



soil sequences atlas V

edited by
Marcin Świtoniak
Przemysław Charzyński

WYDAWNICTWO NAUKOWE
UNIwersYTETU
MIKOŁAJA KOPERNIKA

SOIL
SEQUENCES
ATLAS
V

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EDITED BY
MARCIN ŚWITONIAK
PRZEMYSŁAW CHARZYŃSKI



TORUŃ 2022

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FOREWORD

The significant spatial variability of soil cover results from the diverse impacts of different soil-forming factors. This book presents pedovariability in the form of a collection of soil sequences typical of particular landscape types. The fifth part of the Soil Sequences Atlas contains description of 73 pedons (with soil profile photo, description of morphology and laboratory data) grouped into 15 chapters each representing a different environmental setting specific to very diverse regions from five continents – North and South America, Africa, Europe and Asia. The Atlas begins by presenting a pedo-landscapes from Americas – from Mexico to Peru. Next comes a group of chapters devoted to The Mediterranean Region – Spain, Italy, Slovenia and Tunisia. The next two chapters concern the soils of Central Europe – Hungary and Poland. At the end there are examples of steppe (Russian chernozems), semi-arid (Iran) and subtropical soils of Southeast Asia (Thailand). Out of 32 reference groups, as many as 17 are represented in the fifth part of atlas Soil Sequences Atlas. The most common soils are Calcisols (semi-arid areas) and the soils with clay illuviation (Luvisols) developed in very diverse environments.

The collected data is intended as a useful educational tool in teaching soil science, and in supporting an understanding of the reasons behind the variability of soil cover, and also as a WRB classification guideline. It is intended to be useful not only to students but also to practitioners in agriculture, forestry, environmental protection and landscape planning.

The Atlas was developed as part of the EU Erasmus+ SYStem project (Share Your Soils – Project No 2019-1-PL01-KA203-065101 Strategic Partnerships for higher education (KA203) of Erasmus+ programme of the European Union).

Marcin Świtoniak
Przemysław Charzyński

LIST OF ACRONYMS

Al_o – aluminium extracted by an acid ammonium oxalate solution
BD – bulk density
BS – base saturation
CEC – cation exchange capacity
COLE – The coefficient of linear extensibility
ECe – electrical conductivity of the saturated paste extract
EC – electrical conductivity
FAO – Food and Agriculture Organization of the United Nations
Fe_d – iron extracted by a dithionite-citrate-bicarbonate solution
Fe_o – iron extracted by an acid ammonium oxalate solution
IUSS – International Union of Soil Science
N_t – total nitrogen
OC – organic carbon
OM – organic matter

METHODS

The soils were classified according to WRB 2015¹. The soil morphology descriptions, textural classes and symbols of soil horizons are given after Guidelines for Soil Description². The samples were taken from selected soil horizons and after preparation (drying, separation of root and sand fraction >2 mm by sieving) they were analyzed in the laboratory. In most cases texture was determined by (i) combining the Bouyoucos³ hydrometer and sieve method or (ii) by pipette and sieve method. Organic carbon (OC) content was determined by the wet dichromate oxidation method, and total nitrogen (N_t) content by the Kjeldahl method. The reaction was measured in H₂O and 1 M KCl in 1:2.5 suspension for mineral samples, and 1:10 suspension for organic samples. Calcium carbonate (CaCO₃) content was determined by Scheibler volumetric method. Potential (hydrolytic) acidity (HA) was determined by Kappen method and exchangeable cation (bases) content was estimated by leaching with 1 M ammonium acetate with a buffer solution pH 8.2. Pedogenic forms of iron and aluminum were extracted: Fe_i and Fe_d by HClO₄-HF, Fe_d by sodium dithionite-citrate-bicarbonate⁴ and Fe_o and Al_o by ammonium oxalate buffer solution⁵. Other soil analyses were performed according to the standard methods⁶. Color has been described according to Munsell⁷. It was recorded (i) in the moisture condition (single value) or (ii) in the dry and moisture condition (double values).

¹ IUSS Working Group WRB, 2015. World Reference Base for soil resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Report No. 106. FAO, Rome.

² FAO, 2006. Guidelines for Soil Description, Fourth edition. FAO, Rome.

³ Bouyoucos, G.M., 1951. Particle analysis by hydrometer method. *Agronomy Journal* 43, 434–438.

⁴ Mehra, O.P., Jackson, M.L., 1960. Iron oxides removal from soils and clays. Dithionite-citrate systems buffered with sodium bicarbonate. *Clays and Clay Minerals* 7, 313–327.

⁵ Mckeague, J.A., Day, J.H., 1966. Ammonium oxalate and DCB extraction of Fe and Al. *Canada Journal of Soil Science* 46, 13–22.

