERASLARDAN ANTROPOSEN BAHÇELERE

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TOPRAK BİLİMİ VE BİTKİ BESLEME ANA BİLİM DALI
Toprak Bilimi
Yüksek Lisans, Temmuz/2023
Danışman: Prof. Dr. Orhan DENGİZ

Bu tez, Krakov'daki kumlu toprakların özelliklerini, partikül boyutu dağılımına, dokusuna ve temel olarak World Reference Base for Soil Resources (WRB) dayalı olarak sınıflandırmasına odaklanarak tartışıyor. Çalışma, daha az antropojenik alanlardaki toprakların parçacık boyutu dağılımında daha homojen olduğunu ve kumlu dokulara sahip olma eğiliminde olduğunu ortaya koymaktadır. Buna karşılık, açıkça insanlaşmış bölgelerdeki topraklar daha yüksek silt içeriğine sahiptir. Kum içeriği ve çeşitli toprak özellikleri arasındaki korelasyon, artefaktlar ve insan baskısı ile negatif korelasyonlar ve parlaklık, kroma, lamel ve hafif podzolizasyon süreçleri ile pozitif korelasyonlar gösterir. Artefaktlı antropojenik topraklarda pH değerlerinin daha yüksek olması, insan faaliyetlerinden kaynaklanan fizikokimyasal değişiklikleri düşündürür. Araştırma ayrıca çalışma alanında tespit edilen ana materyalin, kum dağılımının ve çeşitli pedogenetik süreçlerin rolünü vurgulamaktadır. Topraklar, WRB'ye (2022) göre Anthrosols, Phaeozems, Umbrisols, Cambisols ve Arenosols olarak sınıflandırılır. Her bir toprak profilinin spesifik özellikleri ve sınıflandırması, organik madde birikimi, hafif podsolizasyon ve insan müdahalesi gibi faktörler dikkate alınarak açıklanmıştır. Ayrıca, rüzgar malzemelerinin eklenmesinin Kraków'daki toprak oluşum süreçleri üzerinde önemli bir etkiye sahip olduğu bulundu.

Anahtar Sözcükler: Katena, Toprak dokusu, İnsan-toprak ilişkileri, Eserler

ABSTRACT

EXPLORING SANDY SOILS IN KRAKOW: FROM PLEISTOCENE TERRACES TO ANTHROPOCENE GARDENS

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This thesis discusses the characteristics of sandy soils in Kraków, focusing on their particle size distribution, texture, and classification mainly based on World Reference Base for Soil Resources (WRB). The study reveals that soils in less anthropized areas are more homogeneous in particle size distribution and tend to have sandy textures. In contrast, soils in clearly anthropized regions have higher silt content. The correlation between sand content and various soil properties shows negative correlations with artefacts and anthropopressure, and positive correlations with brightness, chroma, lamellae, and slight podzolization processes. The pH values are higher in anthropized soils with artefacts, suggesting physicochemical changes due to human activity. The research also highlights the role of parent material, sand distribution, and various pedogenetic processes detected in the study area. The soils are classified as Anthrosols, Phaeozems, Umbrisols, Cambisols, and Arenosols based on the WRB (2022). The specific characteristics and classification of each soil profile are described, considering factors such as organic matter accumulation, slight podsolization, and human disturbance. Furthermore, the addition of aeolian materials was found to have a significant impact on the soil-forming processes in Kraków.

Keywords: Catena, Texture, Human-soil relationships, Artefacts

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Axel CERÓN-GONZÁLEZ

CONTENTS

SYMBOLS AND ABBREVIATIONS

WRB	: World Reference Base
PTG	: Polish Classification System
USDA	: United States Department of Agriculture

FIGURES LEGENDS

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1. INTRODUCTION

Sandy soils are globally spread and cover 31% of the total land area (Huang and Hartemink, 2020). Nevertheless, they are frequently relegated due to their marginal status as often-low fertile soils. In Poland, sandy landscapes dominate, with almost 55% of the soils classified as Arenosols and Podzols (European Commission, 2005). Despite this, recent research has revealed that academic interest in Polish sandy soils has been focused on biochemistry, particularly in biochar and heavy metals during the last five years (Cerón-González et al., 2022). In the field of soil genesis and classification, the Soil Atlas Sequences is one of the most outstanding efforts that have significantly contributed to shedding light on this crucial topic (Świtoniak and Charzyński, 2014, 2018a, 2018b, 2018c, 2022).

Additionally, there have been several promising soil studies across the country, including Jankowski's investigation of lateral podzolization in northern Poland (Jankowski, 2014); Mazurek et al. (2016) discovered the contact layer of human settlement in central Kraków; Świtoniak (2022) showed lithosequences of Arenosols – Luvisols, mainly affected by underlying changes of parent material; and Gus-Stolarczyk et al. (2022) characterized the effect of podzolization at different depths on the presence and transformation of lamellae in rusty soils of southern Poland. Nevertheless, there are still uncertainties regarding the relationship between human-modified and unmodified sandy soils in Kraków. In this way, the ongoing research will look to understand this topic through the following objectives.

1.1. Objectives

Our study aimed to compare the soil properties of selected regions in Kraków (southern Poland) that have presented human modification versus those that have not, focusing in sand-sized particle distribution.

- Investigate the sandy soil resources in Kraków;
- Use the Polish Classification Systematics (2019) and international systems to classify soil particle sizes distribution;
- Identify the main pedogenetic processes occurring in soils;
- Analyze the impact of human activity on soil texture and other soil properties;

- Classify the studied soils using the most recent version of WRB (2022).

2. LITERATURE REVIEW

2.1.General properties of sandy soils

The main characteristic of sandy soils is their texture, characterized by relatively higher proportions of sand-sized particles in the fine earth (Wang et al., 2022). The particle-size classes are defined according to the diameter of soil particles less than 2.0 mm (USDA, 1987; PTG, 2019; IUSS Working Group WRB, 2022). This information is later used to determine the texture of soils as sandy, silty, or clayey in agreement with the percentages of sand, silt, and clay-sized particles (Yolcubal et al., 2004). Meanwhile, the loamy texture in soils refers to none of these fractions as dominant (Blum et al., 2018).

Since the beginning of contemporary soil science, several soil particle size and texture classifications have flourished nationally and internationally (Yolcubal et al., 2004). At present, the two most recurred are the U.S. Department of Agriculture (USDA, 1987) and WRB of the International Union of Soil Sciences (IUSS Working Group WRB, 2022), which are adapted from the 19th-century Russian system developed to meet agricultural needs (Curtis, 2005). In Poland, the Systematics of Polish Soils (PTG, 2019) has proposed its classifications, generally following USDA and IUSS (Fig. 2.1).

The three systems include five sand subclasses. However, the IUSS considers different diameter ranges compared to USDA and PTG. This difference also affects the sand-silt particle-size limit at 0.125 mm by IUSS and 0.05 mm by USDA and PTG. Another difference refers to the silt subclasses along the three systems. There is only one silt class in the USDA, two subclasses in IUSS, and three subclasses in PTG. Fig. 2.1 smoothly integrates and compares this data adopted as the basis for the ongoing research.

Newly generated insights have conceptually contributed to sandy soil understanding, especially in determining the soil's responses to the environment and assessing suitable land uses. Due to their role in the soil body relationships and pore space constitution, sand-sized particles are closely related to other soil physicochemical properties and parameters (Targulian and Bronnikova, 2019). Because sandy soils have small specific areas, they are often considered with poor

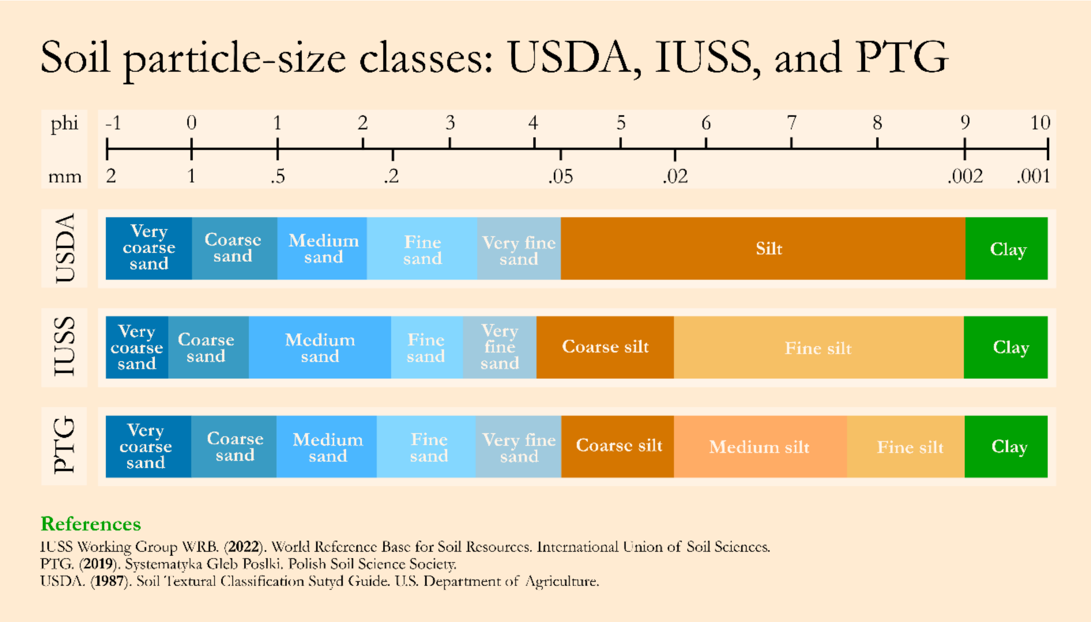

Figure 2.1**.** Comprehensive comparison of three particle-size distribution classifications including the two most widely used (i.e., USDA, 1987; PTG, 2019; IUSS Working Group WRB, 2022).

water retention properties, low organic carbon content, weak or structureless, high permeability, and high sensitivity to compaction.

Nonetheless, those properties also vary depending on other factors such as vegetation, climate, and land use, as Yost and Hartemink (2019) reported. Combining several literature findings on sandy soil properties, Table 2.1 documents fifteen physical, chemical, and biological soil properties. To add a comparative value about other soil textures, it is in three relative categories are included, medium and low values. This way, the valued categories are synthetically explained, addressing the relationship between sand-sized particles and soil properties such as cohesion forces, porosity, and aggregation stability.

For example, a low porosity in sandy soils is expected due to a small surface area despite large pores. This way, a high bulk density in sandy soils is anticipated due to larger but fewer pore spaces. It is remarkable that some soil properties only concern arid regions, such as surface crusting and salt accumulation (Yost and Hartemink, 2019). These explanations are given in Table 2.1 for a better understanding of sandy soils, and they are based on recent sandy soil global approaches (Lesturgez et al., 2014; Yost and Hartemink, 2019; Huang and Hartemink, 2020).

Besides, the synthesis of sandy soil's behaviors and sand-sized particle properties are optimally suited to deal with the interplay factors influencing soil-forming processes in Central Europe and, more precisely, in Kraków city region which is settled in the southern portion of the Late Glacial inland aeolian deposits (Kalińska, 2019; Sokołowski et al., 2022) referred as the European Sand Belt, and surrounding the Vistula River alluvial deposits (Łajczak et al., 2021), which early settlement history dates back to the Stone Age (Zaitz, 2012).

Table 2.1. Soil properties and their relative value in sandy soils compared to other particle sizes. The explanation considers the study of Lesturger et al. 82014); Yost and Hartemink (2019); and Huang and Hartemink (2020)

Soil property	Relative value	Explanation
Water repellency	+++	Hydrophobic surface coatings
Compaction	+++	Weak cohesion forces
Surface crusting	+++	Low aggregation stability
Water inputs and outputs	+++	Sensitive to water changes because of minor porosity
Leaching	+++	The low specific area allows percolation
Bulk density	+++	Larger but fewer pore space
Hydraulic conductivity	+++	Large pores allow high hydraulic conductivity
Thermal conductivity	+++	Sand-sized fractions in soils are mainly composed of quartz
Organic carbon	++	It is assumed to be low but in temperate areas it can be as high as 50 g kg^{-1}
Salt accumulation	++	It is a concern of arid regions where mostly dominant sandy soils
CEC and Base Saturation	+	Because of the low specific area, CEC and BS are low as well
Electrical conductivity	+	Waek adsorption in sandy soils
Porosity	+	Small surface area even though large pores
Field capacity	+	Poor capacity to retain water
Microbial activities	+	Low water and organic carbon contents stop microbial communities

Relative value: +++ high; ++ medium; + low

2.2.Quaternary sands as parent material in Poland

During the Quaternary, various climatic changes have occurred, and their impacts are recorded on terrestrial archives such as sediments (Dietze et al., 2016), peats (Harris-Parks, 2016), soils (Sheinkman et al., 2023), and archaeological remains (Ibarra-Arzave et al., 2019). The Holocene transition generally marks a climatic change towards warmer conditions after a colder period interpreted as the Younger Dryas (Firestone et al., 2007) at the end of the Pleistocene. Those archives are specially identified in the northern hemisphere (Fiedel, 2011; Sweatman, 2021), where they configure several landscapes and parent materials as factors for soil formation.

This way, the Holocene environmental setting reactivated alluvial processes in the Desert of Sonora, Mexico (Ibarra-Arzave et al., 2018), while inland aeolian sediments were deposited in China Plateau (Qiang et al., 2021), Eastern Mediterranean (Roskin et al., 2011; Shalom et al., 2020) and Central Europe (Lehmkuhl et al., 2018a; Lehmkuhl et al., 2018b; Schaetzl et al., 2018; Bertran et al., 2021;). Regarding Europe, Pleistocene coversands sediments have been reworked, transported by aeolian processes, and originated drift-sand fields throughout the Holocene. This well-known geomorphological phenomenon is the European Sand Belt (Koster, 2009; Pierik et al., 2018).

The Belt-related sand deposits are present in southeastern Britain and prominently cover from northern Belgium to Eastern Europe (Pierik et al., 2018; Łapcik et al., 2021; Łopuch et al., 2023). This way, the geography of Poland is vastly dominated by Quaternary fluvial-aeolian sedimentary successions observed throughout the entire European Sand Belt (Moska et al., 2020). Fig. 2.2 illustrates a portion of the Belt's shape over Europe and its relationship to Pleistocene interglacial frontiers, understood as the favored advances of Scandinavian ice sheets moved southwards. The Pleistocene paleo-ice sheet dynamics and distribution are helpful information that indicates the geological and environmental setting during the last millennia in Poland.