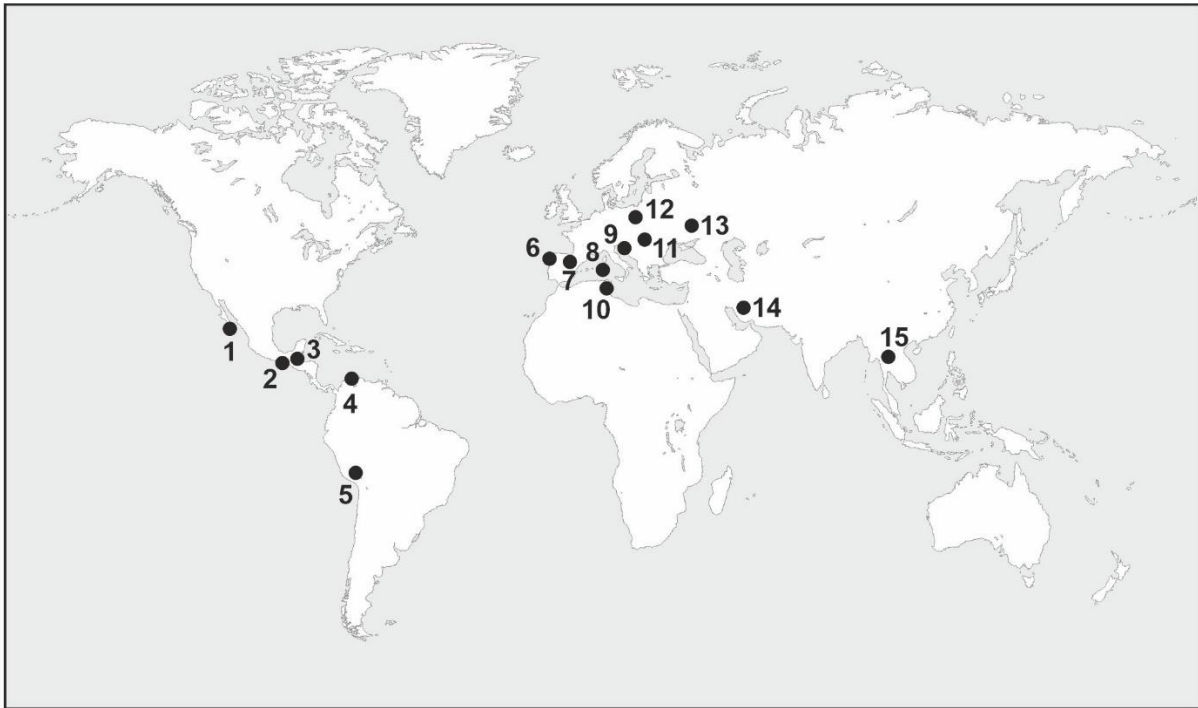
⁶ Van Reeuwijk, L.P. 2002. Procedures for soil analysis. 6th Edition. Technical Papers 9. Wageningen, Netherlands, ISRIC – World Soil Information.

⁷ Munsell Soil Colour Charts, 2009. Grand Rapids, Michigan USA.

SOIL REFERENCE GROUPS INDEX

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STUDY AREAS



NUMBER OF CHAPTER – REGION AND COUNTRY:

- 1 – BAJA CALIFORNIA PENINSULA, MEXICO
- 2 – OAXACA, MEXICO
- 3 – CHIAPAS, MEXICO
- 4 – GUAJIRA, COLOMBIA
- 5 – PUNO AND MADRE DE DIOS, PERU
- 6 – SANTIAGO DE COMPOSTELA, SPAIN
- 7 – EBRO RIVER BASIN, SPAIN
- 8 – SARDINIA, ITALY
- 9 – COAST REGION, SLOVENIA
- 10 – MENZEL CHAKER, TUNISIA
- 11 – NYÍREGYHÁZA, HUNGARY
- 12 – BRODNICA LAKE DISTRICT AND ŚWIECIE PLATEAU, POLAND
- 13 – CENTRAL RUSSIAN UPLAND, RUSSIA
- 14 – ZAGROS MOUNTAINS, IRAN
- 15 – PHRAE PROVINCE, THAILAND

Soils of the southern tip of the Baja California Peninsula: An example from drylands in Northwest Mexico

Fernando Ayala-Niño, Yolanda Maya-Delgado, Miriam Salamanca-Sánchez, Enrique Troyo-Diéguéz

Mexico holds about two thousand millions square kilometers (INEGI 1995); more than a half of its territory corresponds to arid and semi-arid zones, where the most relevant and high-growth human settlements are concentrated. The southern tip of Baja California peninsula in Northwest Mexico is one of the warmest and driest regions of the country, where the La Paz watershed is located (Fig 1). The area covers ~250,000 ha showing a highly varied relief and soil diversity due to complex geological history.

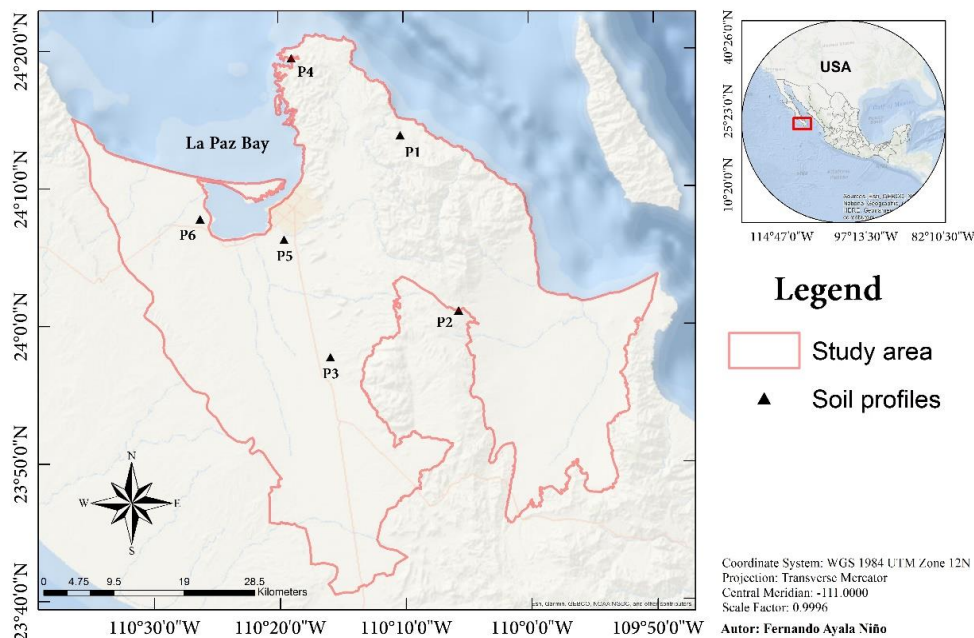


Fig. 1. Study area location in Northwest Mexico

Lithology and topography

The watershed 'La Paz' is located in the sub-province discontinuity 'Llanos de Magdalena' in the central-east part of Baja California Sur State, mainly conformed by a low terrain, which emerged from the seafloor (Beal 1948). It consists primarily of geofoms diversity, such as plains, smooth hilly landscapes with sandy terrain forming dunes fields, hills, plateaus, alluvial plains, mountain ranges and isolated elevations. The study area is located in the 'La Paz' geological province (Ortega et al., 1992), a plutonic complex with several geological environments with metamorphic, igneous (intrusive and extrusive), sedimentary-marine sequences and continental deposits from the late Jurassic to Holocene. The area is characterized by a rock basement of plutonic rocks with ages fluctuating from lower Cretaceous to middle Miocene. The older intrusive corresponds to granodiorite and granite intrusive rocks, gabbro and diorite from early Cretaceous emerging in the Sierra de las Cruces. Subsequently, these rocks are overlaid by a sequence of marine, volcanic and continental origin that varies in age from the Paleocene to the Holocene (Maya et al., 2011; SGM, 2007).

Profile 1 – Eutric Skeletic Leptic **Regosol** (Loamic, Ochric)

Location: Las Cruces Mountains, 45° slope, desert scrub-deciduous forest, altitude 616 m a.s.l.,
N 24° 1'3.58", E 110° 5'41.66"



Morphology:

- A – 0–34 cm, humus horizon, sandy loam with abundant gravels, brown (10YR 6/3; 10YR 5/4), null reaction to HCL, subangular structure, abundant fine roots;
- R – 34–(45) cm, continuous rock (granite).

Table 1. Soil Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]			Textural Class
		Sand 2.0-0.05	Silt 0.05-0.002	Clay < 0.002	
A	0-34	61.7	36.2	2.1	SL
R	34-(45)	-	-	-	-

Table 2. Physicochemical properties

Horizon	Depth [cm]	pH	EC [$\mu\text{S}/\text{cm}$]	OC [$\text{g}\cdot\text{kg}^{-1}$]	N [$\text{g}\cdot\text{kg}^{-1}$]	C/N	CaCO ₃ [$\text{g}\cdot\text{kg}^{-1}$]
A	0-34	7.54	107.8	6.4	2.0	3.2	-

Profile 2 – Eutric Hyperskeletal Nudilithic Leptosol

Location: Las Cruces Mountains, 45° slope, desert scrub, altitude 206 m a.s.l.,
N 24°13'49.59", E 110°10'16.65"



Morphology:

- A** – 0–4 cm, humus horizon, loamy sand, light yellowish (10YR 6/4; 10YR 4/4), null reaction to HCL, granular structure, fine abundant medium and thick roots;
- R** – 4–(30) cm, continuous rock – granodiorite mainly.