The Saagalian generally marks the maximum extent of the Pleistocene glaciations period frontier (Łopuch et al., 2023). The Saagalian period is better known as Odranian in Poland (Marks et al., 2016), and it is assumed to cover a period of about 160 ka and ended circa 150 ka (Krbetschek et al., 2008). It is generally characterized by extensive valley widening (Ehlers et al., 2011) as well as a very high content of aeolian reworked sands (Woronko and Bujak, 2018), mud-sands sediments correlated to the Lublinian interstadial (Marks et al., 2016), and fluvial deposits representing an aqueous environment and a lesser contribution of sand and sand-mud sediments during the Wartanian stadial (Woronko and Bujak, 2018).

On the other hand, the range of the Last Glacial or Weichselian, better known as Vistulian in Poland, is primarily recorded in northern and central Poland (Lindner

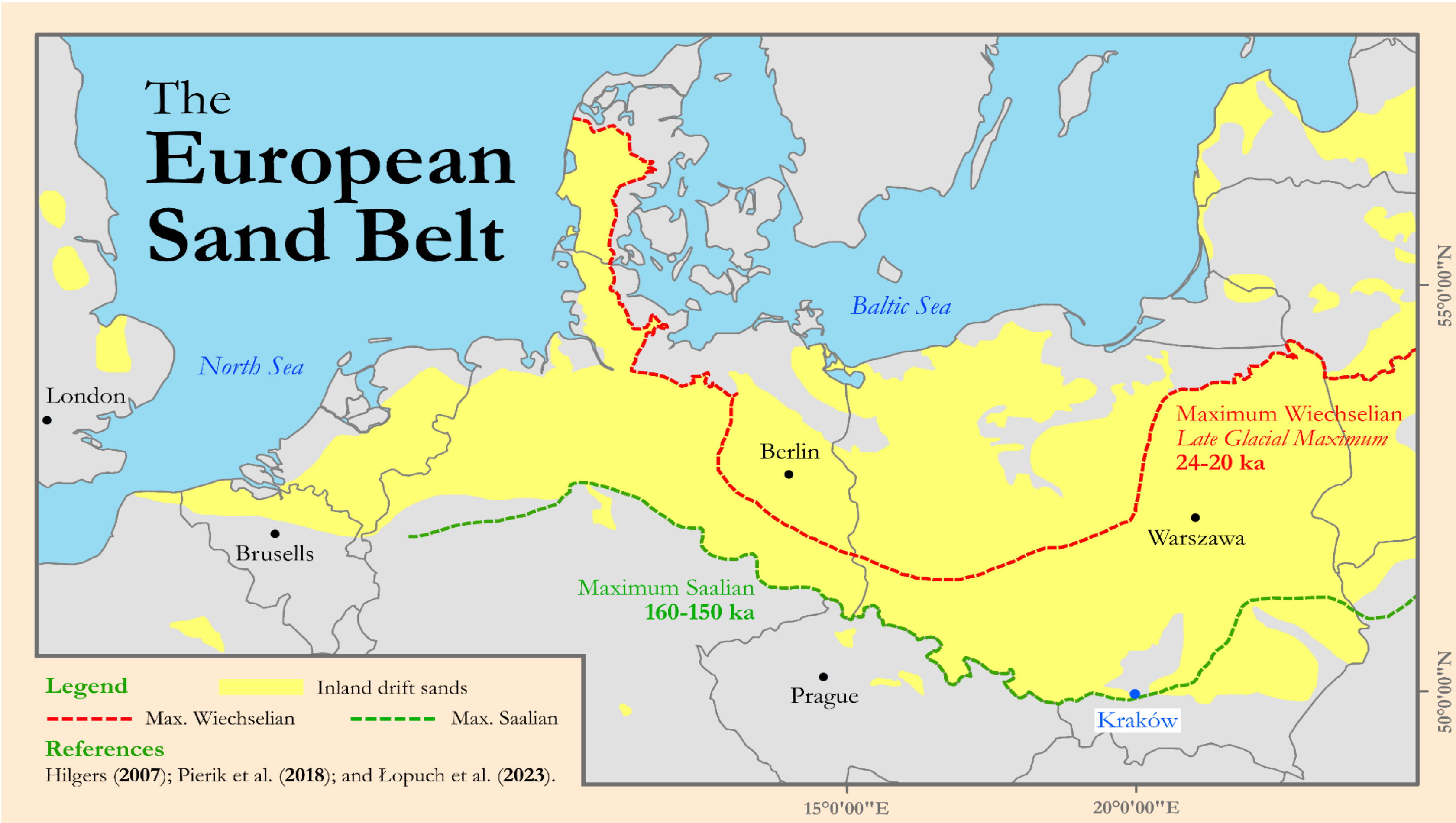

Figure 2.2. The European Sand Belt pattern over a portion of Europe, the city of Kraków is marked at the southern frontier of the Belt. Furthermore, the impact of the Belt on Poland's territory is noticeable. The map was adapted from Hilgers (2007); Pierik et al. (2018); Łopuch et al. (2023).

et al., 2013) as well as in Berlin's region, eastern Germany (Ehlers et al., 2011) as mapped in Fig. 2.2. The Vistulian stratigraphy mainly refers to thick successions of wind-modified sand grains as the sum activity of several aeolian process cycles during the Late Pleistocene – Early Holocene (Woronko and Bujak, 2018; Łapcik et al., 2021). One of the best-expressed Pleistocene inland aeolian features in Poland's lowlands is dunes mainly originating from sand winnowing from plains and river valleys (Łapcik et al., 2021). Furthermore, present-day overall dune field patterns show signs of transformation during the Holocene due to anthropogenic factors (Tolksdorf and Kaiser, 2012).

2.3.Sandy soils in Kraków: A general view

In general, soil genesis, classification, and education have driven particular attention in Poland since the last years (Brożek, 2001), as those show exponential academic growth and global awareness. Diverse activities and materials, such as soil classification workshops and soil sequence atlas publications, have been launched to promote the study of soils in Poland, particularly in the central and northern regions. Through these efforts, a precise and synthetic vision of the sandy soil resources in Poland has been popularized (M. Świtoniak and Charzyński, 2014, 2018a, 2018b, 2018c, 2022). Furthermore, the Soil Science Society of Poland has selected sandy soils twice in a row (2021 and 2022) under the umbrella of the "Soil of the Year" campaign launched in 2018.

In 2021, the rusty soils (*gleba rdzawa* in Polish) were chosen as Soil of the Year due to their historical importance in Polish soil classification and geographical distribution, which is estimated to cover around 22.5% of the whole territory of Poland (Jankowski and Bednarek, 2021). The distribution of rusty soils is mainly related to areas with extensively sedimented sandy material during the Pleistocene and subsequently reworked and transported by aeolian processes in the Holocene (Moska et al., 2020). For 2022, the alluvial soils (*mady* in Polish) were elected as Soil of the Year. Although alluvial soils cover less than 5% of Poland, they are considered highly productive in river valleys for agriculture and forestry (Kabała, 2022). Additionally, they play an essential role in the urban history of the main Polish cities surrounding the Vistula River (i.e., Warszawa, Kraków, and Gdańsk).

As mentioned, understanding sandy soils is currently promoted nationally in Poland. This way, Kraków offers a unique laboratory for sandy soil studies as its urban area is settled over the Vistula River deposits and at the southern frontier of the European Sand Belt (Fig. 2.2). So far, Mazurek et al. (2016) have studied a well-preserved multi-layered urban soil burying a Fluvisol in Kraków's Main Square and demonstrated a crucial role of urban soils in the storage of organic carbon as well as a gradual decrease of artefacts giving way to BC non-anthropogenic horizons. This way, the pedo-cultural sequence marks the beginning and development of human-environment relationships in Kraków's urban landscape. Additionally, Kowalska et al. (2016) used heavy metal concentrations analysis as a proxy for the metallurgical activity of Kraków during the Middle Ages.

Further documented and promising research on rusty soil illuvial bands (lamellae) has been carried out in Kraków (Gus-Stolarczyk et al., 2021). Generally, lamellae indicate clay and Fe-Al compounds' illuminance by water seeping into the soil (Jankowski and Bednarek, 2021). For this reason, they are commonly described as a series of thin layers characterized by higher chromas, redder hues, and lower values than interlamellae (Van Reeuwijk and De Villiers, 1985; Lisá et al., 2019). Hence, their occurrence is considered a qualifier in Arenosols, Retisols, and soil groups with argic horizons (IUSS Working Group WRB, 2022). Recently, Gus-Stolarczyk et al. (2022) have discussed that lamellae are transformed by different mechanisms depending on their position in the soil profile and stage of development. In this way, a well-developed sandy soil that exhibits podzolization and an eluvial horizon certainly promotes the chemical degradation of lamellae due to iron dissolution.

Moreover, two main soil threats have been identified in the Kraków region: heavily eroded soilscapes (Drewnik and Żyła, 2019) and soil pollution by heavy metals (Gąsiorek et al., 2017). On the one hand, Drewnik and Żyła (2019) explored the morphology of former Chernozems strongly affected by erosion related to agricultural activities in the upland of the Proszowice Plateau. The changes due to erosion over more than 50 years include the loss of previously documented A-horizon, cambic horizon, and illuvial features (Józefaciuk and Józefaciuk, 1984; Żyła, 2007). The former Chernozems would be classified as Regosols (IUSS Working Group WRB, 2022). On the other hand, the urban soils of Kraków show a high mixed concentration of Cd, Cu, Pb, and Zn from anthropic sources (Gąsiorek et al., 2017), which have a significant impact on the soil biochemical dynamics, particularly reducing activities of dehydrogenases and urase (Pająk et al., 2018). This is directly related to microbial biomass's potential incapacity in controlling the C and N pool in Kraków (Gąsiorek and Halecki, 2022).

3. MATERIALS AND METHODS

3.1.Study area

The geological and geomorphological setting of Kraków's western region is mainly influenced by sedimentary conditions grouped into three stages. Firstly, numerous Jurassic complexes of carbonates buildups formed by microbialites and benthic fauna settled over elevated Paleozoic blocks due to pre-Jurassic synsedimentary tectonics (Matyszkiewicz et al., 2006, 2012; Kochman et al., 2020; Fijałkowska-Mader et al., 2022). Secondly, Pleistocene terraces created during the Saagalian/Odranian period, mainly characterized by sandy aeolian sediments (Marks et al., 2016; Woronko and Bujak, 2018; Łopuch et al., 2023). Finally, the Holocene fluvial-aeolian plain of the Vistula River (Łanczont et al., 2015a; Krajcarz et al., 2016; Berto et al., 2021).

The three grouped geomorphic features are identified in Fig. 3.1. Especially the Pleistocene glacial terraces over Jurassic carbonates, and their erosional scarps are marked. The Sowiniec horst is distinguished as well, a varied limestone underlying loess cover at different depths due to a dense net of faults surrounding and crossing the structure (Łanczont et al., 2015b). As mentioned, the lowlands in the digital elevation model represent the Holocene Vistula plain affected by both fluvial and aeolian processes (Urząd Miasta Krakowa, 2010; Łanczont et al., 2015a). Furthermore, the Medieval walled Kraków is indicated as it represents the historical center of the city, built on a small hill among wetlands (Jankowicz, 2020)

Kraków possesses a temperate climate, typical in central Europe, where the annual mean temperature is around 8 °C, with minimum temperatures of -5 °C in January and a maximum of 25 °C in July. Furthermore, the most rain occurs from May to August, with a yearly mean of 678 mm (Jasek-Kamińska et al., 2020). Caputa (2016) has recently documented variations in net solar radiation based on topographic position in Kraków. Specifically, the lowlands receive up to 27% less mean annual solar radiation than the uplands, which directly affects physical soil properties such as moisture. The vegetation is generally composed of lowland forb-rich beech forests (*Melico-Fagetum*) with some patches of submontane Carpathian and Sudentian forb-rich beech forests (*Dentario glandulosae Fagetum* and *Dentario enneaphyllidis Fagetum*) as well as acidophilous birch-oak (*Betulo-Quercetum roboris*) and Middle-European pine forests (*Leucobryo-Pinetum* complex) (Wasylikowa, 2004).

This way, the local conditions in Kraków have promoted the development of Eutric Fluvisols in the Vistula plain, patches of Podzols and Haplic Luvisols in the Pleistocene terraces, and a mosaic of Rendzic Leptosols, Mollic Umbrisols, Stagnic Luvisols, and Calcaric Cambisols in the uplands (European Commission, 2005). More detailed, Skiba et al. (2010) mapped Haplic Fluvisols and Cambic Fluvisols in the Vistula plains; a combination of Rendzic Leptosols and Calcaric Leptosols, Podzols, Cambic Fluvisols, and Brunic Arenosols in the terraces; and Stagnic Luvisols and Albic Luvisols in the Sowiniec horst. Notably, the soil diversity in Kraków's western region is mainly based on the geomorphology and characteristic times of the parent material.

For the ongoing research, the six soil profiles studied were strategically located near or on Pleistocene terraces (Fig. 3.1). Moreover, the human impact factor was also included when selecting the sites, as considered of high importance to understand the long-term human-soil relationship in the western region of Kraków (Mazurek et al., 2016; Gąsiorek et al., 2017; Gąsiorek and Halecki, 2022). Like this, the soils P1, P2, and P3 are in lesser anthropized areas, while P4, P5, and P6 are part of the modern Kraków (Table 3.1).

3.2.Methods

The soil description, sampling, and classification were done following the IUSS Working Group WRB (2022), specifically using the recently added annexes for soil fieldwork guidance (Table 3.1). Furthermore, the WRB (2022) based illustrated handbook launched by Świtoniak et al. (2023) was primarily used to determine specific soil properties in the field. Genetic horizons were studied in the six soil profiles, and samples were taken from each horizon (Table 3.1).