Table 3. Soil Texture

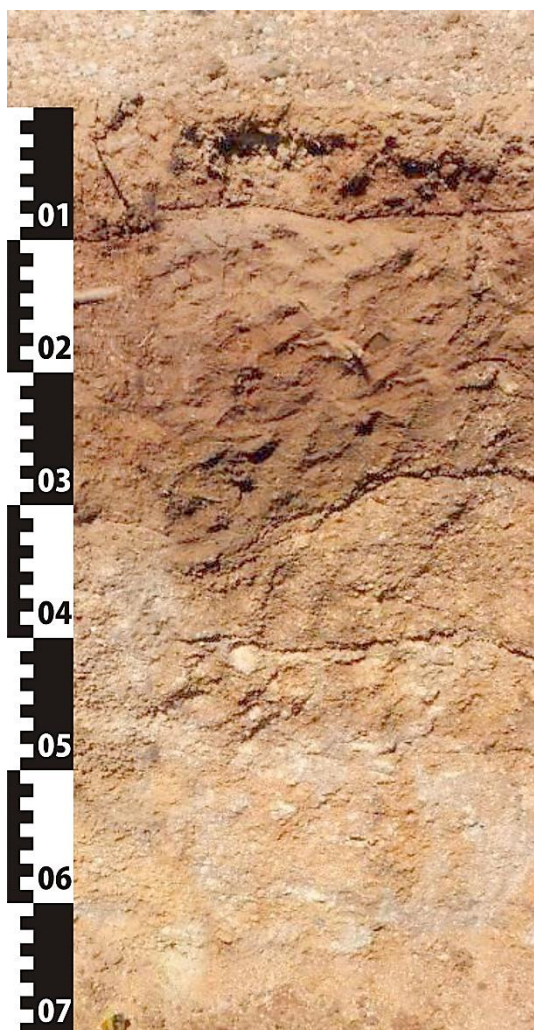
Horizon	Depth [cm]	Percentage share of fraction [mm]			Textural Class
		Sand 2.0-0.05	Silt 0.05-0.002	Clay < 0.002	
A	0-4	73.9	25.6	0.5	LS
R	4-(30)	-	-	-	-

Table 4. Physicochemical properties

Horizon	Depth [cm]	pH	EC [$\mu\text{S}/\text{cm}$]	OC [$\text{g}\cdot\text{kg}^{-1}$]	N [$\text{g}\cdot\text{kg}^{-1}$]	C/N	CaCO ₃ [$\text{g}\cdot\text{kg}^{-1}$]
A	0-4	5.90	414	6.9	3.5	1.9	-

Profile 3 – Leptic Cambic Skeletic **Calcisol** (Amphiloamic, Ochric)

Location: San Pedro hilly landscape, 15° slope, desert scrub, altitude 214 m a.s.l.,
N 23°57'41.92", E 110°15'55.03"



Morphology:

- A1** – 0–7 cm, humus horizon, loamy sand, reddish brown (5YR 4/4; 5YR3/4), null reaction to HCL, angular blocky structure, fine abundant and medium scarce roots;
- A2** – 7–18/22 cm, humus horizon, silt, reddish brown (5YR 4/4; 2.5YR 2.5/4), null reaction to HCL, angular blocks, roots scarce;
- Bc** – 18/22–26/33 cm, *cambic* horizon, silt, reddish brown (5YR 4/3), dark reddish (5YR 3/4), very strong reaction to HCL, angular blocks, medium scarce roots. Accumulation in the form of concretions;
- Ck** – 26/33–26/40 cm, *calcic* horizon, loamy sand, reddish brown (5YR 5/4), brown (7.5YR 5/4), very strong reaction to HCL, subangular blocks, without roots, accumulation of secondary calcium carbonates;
- C2** – 40–(70) cm, parent material, sandy loam, light reddish brown (7.5YR 6/3; 7.5YR 5/4), without roots.

Continuous rock – about 80–90 cm.

Table 5. Soil Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]			Textural Class
		Sand 2.0-0.05	Silt 0.05-0.002	Clay < 0.002	
A1	0-7	78.5	19.2	2.3	LS
A2	7-18/22	0.5	86.8	12.7	Si
Bc	18/22-26/33	4.4	88.6	7.0	Si
Ck	26/33-26/40	74.3	23.7	2.0	LS
C2	40-(70)	28.3	70.0	1.7	SL

Table 6. Physicochemical properties

Horizon	Depth [cm]	pH	EC [μS/cm]	OC [g·kg ⁻¹]	N [g·kg ⁻¹]	C/N	CaCO ₃ [g·kg ⁻¹]
A1	0-7	7.44	220	4.6	3.8	1.2	-
A2	7-18/22	7.75	574	5.8	4.2	1.3	-
Bc	18/22-26/33	7.35	1446	4.0	3.3	1.2	-
Ck	26/33-26/40	7.23	1742	2.9	2.7	1.0	-
C2	40-(70)	7.29	2320	0.5	1.8	0.2	-

Profile 4 – Eutric Hyperskeletal Nudilithic **Leptosol**

Location: Natural Protected Area “Balandra”, 45° slope, desert scrub, altitude 30 m a.s.l.,
N 23°57'41.92", E 110°15'55.03"



Morphology:

- A** – 0–3 cm, humus horizon, sandy loam, brown (10YR 4/3; 10YR 4/3), null reaction to HCL, subangular blocky structure, pH 6.0 slightly acid, fine and abundant roots; medium and thick roots are scarce;
- R** – 3–(30) cm, continuous rock.

Table 7. Soil Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]			Textural Class
		Sand 2.0-0.05	Silt 0.05-0.002	Clay < 0.002	
A	0-3	65.1	31.8	3.1	SL

Table 8. Physicochemical properties

Horizon	Depth [cm]	pH	EC [$\mu\text{S}/\text{cm}$]	OC [$\text{g}\cdot\text{kg}^{-1}$]	N [$\text{g}\cdot\text{kg}^{-1}$]	C/N	CaCO ₃ [$\text{g}\cdot\text{kg}^{-1}$]
A	0-3	6.07	199.6	5.2	1.7	1.9	-

Profile 5 – Eutric Cambisol (Aric, Pantoarenic, Ochric, Technic)

Location: San Patricio Ranch, 1° slope, crop field, altitude 21 m a.s.l.,
N 24° 6'16.27", E 110°19'34.40"



Morphology:

- Ap** – 0–10/15 cm, humus horizon, loamy sand, very dark grayish brown (2.5Y 5/3; 2.5Y 3/2), null reaction to HCL, subangular blocky structure, fine abundant and medium scarce roots, artefacts – pieces of plastic hoses for irrigation (>10%), perturbations by agricultural activities;
- Ap2** – 10/15–36/40 cm, humus horizon, loamy sand, dark olive brown (2.5Y 5/3; 2.5Y 3/3), null reaction to HCL, sub-angular blocks, fine and abundant roots, perturbations by agricultural activities, artefacts – pieces of plastic hoses for irrigation (>10%);
- Bw** – 36/40–69 cm, loamy sand, very dark grayish brown (2.5Y 5/3; 2.5Y 3/2), null reaction to HCL, sub-angular blocky structure, fine and medium scarce roots;
- Bw2** – 69–(123) cm, loamy sand, very dark grayish brown (2.5Y 5/3; 2.5Y 3/2), very strong reaction to HCL, subangular blocks, without roots.

Table 9. Soil Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]			Textural Class
		Sand 2.0-0.05	Silt 0.05-0.002	Clay < 0.002	
Ap	0–10/15	83.2	16.7	0.1	LS
Ap2	10/15–36/40	80.5	19.2	0.3	LS
Bw	36/40–69	80.4	19.4	0.2	LS
Bw2	69–(123)	88.1	11.6	0.3	LS

Table 10. Physicochemical properties

Horizon	Depth [cm]	pH	E.C. [$\mu\text{S}/\text{cm}$]	OC [$\text{g}\cdot\text{kg}^{-1}$]	N [$\text{g}\cdot\text{kg}^{-1}$]	C/N	CaCO_3 [$\text{g}\cdot\text{kg}^{-1}$]
Ap	0–10/15	7.68	193.7	6.3	5.2	1.2	-
Ap2	10/15–36/40	7.78	446	1.1	2.9	0.3	-
Bw	36/40–69	7.66	883	1.7	2.4	0.7	-
Bw2	69–(123)	7.45	1520	1.7	1.4	1.2	-

Profile 6 – Eutric Cambisol (Anoarenic, Ochric, Endosiltic)

Location: Experimental Terrestrial Reserve of the Centro de Investigaciones Biológicas del Noroeste (CIBNOR), 2° slope, desert scrub, altitude 10 m a.s.l., N 24° 7'46.56", E 110°26'15.48"



Morphology:

- A** – 0–5 cm, humus horizon, sand, brown (10YR 6/3; 10YR 4.5/3), very weak reaction to HCL, subangular blocky structure, fine frequent roots;
- A2** – 5–17/22 cm, humus horizon, loamy sand, brown (10YR 6/3; 10YR 4/3), very weak reaction to HCL, subangular blocky structure, frequent fine roots and abundant medium roots;
- Bw** – 17/22–56 cm, *cambic* horizon, loamy sand, grayish brown (7.5YR 7/2; 10YR 5/2), strong reaction to HCL, subangular blocky structure, some artefacts, frequent fine and medium roots;
- Bw2** – 56–64 cm, *cambic* horizon, loamy sand, brown (7.5YR 6/2; 7.5YR 5/2), very strong reaction to HCL, subangular blocky structure, frequent fine roots;
- C** – 64–(110) cm, parent material, silt, brown (7.5YR 7/2; 7.5YR 4/3), subangular blocky structure, thick scarce roots.

Table 11. Soil Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]			Textural Class
		Sand 2.0-0.05	Silt 0.05-0.002	Clay < 0.002	
A	0-5	93.2	6.2	0.6	S
A2	5-17/22	87.6	11.5	0.9	LS
Bw	17/22-56	88.5	10.7	0.8	LS
BW2	56-64	82.7	15.9	1.4	LS
C	64-(110)	5.6	91.5	2.9	Si

Table 12. Physicochemical properties

Horizon	Depth [cm]	pH	E.C. [μS/cm]	OC [g·kg ⁻¹]	N [g·kg ⁻¹]	C/N	CaCO ₃ [g·kg ⁻¹]
A	0-5	7.2	249	6.9	0.6	11.5	-
A2	5-17/22	7.3	149.4	1.1	0.9	1.2	-
Bw	17/22-56	7.5	149.9	1.7	0.7	2.42	-
Bw2	56-64	7.5	188.8	0.5	2.0	0.25	-
C	64-(110)	7.6	202	0.5	0.6	0.83	-

Land use

Several land-use types demark the study area, including natural vegetation, irrigated and temporal agriculture, livestock, mangroves, cultivated pasture, and human settlements, taking advantage of a large edaphic diversity. However, the previously identified land uses occur only in alluvial plains, with flat surfaces and slopes lower than 10%. The vegetation is a desert scrub where representative plants have large swollen trunks to allow water storage. The species with wider distribution in the study area are *Cyrtocarpa edulis* (Brandege) Standl, *Jathropha cinerea* (Ortega) Muell. Arg, *J. cuneata* Wiggins & Rollins, *Bursera microphylla* A. Gray, *Prosopis articulata* S. Watson, *Fouquieria diguetii* (Tiegh.) and numerous species of cacti, such as *Pachycereus pringlei* (S. Watson) Britton & Rose, *Stenocereus gummosus* (Engelm.) A. Gibson & K.E. Horak, *S. thurberi* (Engelm.) Buxb., and *Opuntia* spp. (Maya and Arriaga, 1996).