For laboratory analysis at URK, the samples were dried at room temperature and then passed through a sieve of 2 mm mesh. The aerometric and sieve method was used to determine the soil particle size based on PN-R-04032 Polish standard (Polski Komitet Normalizacyjny, 1998). Soil textural classes were assessed according to Polish and international systems. The total organic carbon content was calculated following Tiurin's method (Lityński et al., 1976), modified by

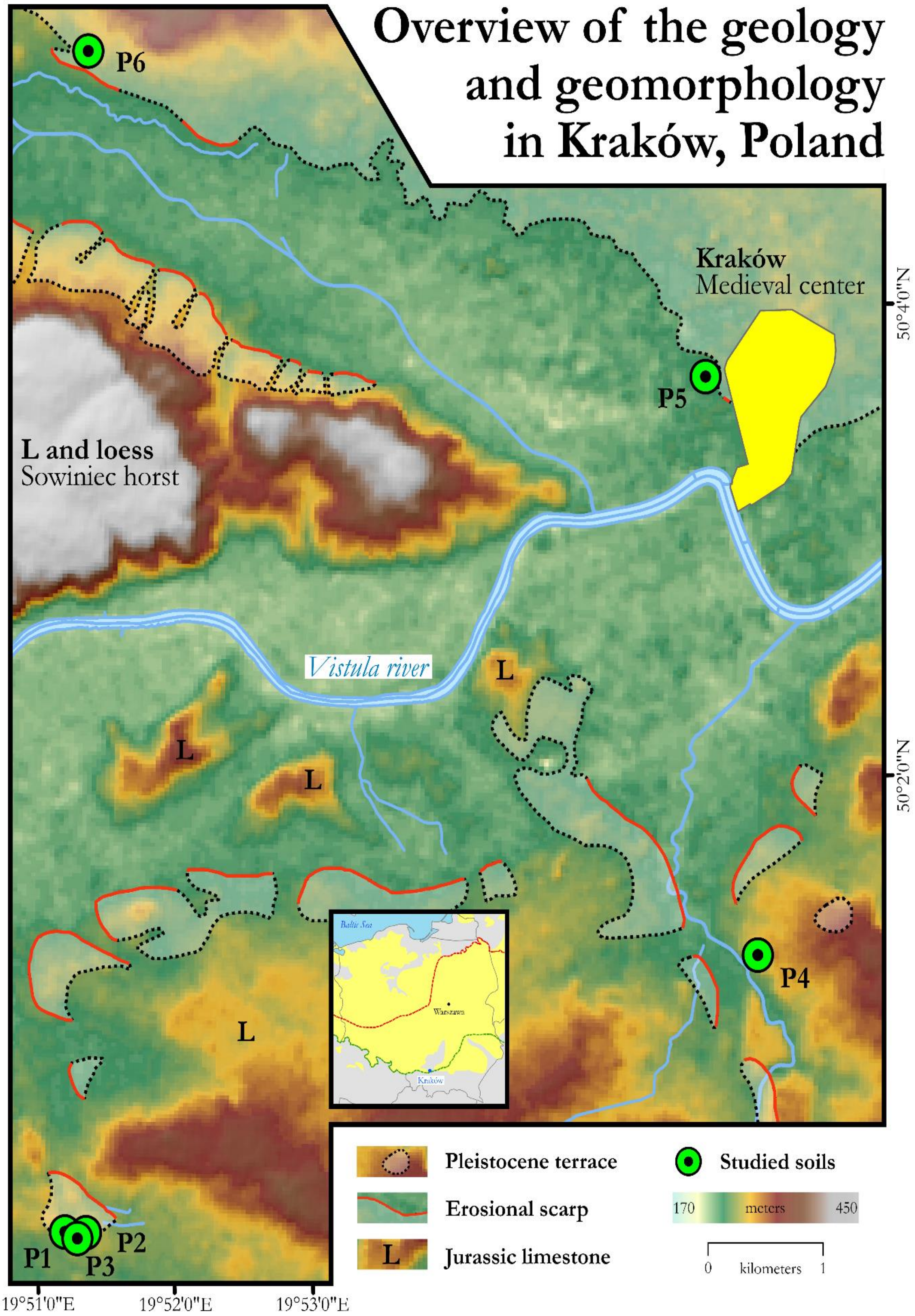

Figure 3.1. Geological and geomorphological setting of Kraków's western region. The Medieval walled city is marked as a yellow polygon. The Pleistocene terraces and their erosional scarps were modified from Łanczont et al. (2015a) and Urząd Miasta Krakowa (2010).

Oleksynowa et al. (1993). The pH was measured potentiometrically in a 1:2.5 (w/v) distilled water suspension and 1mol/dm^3 KCl (Lityński et al., 1976) using CPI-551 Elmetron pH-meter and standard combination electrode. For P5, the phosphorous content in the Mehlich-3 extract and base saturation were analyzed. The data was managed through Origin 2019b and R 3.3.0+, the maps were constructed on the ArcGIS 10.3.1 suite, and the figures were developed on Inkscape 1.2.2.

Table 3.1. Synthesis of the studied soils.

Soil Profile	Location			Slope (°)	Parent Material	Vegetation
	North	East	Elevation			
P1	50°0’1.2”	19°51’10”	220	3	UE2	WT
P2	49°59’60”	19°51’16”	216	2	UE2	WT
P3	50°00’0.1”	19°51’20”	239	5	UE2	WT
P4	50°01’14”	19°56’12”	229	1	UA1/UE2	WS
P5	50°03’41”	19°55’46”	206	1	UE2	WS
P6	50°05’02”	019°51’14”	221	8	UF1/UE2	NG

Abbreviation: UE2 - aeolian sand; UA1 - anthropogenic redeposited; UF1 - fluvial sand and gravel; WT - seasonally green trees mainly not planted; WS - seasonally green shrubs; NG - grasses.

4. RESULTS

4.1.Correlation analysis of selected properties

The three soils in less anthropized areas (P1, P2, and P3) are more texturally homogeneous than the soils in anthropized regions (P4, P5, and P6), showing a tendency to sand textures according to USDA (1987) and IUSS Working Group WRB (2022). Following the textural triangles proposed by PTG (2019), which considers deeper differentiations in the sandy fractions, the texture data for P1, P2, and P3 tends to vary. This way, it is noticeable the capacity of the Polish system to describe detailed the sandy soil textural classes more than the international systems, even though the U.S. system considers the same particle-size classes as shown in Fig. 2.1. The soils in anthropized areas present higher content of silt particles, especially the P4 with silt amounts as high as 45% in cultural layers with artefacts.

A correlation matrix was constructed to analyze the relationship between the sand content based on the Polish-U.S. and WRB systems and several other properties and categories for the studied soils. This way, Fig. 4.1 illustrates the intensity and direction of calculated Pearson correlation coefficients. Like this, the above-mentioned negative correlation between the content of sands and the presence of artefacts was proven and is even stronger marked with the Polish system category. In the same way, there is a negative correlation between sand content and anthropopressure, as this category includes the artefacts and location of the soil. Furthermore, it is detectable that the higher the sand, the higher the value (brightness) in soils. Other categories show slightly positive correlations with the sand content, such as chroma, the presence of lamellae, and podzolization processes.

Similarly, the matrix shows a robust negative correlation between roots and depth. Furthermore, as Gus-Stolarczyk et al. (2021) discussed, podzolization features generally occur at upper positions in the profile, while lamellae are found at lower positions. The lesser horizon thickness is negatively correlated to higher total organic carbon content, better soil structure, and the presence of roots. In contrast, the greater horizon thickness positively correlates to higher values and chroma and higher pH values. This information reveals that humus-rich horizons in the studied soils are generally shallow, directly affecting higher pH values.

Regarding the pH, it can be noticed in the matrix that the highest values occur in soils that have been anthropized and with artefacts. This way, physicochemical

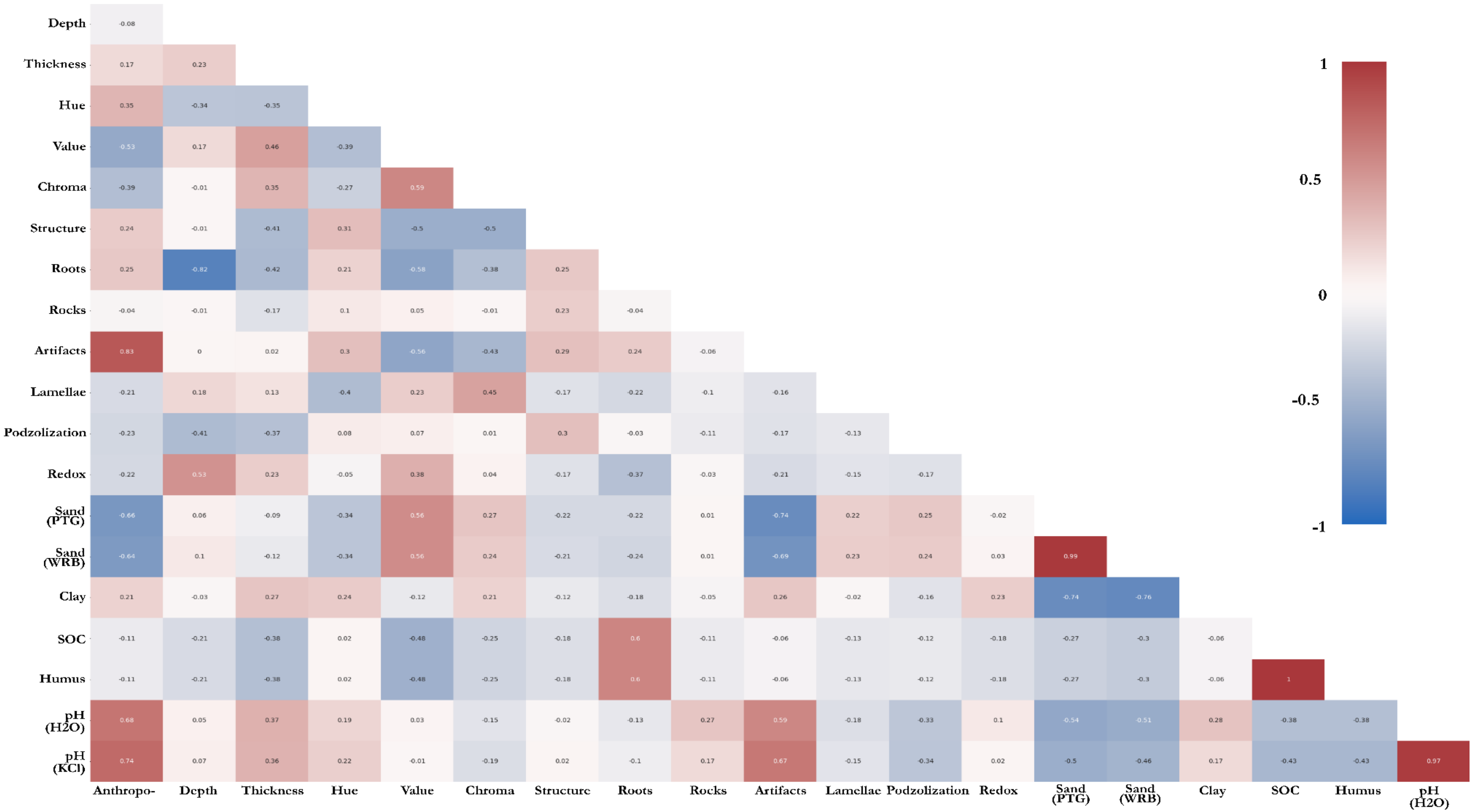

Figure 4.1. Correlation matrix evaluating several soil properties and categories for the soils studied. The redder, the greater the positive correlation between variables. The bluer, the greater the negative correlation.

changes between anthropized and non-anthropized sandy soils in Krakow are detected. Anthropized soils contain less sand, a lower pH, and darker colors. The less sand, the greater the presence of artefacts in the soils studied. Finally, artefacts are also positively correlated with clay, and negatively correlated with pH.

4.2. Description and basic properties of Profile 1 (P1)

Figure 4.2. Modified birch-oak forest

Figure 4.3. Soil profile 1, slightly podzolization on the top and redox on the bottom are visible

Morphology

Oe 6-0 cm, medium-decomposed organic material, 5YR 2/3, abrupt.

Ah 0-10 cm, sand, 10YR 5/3, granular, common roots, Fe concretions on the top, abrupt.

AE1 10-18 cm, sand, 10YR 5/4, weakly granular, common roots, clear.

AE2 18-26 cm, sand, 10YR 7/3, weakly granular, common roots, abrupt.

Bhs 26-42 cm, sand, 10YR 3/4, well-developed angular blocky, few roots, sesquioxide accumulations, AE2-horizon tongues, clear.

2Bw 42-68 cm, loamy sand, 10YR 5/6, subangular blocky, common roots, gradual.

2BC 68-91 cm, sand, 10YR 6/8, friable subangular blocky, common roots, gradual.

2Cg 91-(110) cm, sand, 2.5YR 7/6, single grain, few roots, redox processes.

P1 shows a medium-decomposed Oe organic horizon on top (Fig. 4.3), rich in carbon and around 160 g/kg (Fig. 4.5) and pH 4.0 (Fig. 4.6). An Ah horizon is found right below with a considerable decrease of total carbon reaching 12 g/kg. Iron accumulation is present at the top of the Ah horizon (Fig. 4.4) as subangular, reddish concretions. Slight podzolization processes are detected. Specifically, the AE1 and AE2 horizons present an increment in the sand (Fig. 4.7) and pH and a decrease in carbon, while the opposite occurs in the illuvial underlying Bhs.

Figure 4.4. Iron concretions, Ah horizon

There is a change in the origin of sands downwards the soil profile, which can be proven in Fig. 4.7. The coarse sands dominate for the 2Bw, 2BC, and 2Cg horizons, while the fine sands predominate in the upper horizons. The pH remains constant at 4.4 (Fig. 4.6) in water, while the total carbon goes down from 2.33 in 2Bw to 0.36 in 2Cg (Fig. 4.5).