Climate

In Baja California Sur, Northwest Mexico, prevail very arid, semi-dry warm and warm climates associated with an extreme trend of diurnal temperatures and the environmental dryness. Annual mean temperature is 23.5°C, and it reaches 45°C in July, August and September. The highest radiation occurs from April through August. Average annual precipitation is 178 mm with a major peak in August and September, often associated with tropical storms and occasional minor peaks in winter. Average moisture retention is 0.1135 cm³ water cm⁻³ soil, suggesting a pronounced water deficit (Troyo-Diéguez et al., 2014).

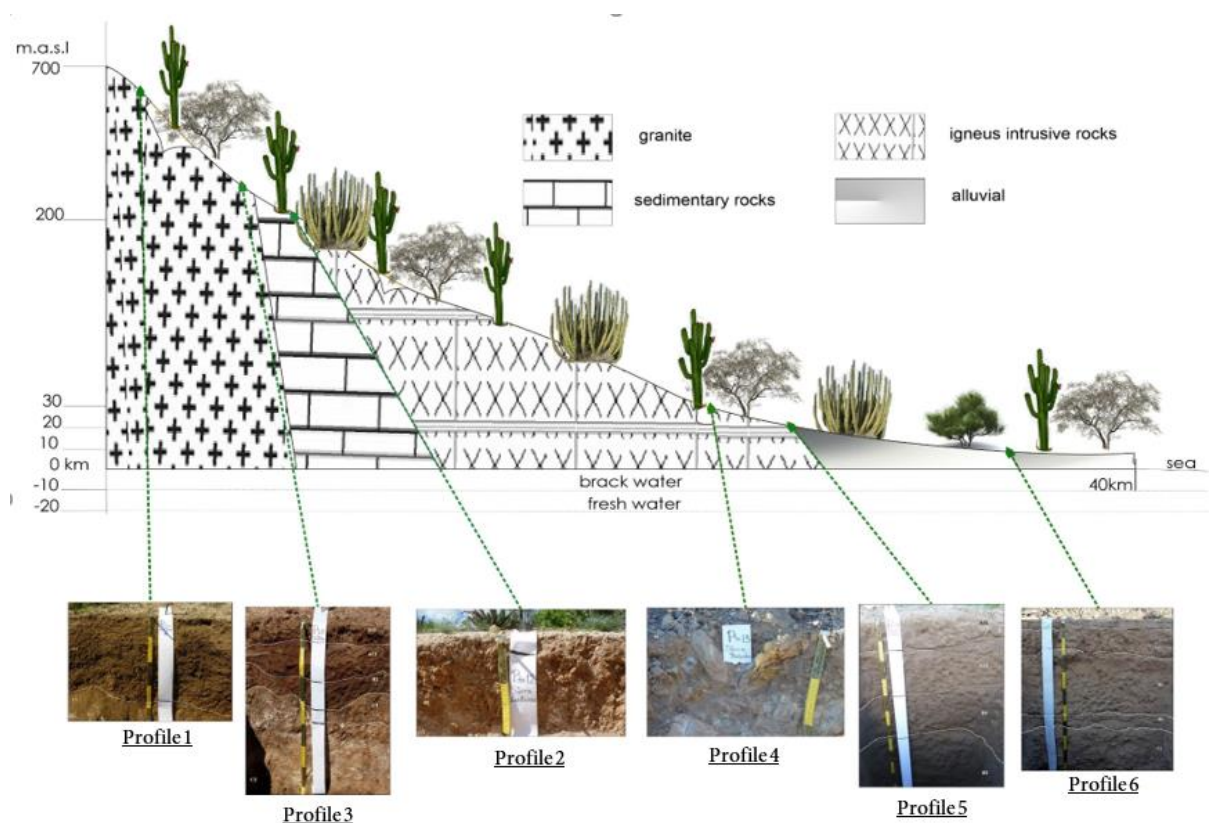


Fig. 2 Toposequence of the Soils of the southern tip of the Baja California Peninsula

Soil Sequence

Extreme conditions prevail in the arid region of northwest of Mexico, including high temperatures, droughts, the occurrence of meteorological events associated with tropical storms, the diversity of geological materials, and the influence of transitional areas between ecoregions. Such conditions define the dominant vegetation types, determining the actual types of soils. All tested soils are alkaline (*Eutric* qualifier) or even have secondary carbonates accumulation (**Calcisol**) and have poorly developed humus horizons (*Ochric* qualifier) which is typical for dry and hot climates.