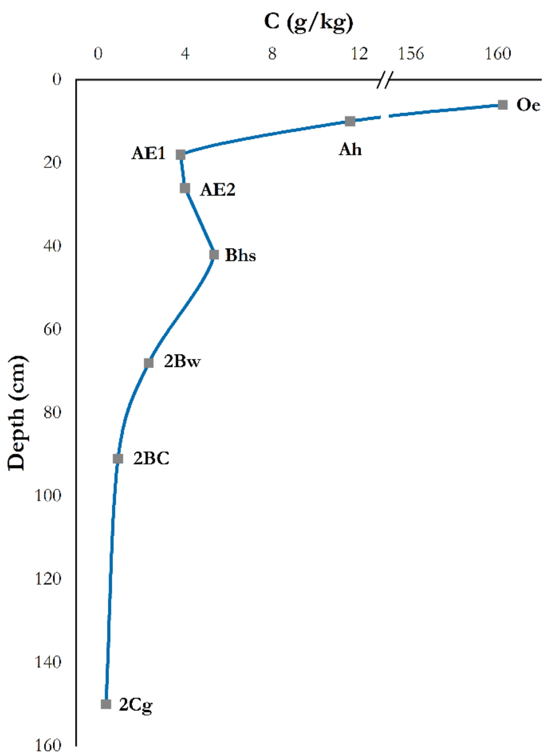

Figure 4.5. Total organic carbon for P1

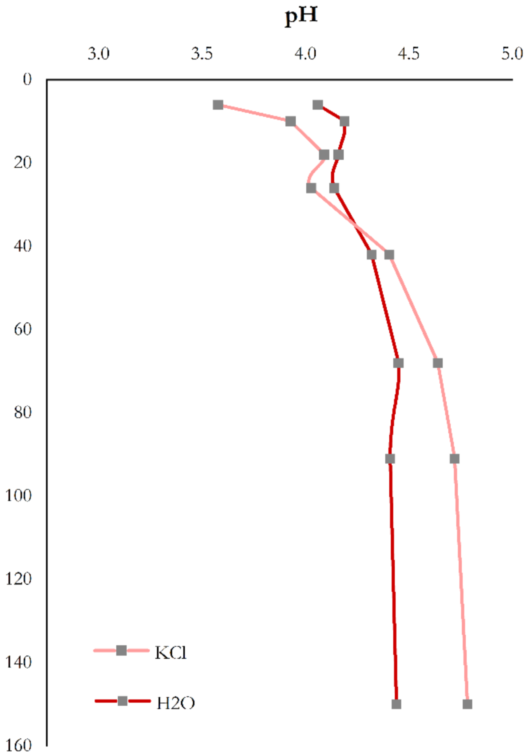

Figure 4.6. pH values for P1

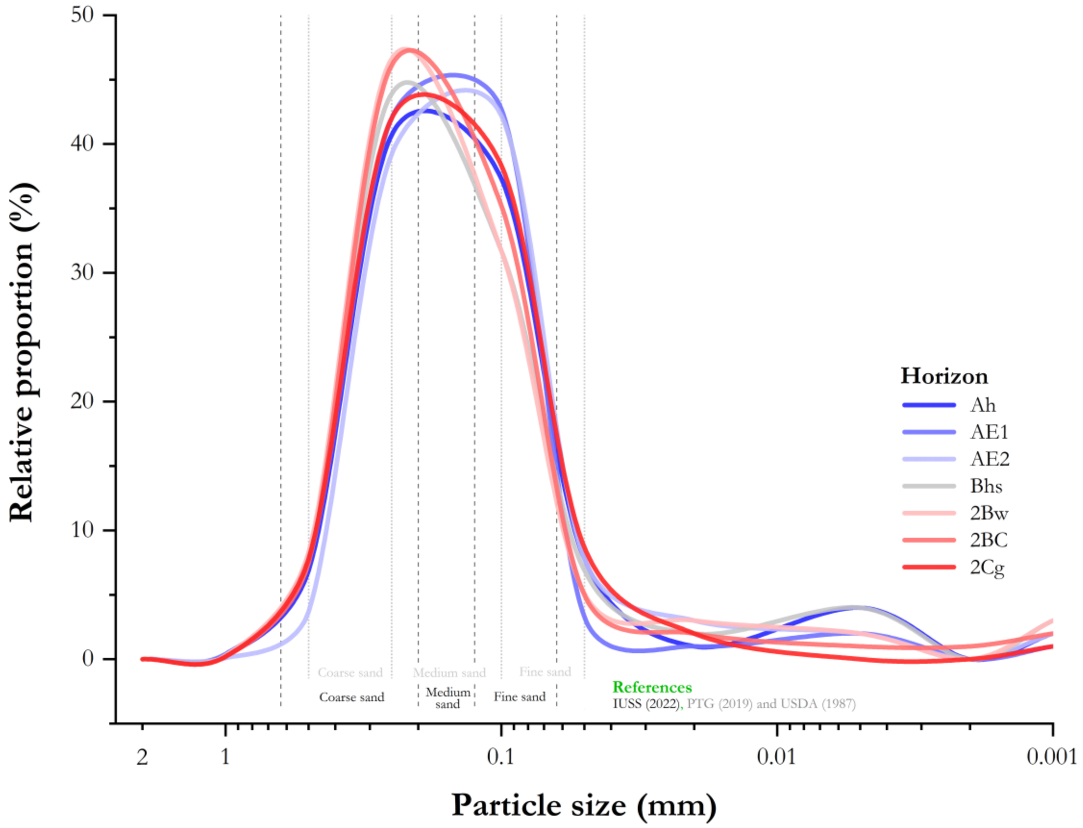

Figure 4.7. Soil particle size distribution for P1. The subclasses of sand are indicated according to USDA (1987); PTG (2019); and IUSS Working Group WRB (2022)

P1 can be considered polygenetic, in which aeolian deposits bury a Cambisol with slight podzolization. The buried soil is classified with preference as Eutric Chromic Endostagnic Cambisol (Arenic, Aeolic, Aeoli-Areninovic, Protospodic-Novic) according to (IUSS Working Group WRB, 2022), and a short explanation is given in Table 4.1.

Table 4.1. WRB (2022) based soil classification explanation for P1

A reason for naming P1	Key
Two pedogenetical cycles are detected, the buried soil is classified with preference as the overlaying soil is < 50 cm thick. Development of structure	*cambic horizon*
cambic horizon starting ≤ 50 from the buried mineral soil surface	Cambisol
stagnic properties starting below 50 cm	Endostagnic
low base saturation	Eutric

Table 4.1. *Continue*

A reason for naming P1	Key
sand and loamy sand texture in the whole buried soil	Arenic
sandy *aeolic material* in the overlying soil	Aeolic-Areninovic
aeolic material in the whole buried soil	Aeolic
spodic horizon and *claric material* in the overlying soil	Protospodic-Novic

4.3.Description and basic properties of Profile 2 (P2)

Figure 4.8. Modified birch-oak forest

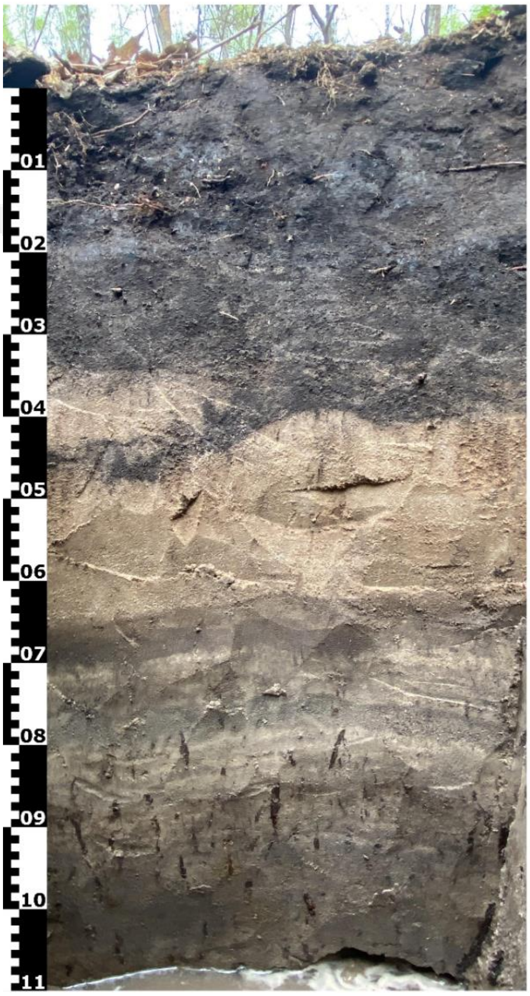

Figure 4.9. Soil profile 2, the redox conditions start at 67 cm, and water level is visible at 110 cm

Morphology

Oi 3-0 cm, rare-decomposed organic material, 7.5YR 2/3, abrupt.

Ah 0-23 cm, loamy sand, 7.5YR 2/1, granular, many roots, abrupt.

ABw 23-44 cm, sandy loam, 7.5YR 3/1, granular some angular blocky, common roots, gradual.

C 44-67 cm, sand, 10YR 6/4, single grain, none roots, clear.

2AEg 67-86 cm, sand, 2.5YR 5/2, granular, none roots, reduction mottles, clear.

2BCg 86-(110) cm, sand, 10YR 4/2, subangular blocky, none roots, reduction mottles, water level.

The P2 locates in a geomorphic micro-depression which allows the presence of a shallow Oi horizon as well as a 23-cm thick Ah horizon (Fig. 4.9) with around 98 g/kg of total organic carbon (Fig. 4.10) and low base saturation (pH ~ 3.5) (Fig. 4.11), underlaid by a finer (Fig. 4.12) and lighter transition to ABw and C horizons. This pedogenic cycle overlays former slightly podzolic soil represented by 2AEg and 2BCg, which have strong gleyic properties due to the present-day water level. The total organic carbon decreases the soil profile downwards with a slight increase of 2BCg, which supports the hypothesis of previous podzolization processes. Furthermore, an increase in the relative proportions of sands is detected for the buried soil, even though the parent material seems to have the same origin since the particle size pattern demonstrates a peak in coarse sands for all the horizons in the pedo-complex.

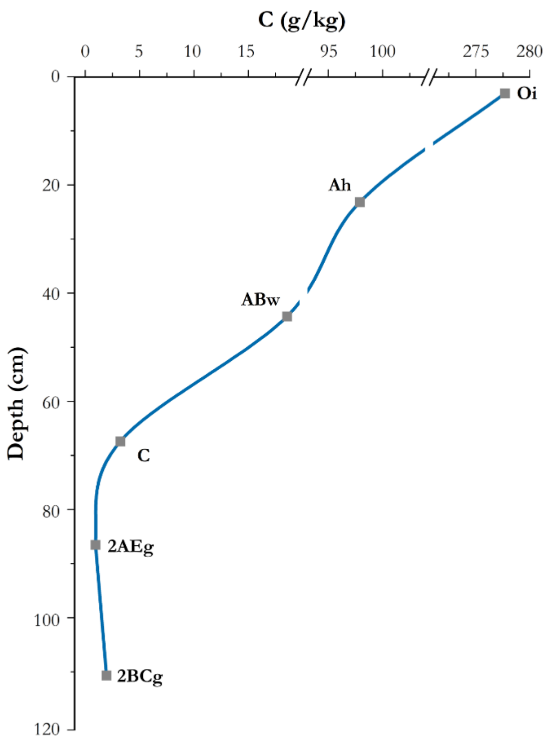

Figure 4.10. Total organic carbon for P2

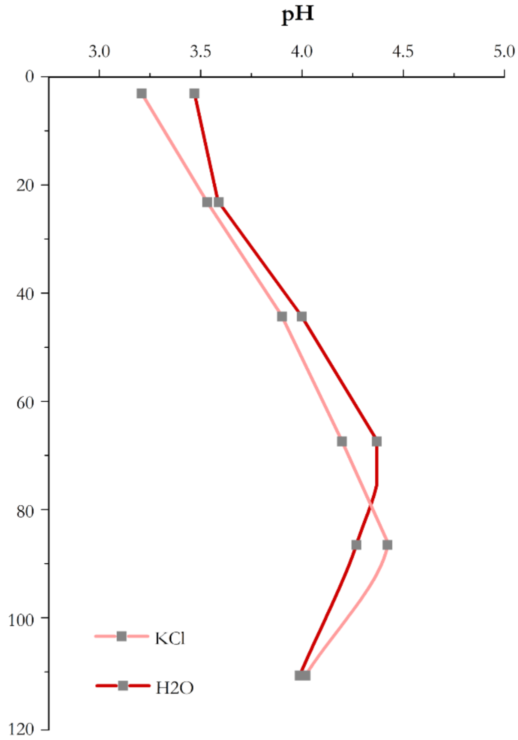

Figure 4.11. pH values for P2

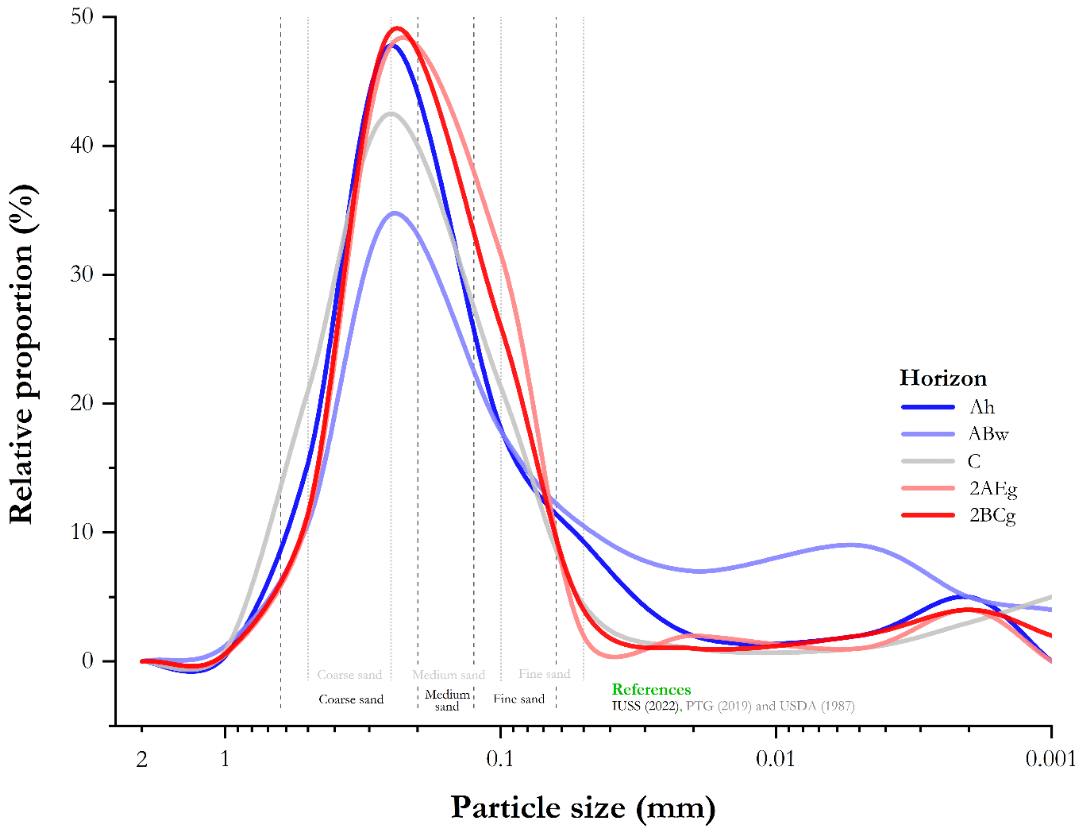

Figure 4.12. Soil particle size distribution for P2. The subclasses of sand are indicated according to USDA (1987); PTG (2019); and IUSS Working Group WRB (2022)

The P2 also presents polygenesis, digging into a pedo-complex idea as it comprises relict pedofeatures mixed with present-day soil-forming properties. In this case, thick umbric and cambic horizons compose a Umbrisol, which overlies an albic horizon. Gleyic processes occur on the bottom of the profile due to the geomorphic position, affecting the bottom of the buried soil with relict podzolization majorly. The topsoil is classified with preference as Endogleyic Cambic Umbrisol (Pantoarenic, Thaptoalbic, Pantoeutric, Humic) according to (IUSS Working Group WRB, 2022), and a short explanation is given in Table 4.2.