The first profile *Eutric Skeletic Leptic Regosol* (*Loamic, Ochric*), is located at the highest point of a hilly area, resulting in shallow soils with little development (young). The dominant *Leptic Regosol* shows a notoriously limited formation due to adverse climatic conditions. However, these soils support predominantly deciduous forest vegetation perfectly adapted to dry and arid conditions. The scarce development, shallow depth to continuous rock (*Leptic*) and the presence of skeletal fragments (*Skeletic*) are the most characteristic features of this soil.

Profile 2 (*Eutric Hyperskeletic Nudilithic Leptosol*) is located on a steeper slope and is evidenced by characteristics very similar to profile 1. However, this site presents continuous rock from the surface (*Nudilithic*) and the presence of fine materials in some places with more than 80% (in volume) of skeletal fractions (*Hyperskeletic*). The soil in general has low development and shallow depth with visible influence of erosion processes down the slope.

Soils in profile 3 (*Cambic Skeletic Calcisol*) are located on a hill with transitional vegetation between low forest and sarcocaulis scrub. It presents a more advanced development in contrast to profiles 1 and 2. The geological material of this residual soil corresponds to sedimentary and igneous rocks, which explains the reaction of HCL, very strong in the lower horizons (Bc and Ck), characterized by calcium carbonate accumulation and concretions formation, as well as a whitish coloration (**Calcisol**), with evidence of pedogenetic change (*Cambic*).

The fourth profile (*Eutric Hyperskeletic Nudilithic Leptosol*) is another clear example of the limited development of the soil (3 cm) and continuous rock in a layer of 5 cm or a thicker product in the extreme environmental conditions coupled with the characteristics of the relief. However, this very thin soil supports a desert scrub vegetation with representative species such as *Pachycereus pringlei* (S. Watson) Britton & Rose (cardón) giant cactus with individuals that can reach heights around 20 m and 1.5 m in diameter.

The fifth and sixth profiles (*Eutric Cambisols*) correspond to colluvial/alluvial material located in plains formed by the transport and prolonged accumulation of materials; these soils are commonly used for the main productive activities and population growth (urban centers). With slopes less than 5% in both cases and more than 1 m in depth, productive activities have been developed throughout more than 30 years with different types of crops (temporary and under irrigation), with contributions of organic fertilizers. In profile 5, the presence of artifacts with total amount of 10% (averaged up to 100 cm) related mainly to the irrigation infrastructure was expressed by the *Technic* qualifier. The mentioned activities have increased the extraction of groundwater for irrigation raising the salinity of the soils as a result of the use of saline water from an aquifer with marine intrusion problems due to its proximity to the sea. Besides, soil and water quality are also affected by the excessive use of agrochemicals.

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Soils of coffee agroforestry systems in Southern Mexico

Alma Barajas, Axel Cerón González

The soil-forming theoretical model in mountainous subtropical areas of the Sierra Madre del Sur (Oaxaca, Southern Mexico) describes three major processes: deposition by slope activity, litter accumulation and weathering of parent material (García-Calderón et al., 2006, Krasilnikov et al., 2007). Krasilnikov et al. (2005) exposed that the high soil diversity in the Sierra Madre del Sur is regulated by its complex topography, high lithological diversity, and slope processes. As a result of the morphogenetical activity, the landscape and soilscape transformations increase the soil diversity.

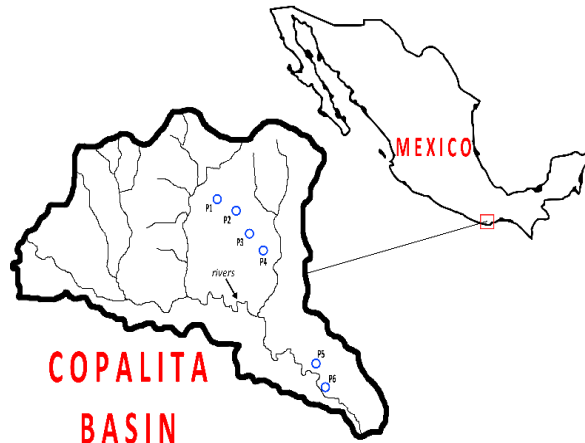


Fig. 1. Location

Lithology and topography

The Copalita basin is part of the Sierra Madre del Sur physiographic-national province in the Southern Mexico, located in Oaxaca State. The altitudinal range varies between 2,900 m a.s.l. and the sea level. The Copalita basin also has access to the Pacific Ocean and its hydrological system is characterized by exogenic-semidentritical rivers. In the basin, the main reliefs are mountain chains, hills, and V-shaped valleys. Furthermore, there are plains near the sea. The slopes are erosional-and-depositional active systems which have an important role in the re-start of the pedogenic clock.

The Sierra Madre del Sur is constituted by a mountain range parallel to the Pacific coastline, derived from tectonic processes and currently it represents an active seismic zone (Hernández-Santana et al., 2009). Because of the geological complex setting of the Copalita basin, there is a high lithological diversity with: gneiss, squist, granite, limestone and sandstone. In the plains, there are Quaternary non-consolidate sediments as well.