Table 1.2. WRB (2022) based soil classification explanation for P2

A reason for naming P2	Key
two pedogenetical cycles are detected, and the topsoil is classified with preference as it is more profound than 50 cm from the mineral soil surface. Low base saturation, high amount of total organic carbon, and both value and chroma < 3	*umbric horizon*
develpment of granular structure and color change	*cambic horizon*
umbric horizon	Umbrisol
reduction patterns starting at 67 cm	Endogleyic
cambic hrorizon	Cambic
sandy texture in the whole topsoil	Pantoarenic
a buried horizon with claric material and overlies a horizon enriched with illuvial organic matter	Thaptoalbic
acidic conditions in the whole topsoil	Pantoeutric
> 1% weighted average soil organic carbon in the first 50 cm from the mineral soil surface	Humic

4.4.Description and basic properties of Profile 3 (P3)

Figure 4.13. Modified birch-oak forest

Figure 4.14. Soil profile 3, lamellae are present from 66 cm to depth

Morphology

Oe 6-0 cm, medium-decomposed organic material, 2.5YR 2/2, clear.

Ah 0-18 cm, sand, 10YR 4/2, granular, few roots, clear.

E1 18-33 cm, sand, 2.5YR 5/6, single grain, very few roots, clear.

E2 33-39 cm, sand, 10YR 5/3, single grain, very few roots, clear.

Bhs 39-57 cm, sand, 10YR 4/6, granular, very few roots, sesquioxide accumulation, clear.

2C1 57-66 cm, sand, 2.5YR 6/8, single grain, very few roots, lamellae, gradual.

2C2 66-93 cm, sand, 2.5YR 6/6, single grain, very few roots, lamellae, gradual.

2C3 93-(140) cm, sand, 2.5YR 6/6, single grain, very few roots, lamellae.

P3 presents slightly podzolization processes, similar to P1 and the buried soil in P2. Notably, P3 differs in having lamellae starting at 57 cm downwards the profile. Furthermore, at 57 cm depth, there is a change in the particle size pattern into finer sands. In this way, the podzolic-like topsoil texture mainly comprises coarse sand. In contrast, fine sand dominates in the lower lamellae horizons (Fig. 4.17). The total organic carbon decreases to depth, having slight accumulation in the Bhs horizon due to organic carbon illuviation (Fig. 4.15). Consequently, a slight decrease in pH in the Bhs horizon is observed (Fig. 4.16).

P3 schematically shows two types of Fe-Al illuviation acting at different depths in the same soil profile. On the one hand, slight podzolization with eluvial (E1, E2) and illuvial (Bhs) horizons. On the other hand, lateral movement as a series of higher chromas thin layers (2C1, 2C2, 2C3).

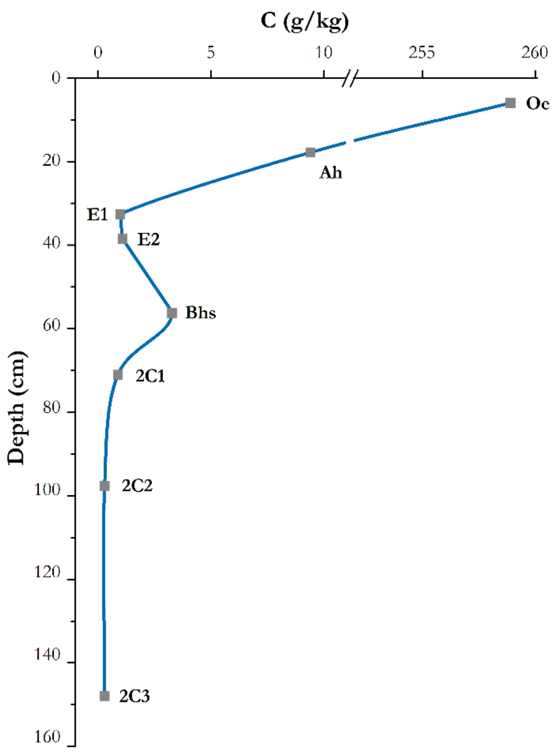

Figure 4.15. Total organic carbon for P3

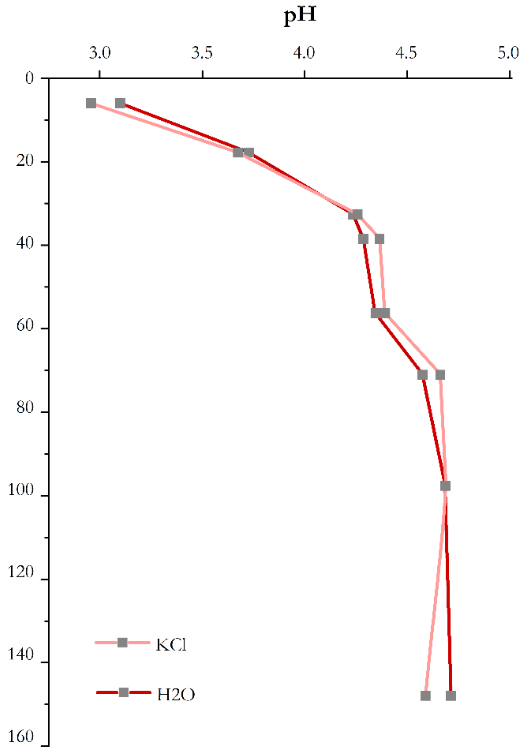

Figure 4.16. pH values for P3

P3 was classified as a whole, primarily considering its homogeneous sandy texture throughout the soil profile and both types of Fe-Al illuviation presenting. In this way, P3 corresponds to Eutric Pantoaeolic Arenosol (Endolamellic, Ochric, Endorubic, Amphiprotospodic) according to (IUSS Working Group WRB, 2022), and a short explanation is given in Table 4.3.

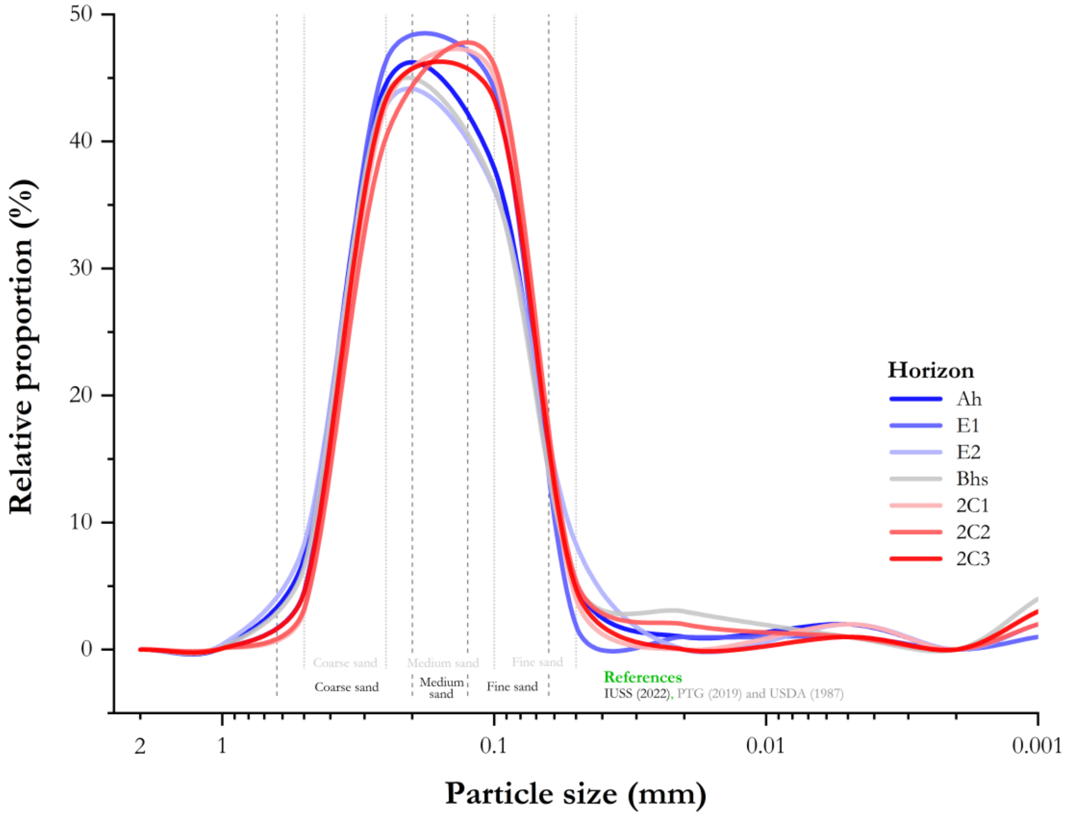

Figure 4.17. Particle size distribution for P3. It is noticeable a change into fine sands downward the profile. The subclasses of sand are indicated according to USDA (1987); PTG (2019); and IUSS Working Group WRB (2022)

Table 4.3. WRB (2022) based soil classification explanation for P3

A reason for naming P3	Key
a weighted average sandy texture within 100 cm of the mineral soil surface	Arenosol
aeolic material in the whole profile	Pantoaeolic
low base saturation	Eutric
having lamellae starting at 57 cm	Endolamellic
> 0.2% soil organic carbon in the upper 10 cm of the mineral soil	Ochric
a package of sand that does not consist of *claric material* with a chroma ≥ 5 starting at 57 cm	Endorubic
claric material in the eluvial horizons overlying a *spodic*(-like) *horizon* from 39 to 57 cm	Amphiprotospodic

4.5.Description and basic properties of Profile 4 (P4)

Figure 4.18. Urban Garden

Figure 4.19. Soil profile 4, urban garden soil with strong redox on the bottom

Morphology

Au 0-24 cm, loamy sand, 10YR 3/1, granular, common roots, abrupt.

2Bw 24-72 cm, loamy sand, 10YR 4/6, subangular blocky, few roots, clear.

2C 72-115 cm, sand, 10YR 7/4, single grain, none roots, clear.

3Cg 115-(144) cm, loam, 10YR 6/8 – 5Y 7/2, massive, none roots, redox conditions.

P4 is found in an urban garden in modern Kraków (Fig. 4.18). This way, the anthropic factor pressures stronger P4 than the previous soils discussed (P1, P2, P3). P4 shows a strongly human-modified upper horizon (Au) rich in organic carbon (Fig. 4.20), increased in silty particles (Fig. 4.22), and an abrupt lower boundary evidencing human disturbance (Fig. 4.19). Right below, 2Bw presents a subangular blocky structure. At the same time, 2C mainly consists of loose sands. The particle size pattern in the 3Cg horizon expresses a change in the parent material, composed of a finer texture with almost 24% of clay. The total organic carbon content and pH act according to depth; while the total organic carbon content decreases, the pH increases. Nevertheless, the 3Cg horizon decreases to pH 6.6 (Fig. 4.21).

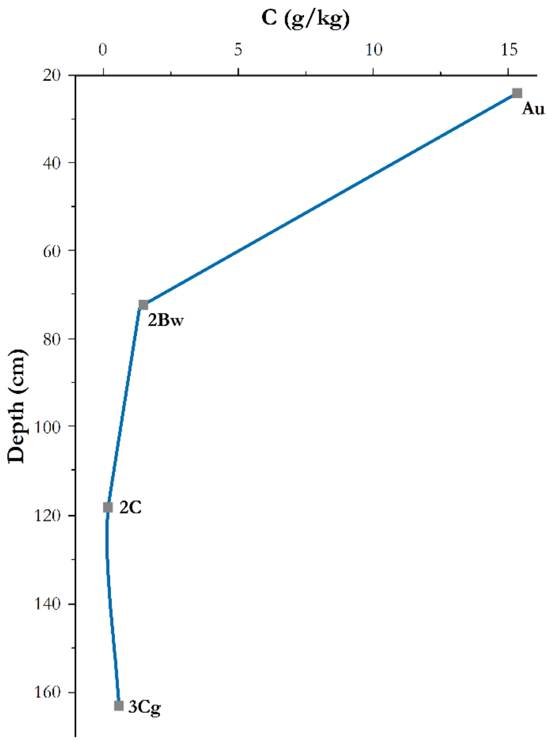

Figure 4.20. Total organic carbon for P4

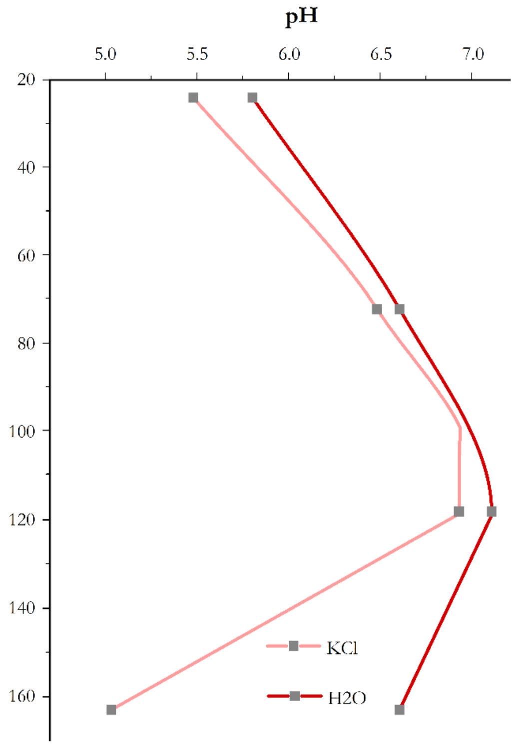

Figure 4.21. pH values for P4

The 24-cm thick Ah horizon fulfills the requirements for a Mollic horizon which in turn drives into a Phaeozem. Furthermore, the human-modified Mollic is highlighted through Anthric properties. In this way, the P4 was classified as Amphicambic Bathystagnic Phaeozem (Pantoarenic, Bathyloamic, Anthric, Amphichromic) according to (IUSS Working Group WRB, 2022), and a short explanation is given in Table 4.4.

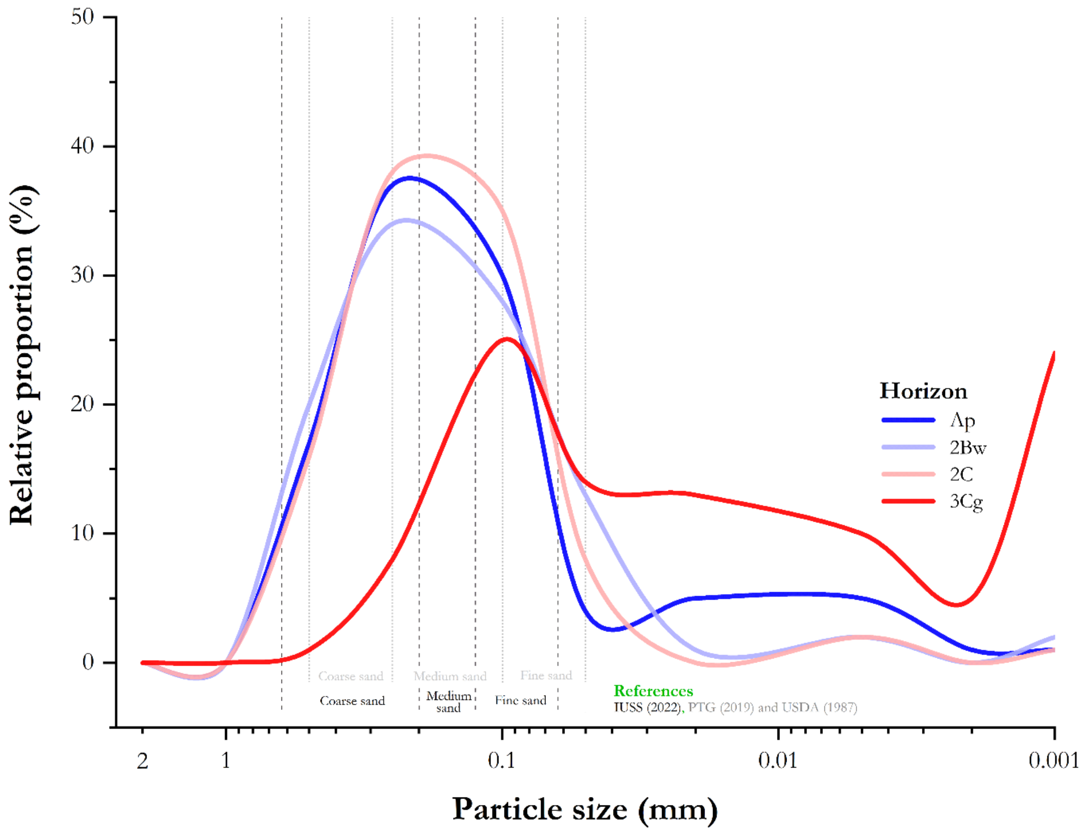

Figure 4.22. Particle size distribution for P4. It is noticeable a change into a finer texture in the lowest horizon (3Cg). The subclasses of sand are indicated according to USDA (1987); PTG (2019); and IUSS Working Group WRB (2022)

Table 4.4. WRB (2022) based soil classification explanation for P4

A reason for naming P4	Key
a mineral surface horizon consisting of > 0.6 organic carbon and a base saturation of ≥ 50%	*mollic horizon*
development of soil structure in a subsurface horizon	*cambic horizon*
mollic horizon and a base saturation ≥ 50% through to a depth of 100 cm	Phaeozem
cambic horizon from 24 to 72 cm	Amphicambic
stagnic properties in a layer starting below 100 cm	Bathystagnic
sandy texture through to a depth of 100 cm	Pantoarenic
loamy texture in a layer starting below 100 cm	Bathyloamic
anthric properties in the Mollic horizon	Anthric
cambic horizon redder than 7.5YR and a chroma > 4	Amphichromic

4.6.Description and basic properties of Profile 5 (P5)

Figure 4.23. Urban Garden

Figure 4.24. Soil profile 5, several artifact- and humus-rich layers in an urban garden

Morphology

Auα1 0-14 cm, sandy loam, 10YR 2/1, granular, 3% coarse fragments (bricks and plaster), abundant roots, clear. P: 556.5 mg kg^{-1}.

Auα2 14-35 cm, sandy loam, 10YR 2/1, granular, 3% coarse fragments (bricks, plaster, and ceramics), abundant roots, gradual. P: 545.4 mg kg^{-1}.

Au 35-60 cm, sandy loam, 10YR 2/2, granular, 3% coarse fragments (bricks, ceramics, and bones), few roots, gradual. P: 740.4 mg kg^{-1}.

Auα3 60-90 cm, sandy loam, 10YR 2/2, granular, 1% coarse fragments (bricks, plaster, and bones), none roots, gradual. P: 828.0 mg kg^{-1}.

2Auα1 90-120 cm, sandy loam, 10YR 2/2, granular, 1% coarse fragments (bricks, carbon, silex, bones, and plaster), none roots, gradual. P: 1,051.1 mg kg^{-1}.

2Auα2 120-151 cm, sandy loam, 10YR 2/2, granular, 1% coarse fragments (bones and plaster), none roots, clear. P: 915.9 mg kg^{-1}.

3AC 151-164 cm, sand, 10YR 5/4, single grain, none roots, redox mottles, clear. P: 190.4 mg kg^{-1}.

P5 represents a set of pedo-cultural layers near Kraków's old town, which includes the accumulation of organic-enriched blackish horizons with several artefacts such as bones, bricks, silex, ceramics, and plaster[1]. Among the main differences, it is distinguished three human-soil cycles, based on the changes in total organic carbon (Fig. 4.25), pH (Fig. 4.26), and particle size (Fig. 4.27). The first cycle is composed of loamy textures, which can be understood as the addition of finer particles by humans in a sand-dominated environment (Fig. 4.27) and a progressive decrease in organic carbon to depth (Fig. 4.25). Additionally, even though the first cycle includes artefacts in all the subhorizons, their nature changes. Specifically, the Au horizon does not include plaster residues, which confers the α suffix symbol to the other horizons indicating the presence of primary carbonates.

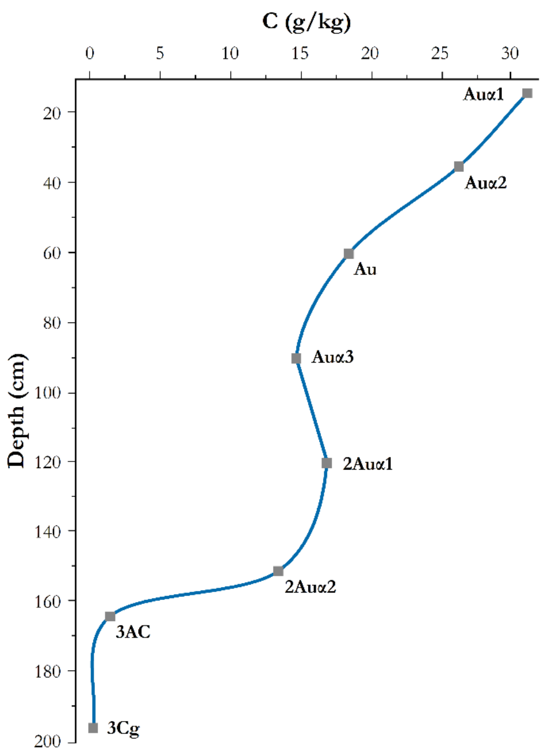

Figure 4.25. Total organic carbon for P5

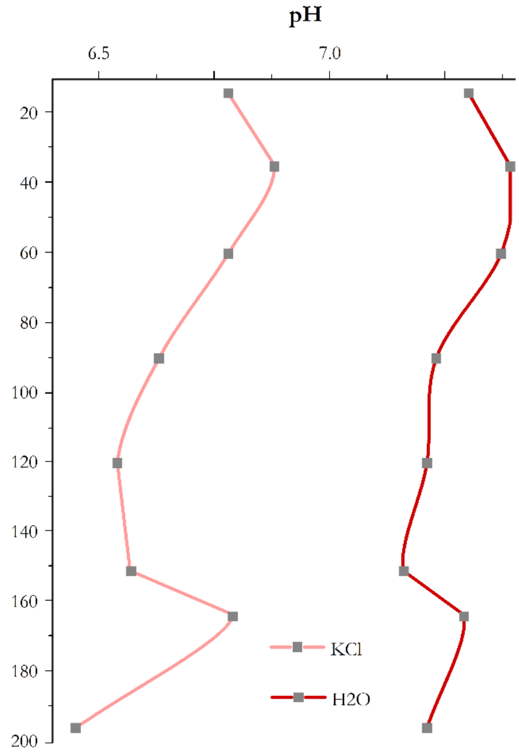

Figure 4.26. pH values for P5

The second cycle maintains a human-modified behavior with a loamy texture (Fig. 4.27), but a slight increase in total organic carbon (2Auα1) which later decreases to depth (2Auα2) (Fig. 4.25). The third cycle can be considered as the unmodified

[1] Residues of lime-based mortar, *calcaric material*.

basement rich in late Quaternary aeolian coarse sands which was later arrived by human settlements. Then the genesis of the human-soil cycles started. Considering this information, P5 was classified as Bathygleyic Hortic Anthrosol (Pantoloamic, Bathyarenic, Eutric, Polycalcaric), and a short explanation is given in Table 4.5.

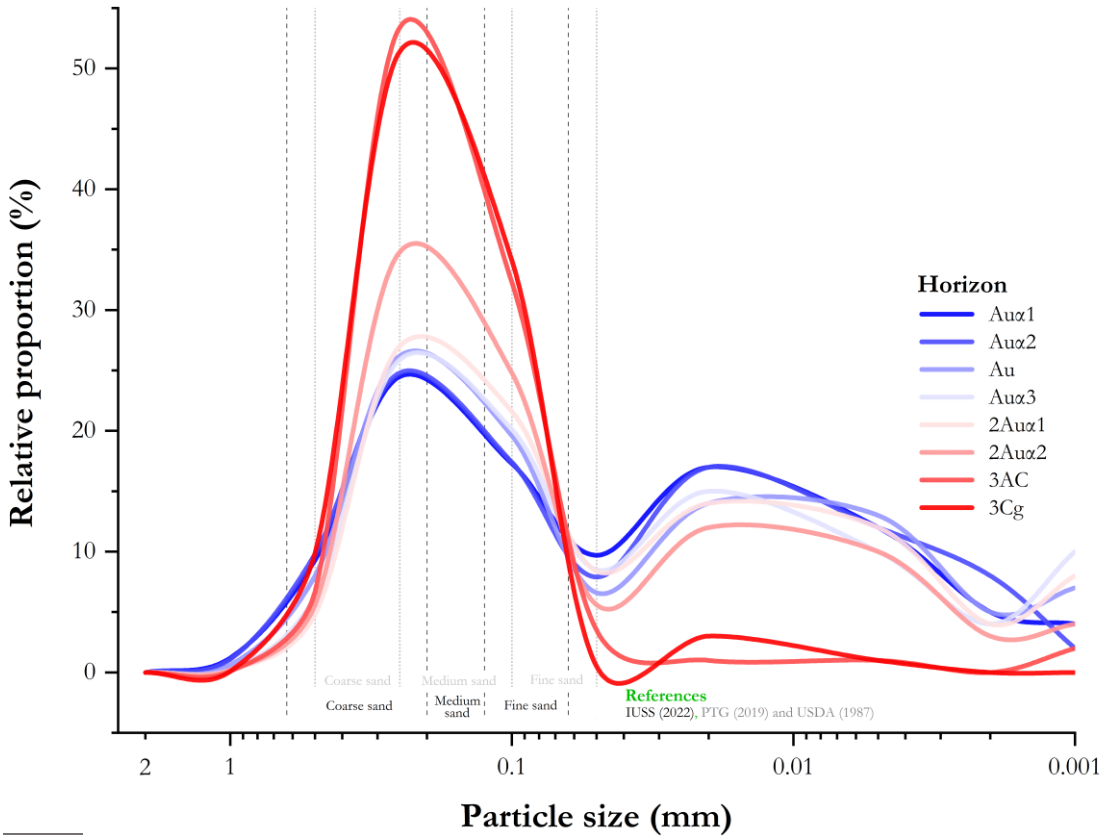

Figure 4.27. Particle size distribution for P5. It is noticeable an increase in silty particles for the upper first two soil-forming cycles while sandy particles dominate in the lower third cycle. Even though this change, the origin of sands seems to be the same as they show similar particle size patterns with a peak in coarse sand range. The subclasses of sand are indicated according to USDA (1987); PTG (2019); and IUSS Working Group WRB (2022)

Table 4.5. WRB (2022) based soil classification explanation for P5

A reason for naming P5	Key
a mineral surface horizon consisting of > 0.6 % organic carbon and a base saturation of≥ 50%	*mollic horizon*
a mineral surface horizon that shows evidence of material addition substantially different from the environment	*terric horizon*
a mineral surface horizon rich in phosphorous and with evidence of porous made by animals	*hortic horizon*
hortic horizon ≥ 50 cm thick	Anthrosol

Table 4.5. *Continue*

A reason for naming P5	Key
gleyic properties in a layer starting below 100 cm	Bathygleyic
loamy texture starting at the mineral soil surface to 151 cm	Pantoloamic
sandy texture in a layer starting below 100 cm	Bathyarenic
high base saturation	Eutric
calcaric material at two or more layers interrupted by other layers	Polycalcaric

4.7.Description and basic properties of Profile 6 (P6)

Figure 4.28. Arable land

Figure 4.29. Soil profile 6, formerly ploughed soil, with alluvial primary carbonates and stagnic properties from 78 to 118 cm

Morphology

Ap 0-22 cm, loamy sand, 10YR 3/2, granular, 1% coarse fragments (small pieces of bricks, 0.5 cm), abundant roots, clear.

ACα 22-29 cm, loamy sand, 10YR 4/3, granular, 60% stony (10-cm rounded stones), common roots, clear.

2BCα 29-38 cm, sand, 10YR 5/4, subangular blocky, 60% stony (10-cm rounded stones), few roots, clear.

3C 38-78 cm, sand, 2.5YR 7/6, single grain, very few roots, abrupt.

4Cg 78-118 cm, sand, 10YR 5/6 – 2.5YR 7/6, single grain, very few roots, redox conditions, abrupt.

4Cα 118-(125) cm, alluvial primary carbonate stones.

The morphology of P6 shows two main features based on the human impact and parent material. First of all, a 22-cm thick ploughed horizon with granular structure and a chroma ≤ 3, but not enough total organic carbon to be considered as a diagnostic horizon (Fig. 4.30). Second, a combination of two parent material sources, including aeolian sands and fluvial stones mainly composed of rounded limestones and cryptocrystalline quartz. The fluvial sedimentation is recorded primarily in two episodes in 2BCα and 4Cα. Furthermore, there are changes in the particle size pattern of the sands along the profile. While the upper Ap and ACα horizons mark a similar peak tendency in medium sand, 2BCα is tiny right-turned into fine sand, 3C oppositely is a little left-turned into coarse sand, and 4Cg overlaps the 2BCα pattern (Fig. 4.32). In general, the changes in sandy particle sizes and the alluvial depositions could be understood as a continuous reassemble of parent material sources and alternate aqueous-aeolian (paleo-)environmental setting.

The total organic carbon and pH show tendencies to decrease (Fig. 4.30) and slightly increase downwards (Fig. 4.31), respectively.

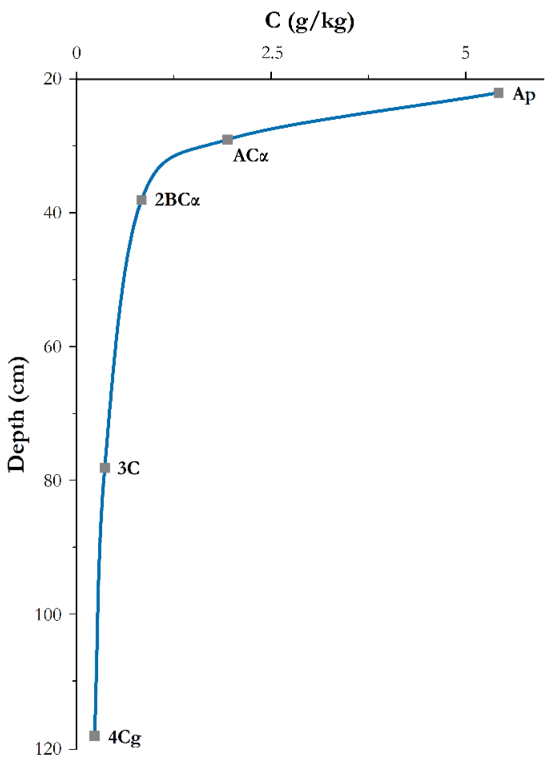

Figure 4.30. Total organic carbon for P6

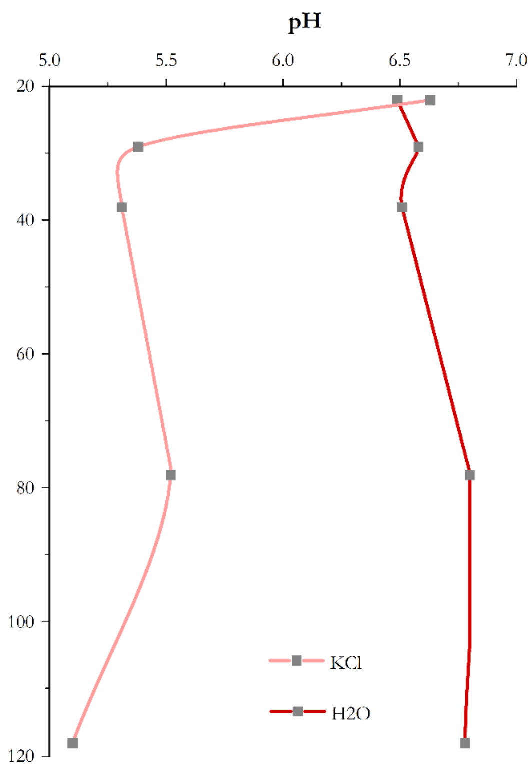

Figure 4.31. pH values for P6

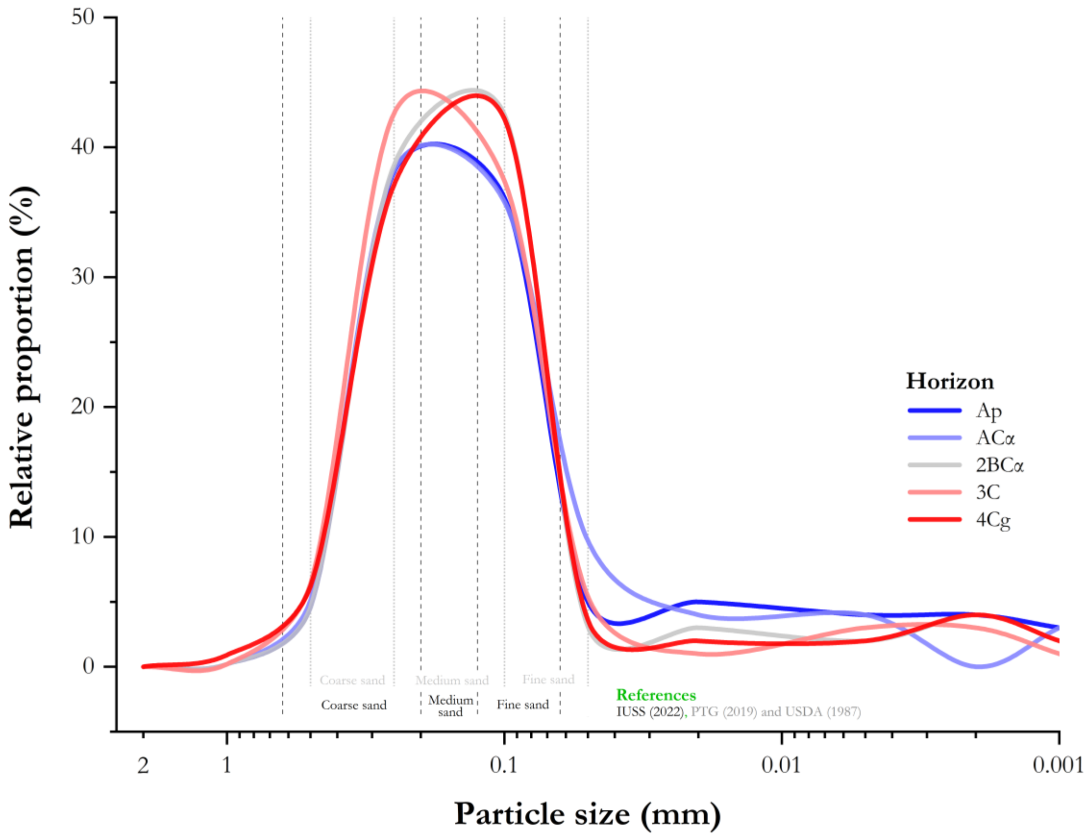

Figure 4.32. Particle size distribution for P6. It is noticeable changes in the peak patterns along the horizons which could the theory of a continuous reassemble of parent material sources.

P6 does not show evidence of buried soils, even though an active sedimentary environment probably did not allow the formation of soils in the past due to rapid rate changes of sedimentation sources. In the same way, continuous sedimentation processes have yet to promote the development of diagnostic horizons. Even so, P6 is a whole body in the present-day soil-forming process. P6 was classified as Polycalcaric Polyaeolic Arenosol (Ochric, Endostagnic), and a short explanation is given in Table 4.6.

Table 4.6. WRB (2022) based soil classification explanation for P6

A reason for naming P6	Key
a weighted average sandy texture within 100 cm of the mineral soil surface	Arenosol
calcaric material at two or more layers interrupted by other layers	Polycalcaric
aeolic material at two or more layers interrupted by other layers	Polyaeolic
> 0.2% soil organic carbon in the upper 10 cm of the mineral soil	Ochric
stagnic properties starting at 78 cm	Endostagnic

5. DISCUSSION

5.1.The role of parent material in soil formation in Kraków

The terrestrial archives from the late Quaternary have been extensively studied worldwide (Ibarra Arzave et al., 2018; Shalom et al., 2020; Sheinkman et al., 2023) as they offer pedological and ecological information which can be used to decode complex human-nature relationships (Jankowski et al., 2023). Indeed, the geography of Poland provides a unique laboratory for Quaternary studies as most of its vast territory was affected by the Scandinavian ice-sheet migrations during the last millennia (Fig. 2.2), and after melting it contributed to the so-called Younger Dryas (Firestone et al., 2007). The environmental changes during this period reshaped the lowlands in Poland with large aeolian inland sand deposit fields referred to as the European Sand Belt (Hilgers, 2007; Tolksdorf and Kaiser, 2012; Bertran et al., 2021), covering more than half of the country (Pierik et al., 2018; Łopuch et al., 2023).

Kraków stands out as one of the most southern regions in Europe and Poland greatly influenced by the drift-sand geomorphological phenomenon (Hilgers, 2007; Pierik et al., 2018; Łopuch et al., 2023). The spatial pattern of the Belt was analyzed, and a map was developed to identify the location of Kraków in a regional understanding. This map as shown in Fig. 2.2 also indicates the southward extent of ice sheets during the Pleistocene, and it helps to refer to Kraków at the border extent. Certainly, the aeolian phenomena have conditioned the geographical attributes of this region over time, being soils an interesting proxy to analyze.

In this way, the thesis focuses on exploring the sandy soils in Kraków, and special attention was driven to examining the soil particle size distribution and texture according to the Polish Classification and the international guidelines (USDA, 1987; PTG, 2019; IUSS Working Group WRB, 2022). It was found that PTG (2009) demonstrates more delicate categories for the sandy soil textures than USDA (1987) and IUSS Working Group WRB (2022). Despite the differences in the sand-silt limit, all the systems detected changes in the particle size patterns of sand subclasses. This information supported the idea of new parent material addition during active aeolian sedimentation processes and even highlighted the human impact in the long-term anthropized soils. Based on the results, the soils studied are divided into unmodified and human-modified groups and were settled in a catena model (Fig. 5.1).

The unmodified group composed of P1, P2, and P3 exhibits variations in sandy particle distributions across the three profiles, likely resulting from sedimentation and the accumulation of organic matter. P2 seems to settle in a micro-depression topographically, while P1 and P3 occupy the highest positions (Table 3.1). It is pertinent to note that the three soils have undergone two reactivations of their parent material, with possible differences in their source based on the particle size patterns. The particles vary from fine sands to coarse sands between the upper and lower parts of P1 (Fig. 4.7), while the opposite holds for P2 (Fig. 4.17). Lastly, P3 also demonstrates two reactivations but the patterns drive to only one peak in coarse sand with finer particles in the Ah and ABw horizons (Fig. 4.12), mainly related to organic matter accumulation and incipient illuviation, respectively.

Additionally, the human-modified soils are found in urban gardens (P4 and P5) and agricultural lands (P6). It is worth noting that P5 is located within an old granary that now serves as a museum. In this way, P5 exhibits loamy pedo-cultural layers due to long-term gardening activities, overlaying a sandy package that can be dated back to the 17th century when the granary was constructed. P4 presents wavy patterns in its particle size distribution, with the 3Cg horizon leaning towards fine sand and increasing clay particles. The textural contrast of sands overlying clay-rich horizons has been reported in Poland as the effect of sandy deposits covering loamy materials and glacial tills (M. Świtoniak, 2022). Finally, P6 has experience episodes of fluvial-aeolian deposits that have halted the development of diagnostic horizons.

The categorization of soils into two different groups provides insight into the intricate relationship between humans and the environment. As demonstrated in Fig. 5.1, the catena model can be used to depict the relative impact of human activity on the landscape and the distribution of sand particles. This model highlights the fact that in the sandy landscape of Kraków, anthropogenic factor plays a significant role in reducing the amount of sand present in soils, as evidenced by the P5 – Hortic Anthrosol. Additionally, specific positions within the landscape that accumulate organic matter and illuviation can also contribute to a decrease in sand particles, as seen in P2 – Umbrisol (Thaptoalbic). On the other hand, a change in the underlying parent material can result in a completely different soil texture, as demonstrated by P4 – Phaeozem (Anthric).

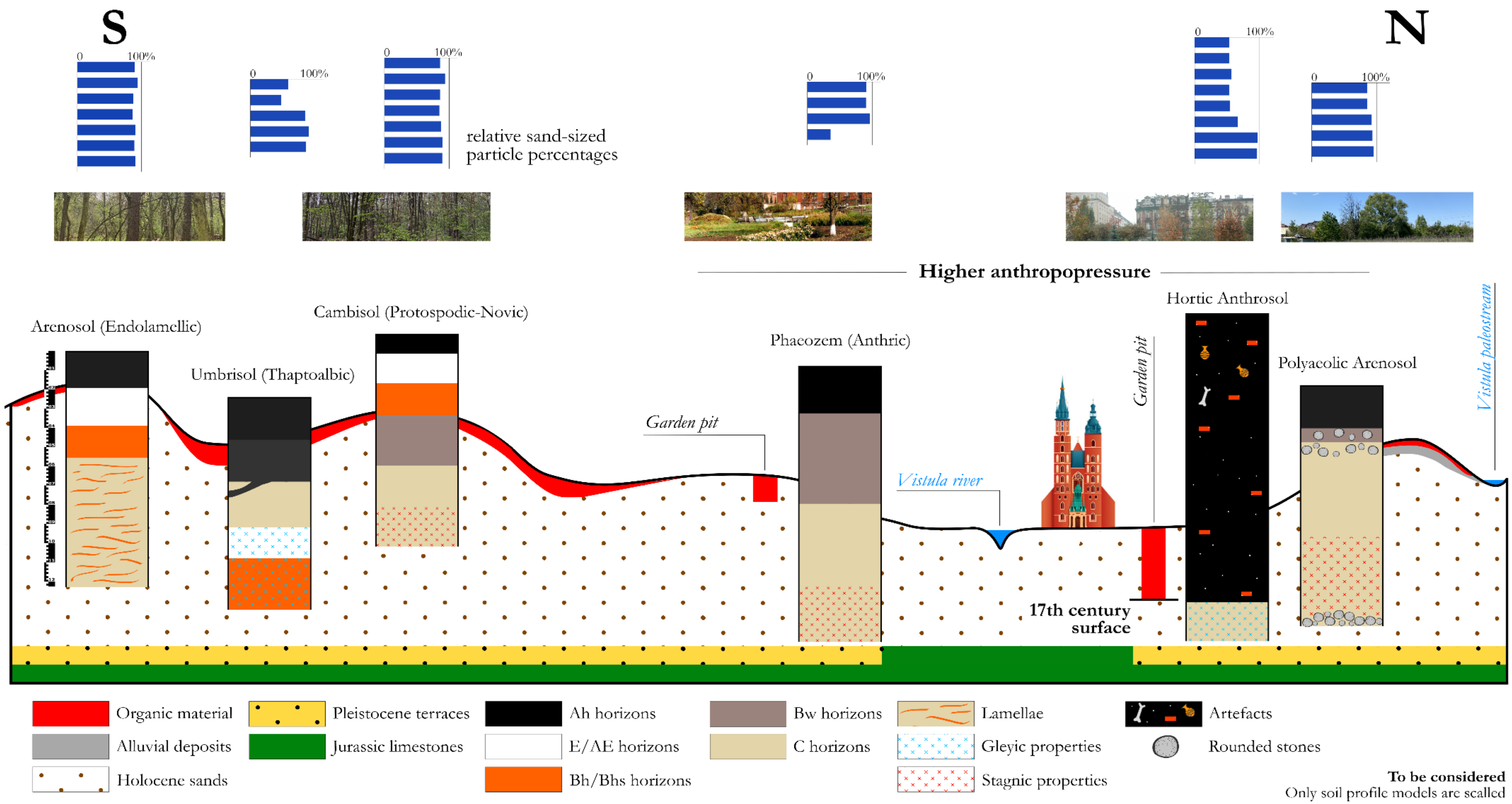

Figure 5.1. Comprehensive catena model describing the main characteristic of the studied soils and a short name based on its WRB (2022) classification

This way, the role of parent material in Kraków and the diversity of sand distribution within soils is a topic of great interest, influenced by several factors including specific positions in the landscape, organic matter accumulation, human activity, underlying materials, and alterations in sand sources or changes in mechanical resistance by sand abrasion during aeolian erosion and sedimentation processes. The impact of these variables on the landscape can give rise to complex human-nature relationship features within the soil body (Targulian and Bronnikova, 2019). Classifying these relationships can present challenges that require careful consideration, especially in garden soils (Charzyński et al., 2018) and with podzolization processes (Jankowski, 2014).

5.2. Pedogenetic processes detected and classification issues

Within the study area, a diverse array of soil-forming processes was detected. These processes include changes in color, the illuviation of organic matter and Al, oxidation-reduction, and human transformations. Notably, aeolian materials were found to have a significant impact on all the soils in the area. Additionally, P6 showed evidence of fluvial episodes, which resulted in the deposition of rounded quartz and limestones. These findings provide valuable insights into the complex soil-forming processes of the area, especially when considered along with the role of the parent material discussed in Chapter 5.1. The soils studied were classified according to IUSS Working Group WRB (2022) as Anthrosols (P5), Phaeozems (P4), Umbrisols (P2), Cambisols (P1), and Arenosols (P3, P6).

Based on the available information discussed, it appears that P1 exhibits polygenetic characteristics with slight podzolization processes and a *cambic horizon* at a lower depth. The change in parent material is primarily supported by the particle size distribution (Fig. 4.7), where a former Cambisol developed by fine sands is now overlaid by a coarser sand layer measuring 42 cm in depth., which is currently undergoing protospodic conditions. According to the IUSS Working Group WRB (2022), the Cambisol is classified with preference since the overlying material is less than 50 cm in thickness.

Even though the Cambisol is preferentially classified in P1, the diagnostic attributes of the overlying material can be described with the Novi qualifier. Therefore, the proposed classification is Eutric Endostagnic Cambisol (Arenic, Aeolic, Aeoli-Areninovic, Prospodic-Novic), indicating that a Cambisol that developed from aeolian sands presents stagnic properties below 50 cm from the mineral surface (of the Cambisol) and a high base saturation. In other words, the Cambisol is buried by a new aeolian sand deposit, which is currently undergoing initial podzolization.

P2 is certainly complex to describe, two main theories could explain this soil. The first theory, called *lateral podzolization* suggests that organic matter and Al are laterally illuviated from higher geomorphic positions to lower ones in geomorphic catchments (Sommer et al., 2001; Jankowski, 2014; Bailey et al., 2019). The second theory run in this research proposes the existence of a pedocomplex with three attributes of polygenesis, explain as follows. A granular structure is reported at a depth of 67-86 cm (Fig. 4.9), indicating a former superficial A horizon mixed with light-colored coarse sands, followed in depth by a horizon increased in organic carbon and darker colors (1). However, these properties are overshadowed by present-day reduction conditions (2). Additionally, a single grain and thick A-darkened horizons are overlying (3).

Assuming the existence of a buried soil with slight podzolization that is currently affected by upward water level, the pedocomplex can be classified as Endogleyic Cambic Umbrisol (Pantoarenic, Thaptoalbic, Pantoeutric, Humic). This classification indicates the presence of both *umbric* and *cambic horizons*, conforming to a Umbrisol with *gleyic properties* at the bottom. The texture is completely sand with high base saturation and organic carbon > 1% at a depth of 50 cm, and this soil is overlying an *albic horizon*. Overall, P2 is an intriguing pedocomplex that requires careful consideration and analysis.

P3 displays a slight podzolization behavior and exhibits illuvial lateral bands known as lamellae, which have been extensively studied in Poland and more recently in Kraków (Gus-Stolarczyk et al., 2021, 2022). Due to its strong sandy character and the absence of diagnostic horizons, P3 is classified as an Arenosol by the IUSS Working Groups WRB (2022). The WRB2022 considers the constant addition of alluvial/aeolian materials as part of the genesis in Arenosols. Furthermore, even with a shift in the sands such as P1, incorporating the buried soil's idea is deemed unnecessary. As a result, P3 has been classified as Eutric Pantoaeolic Arenosol (Endolamellic, Ochric, Endorubic, Amphiprotospodic).

The genetic narrative of P3 is regionally correlated and is more effectively conveyed through Fig. 5.1. Essentially, it is an Arenosol fully developed by aeolian sands possessing a high base saturation and exhibiting lamellae and interlamellae characterized by chroma greater than 5 below a depth of 50 cm (Endolameic and Endorubic). The upper 10 cm of the mineral soil is rich in organic carbon with a content of more than 0.2% (Fig. 4.15) and displays slight podzolization at intermediate depths. This implies that both processes, lamellae and podzolization, take place in close proximity but at different depths (Gus-Stolarczyk et al., 2022). Podzolization manifests in the upper coarse sands, while lamellae are observed in the lower fine sands (Fig. 4.14 and 4.17).

Located in the modern city of Kraków (Fig. 4.18), P4 has undergone human disturbance and still retains an organic-rich superficial horizon. Furthermore, it shows the development of soil structure and change of color. As highlighted in Chapter 5.1., textural variation is evident in P4's profile, resulting from changes in the underlying parent material (Świtoniak, 2022). This, in turn, can promote stronger redox processes in the finer particles in contact with water. According to the IUSS Working Group WRB (2022), P4 is classified as an Amphicambic Bathystagnic Phaeozem (Pantoarenic, Bathyloamic, Anthric, Amphichromic). Indicating the presence of both *mollic* and *cambic horizons* developed from sand deposits that extend deeper than 100 cm (Fig. 4.19). Human activity has abruptly impacted the boundary between both horizons, and the *cambic* horizon is associated with the reddish colors visible at intermediate depths. As above-mentioned, P4 still maintains its superficial Ah horizon which could act as a valuable pool of organic carbon in the urban environment.

A promising historical environmental feature was identified in P5 related to the rich settlement history of Kraków which dates to the Stone Age, according to Zaitz (2012). During the Jagiellonian reigns (1389-1596), Kraków flourished as a multi-ethnic metropolis within the *urbs Cracovia* (Fig. 5.2a). By the mid-16th century, the population had grown to 30,000 inhabitants, leading to the development of new settlements in the surrounding areas. These settlements had various purposes, including gardening, agriculture, and granary storage, especially in the western part of Kraków, as depicted in paintings from that time (Fig. 5.2b). The P5 is situated in a 17th-century granary, and a layer at a depth of 151 cm with no artefacts present, could indicate the contact layer (Fig. 4.24). Based on this, it appears that the 151-cm layer package with pedo-cultural characteristics has been formed by the gradual accumulation of silty materials over time by humans (Fig. 4.27). This observation

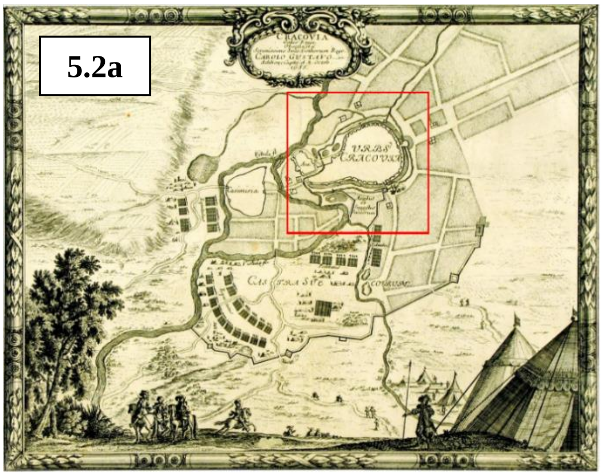

Figure 5.2a. *Upper left*, “The Swedish plan of the Siege of Krakow in 1655” by Samuel Pufendorf in 1969. Further explanation in Łopatecki and Krawczuk (2022)
Figure 5.2b. *Upper rigth*. Location of P5 wihin the historical map.
Figure 5.3. *Lower*, “Cracow and surroundings” by Georg Braun and Frans Hogenberg in 1617-1618

suggests a soil formation rate of 0.4 cm per year.

The P5 classification is notable for its seamless integration of various anthropogenic transformations including the addition of materials substantially different from the environment, phosphorous enrichment, and the presence of artefacts (Fig. 4.24). However, it is important to note that P5 meets the minimum P levels required by the IUSS Working Group WRB (2022) to fulfill the *hortic horizon*, it also satisfies the *terric horizon* requirement. As a result, P5 could be understood as another pedocomplex example but in an urban environment. It has been classified as Bathygleyic Hortic Anthrosol (Pantoloamic, Bathyarenic, Eutric, Polycalcaric). P5 is generally characterized as a loamy Anthrosol with high base saturation, and it features a continuous addition of materials that include primary carbonates. It is important to note that at a depth greater than 100 cm, there is a change in texture to sands with *gleyic properties* (Fig. 4.24).

The P6 sedimentary setting is unique as it exhibits fluvial deposits in two different episodes, interspersed with aeolian deposits (Fig. 4.29), Additionally, traces of human activity have been found in the form of small brick pieces within the upper horizon of this setting. The P6 was classified as Polycalcaric Polyaeolic Arenosol (Ochric, Endostagnic). Expressly, it explains the presence of an Arenosol with interrupted episodes of *aeolian* and *calcaric materials* deposition. Furthermore, it presents a minimum of 0.2 % organic carbon on the top and *stagnic properties* on the bottom.

6. CONCLUSIONS

- The Pleistocene terraces and Anthropocene gardens in Kraków revealed valuable information about pedological and ecological changes and the human-soil relationships.
- The detailed study of soil particle size distribution, especially sand subcategories using Polish and international systems helped to understand the environmental and historical changes memorized in soils.
- The studied soils were divided into unmodified and human-modified groups. The unmodified group differed in sandy particle distributions mainly due to aeolian sedimentation, while the human-modified group showed changes because of gardening activities.
- Pedogenetic processes detected in the study area included changes in color, illuviation of organic matter, oxidation-reduction, and human transformations. Furthermore, aeolian materials showed a significant impact on the soil formation processes.
- Each soil profile exhibited unique pedogenetic processes. For instance, P1 shows polygenetic characteristics with slight podzolization, P2 has (possible) ancient podzolization overshadowed by reduction conditions, P3 presents slight podzolization and lamellae at different depths, P4 exhibits human disturbance and changes in the underlying parent material, P5 displays a pedo-cultural set of layers resulting from almost four centuries of historical human activities, and P6 has mixed fluvial and aeolian deposits.
- The classification of these soils provided insight into the intricate relationship between humans and the environment, highlighting the impact of human activity and parent material. Additionally, the findings emphasize the need for careful consideration when classifying pedocomplexes in urban environments and areas with aeolian processes.
- Overall, the study contributes to understanding pedological processes and human-soil interactions in Kraków that can potentially be extended beyond the region into southern Poland and Central Europe.

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Publications :

1. Domínguez-Guillén, K.A., Solleiro-Rebolledo, E., Sedov, S., Golden, C., Scherer, A.K., and **Cerón-González, A.** (**2022**). Soil toposequence in the Busiljá Valley and its relationship with prehispanic anthropic activities (Chiapas, Mexico). In: Świtoniak, M. and Charzyński, P. (eds.), *Soil Sequences Atlas vol. 5*. Nicolaus Copernicus University. 45 – 53.
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3. Barajas-Alcalá, A.G., Olivares-Martínez, L.D. and **Cerón-González, A.** (**2022**). Estudio de los suelos. Camino recorrido de lo agronómico a lo ambiental. In: Urquijo, P., Lazos, A., and Lefebvre, K. (coords.), *Historia Ambiental de América Latina. Enfoques, procedimientos y cotidianeidades*. National Autonomous University of Mexico. 417 – 434.
4. **Cerón-González, A.** and Ibarrola-Rivas, M.J. (**2021**). Construyendo regiones: diversidad de suelos e interacción geoeconómica en la agroindustria de Sinaloa. In: Ávila, V. and González, T. (coords.), *Biodiversidad y Soberanías Alimentarías en América Latina*. German Academic Exchange Service. 115 – 130.
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Won Awards, Incentives and Scholarships

1. **International Union for Quaternary Research Fellowship 2023** (Rome, Italy)
2. **International Association of Geomorphologists Grant 2023** (Haifa, Israel)
3. **The FAO's King Bhumibol World Soil Day Award 2022** (Bangkok, Thailand)
4. **Vice-chairman 2022 - 2026**, International Union of Soil Sciences "Young and Early Career Scientists" Working Group (Vienna, Austria)
5. **International Union of Soil Sciences Grant 2022** (Glasgow, Scotland)
6. **International Union of Soil Sciences Grant 2022** (Querétaro, México)
7. **Vice-commissioner 2021 – 2023**, Mexican Soil Science Society "Youth Action" Commission (Mexico City, Mexico)
8. **Erasmus Mundus Joint Master's Degree Scholarship 2021** (Brussels, Belgium)
9. **3rd International Soil Judging Contest 2018** (Rio de Janeiro, Brazil), sponsored by the Rector of the National Autonomous University of Mexico