Land use

In the highest portion of the basin, the template forest predominates. The middle part is characterized by cultivated lands mixed with evergreen tropical forests. In the lowest portion, there are gallery forest and semi-evergreen tropical forest. The agricultural land use – in the middle part – is rainfed, and it covers 13% of the total area (INEGI, 2015). The mainly agricultural products are maize and coffee, which has been produced under agroforestry systems for the last decades.

Climate

The basin is found in the global tropical belt and its climatic conditions are directly related to the altitude. At sea level, the warm climate predominates, while on the mountainous peaks the temperate semi-cold climate prevails. Also, the basin presents sub-humid conditions, with average annual rainfall between 1,500 and 2,000 mm.

Profile 1 – Luvic Phaeozem (Colluvic, Pantoloamic)

Location: Saprolitized colluviums of shist and gneiss, back slope, inclination 21°, coffee plantations with semi-evergreen forest as canopy cover, 1,533 m a.s.l., San Juan Ozolotepec Town
N 16.09562°, W 96.29767°



Morphology:

- Ah** – 0–38 cm, humus horizon, clay loam, black (10YR 2/1), strong granular coarse, 10% stony, abrupt and wavy boundary;
- Btg** – 38–45 cm, loam, dark yellowish brown (10YR 4/4), moderate angular blocky very coarse, presence of Fe-Mn concretions and clay coatings, clear and irregular boundary;
- Bt** – 45–56 cm, loam, dark yellowish brown (10YR 4/4), strong angular blocky very coarse, 5% stony, presence of clay coatings, clear and smooth boundary;
- BC** – 56–73 cm, loam, dark yellowish brown (10YR 4/6), strong subangular blocky very coarse, 5% stony, abrupt and smooth boundary;
- CB** – 73–95 cm, sandy clay loam, dark yellowish brown (10YR 3/6), weak subangular blocky very coarse, 20% stony, abrupt and irregular boundary;
- 95–(140) cm, sandy clay loam, dark brown (10YR C 3/3), massive structure.

Table 1. Physicochemical properties and texture of Profile 1

Horizon	Depth (cm)	pH H ₂ O	OM (%)	Texture			
				Sand	Silt	Clay	Class
Ah	0–38	5.9	4.73	38.76	28	33.24	CL
Btg	38–45	6.7	0.07	53.76	32	14.24	L
Bt	45–56	6.6	0.60	53.76	32	14.24	L
BC	56–73	7.0	0.27	53.76	34	12.24	L
CB	73–95	6.7	0.29	48.76	22	29.24	SCL
C	95–(140)	7.0	0.05	50.76	26	23.24	SCL

Table 2. Exchange cations of Profile 1

Horizon	Depth (cm)	Ca		Mg		K		Na		CEC (meq 100g ⁻¹)	BS (%)
		(meq 100g ⁻¹)	(% sat)	(meq 100g ⁻¹)	(% sat)	(meq 100g ⁻¹)	(% sat)	(meq 100g ⁻¹)	(% sat)		
Ah	0–38	16.0	92.5	1.01	5.84	0.20	1.16	0.03	0.17	17.3	99.7
Btg	38–45	12.5	91.2	0.95	6.93	0.18	1.31	0.09	0.66	13.7	100
Bt	45–56	12.4	92.5	0.74	5.52	0.18	1.34	0.08	0.60	13.4	100
BC	56–73	12.3	91.1	0.99	7.33	0.16	1.19	0.05	0.37	13.5	100
CB	73–95	9.50	90.9	0.78	7.43	0.14	1.33	0.06	0.57	10.5	100
C	95–(140)	13.7	91.9	0.99	6.64	0.11	0.74	0.06	0.40	14.9	99.7

Profile 2 – Pantoskeletal Follic Cambisol (Colluvic, Pantoloamic, Raptic)

Location: Saprolized colluviums of shist, quartzite and shale, upper slope, inclination 42°, temperate forest, 1,888 m a.s.l., San Juan Ozolotepec Town **N** 16.08867°, **W** 96.29314°



Morphology:

- Ah1** – 0–3 cm, humus horizon, loam, black (10YR 2/1), moderate granular coarse, 40% stony, abrupt and wavy boundary;
- Ah2** – 3–10 cm, humus horizon, loam, light olive brown (2.5Y 5/3), moderate subangular blocky fine, 40% stony, clear and wavy boundary;
- Ah3** – 10–15 cm, humus horizon, loam, very dark grayish brown (2.5Y 3/2), moderate subangular blocky medium, 40% stony, clear and wavy boundary;
- Bw** – 15–50 cm, loam, light olive brown (2.5Y 5/4), strong subangular blocky coarse, 50% stony, clear and irregular boundary;
- 2Bw** – 50–55 cm, loam, dark yellowish brown (10YR 3/4), moderate subangular blocky fine, 60% stony, abrupt and irregular boundary;
- 2BC1** – 55–90 cm, sandy loam, yellowish brown (10YR 5/4), weak subangular blocky very coarse, 80% stony, gradual and irregular boundary;
- 2BC2** – 90–(111) cm, sandy loam, yellowish brown (10YR 5/4), weak subangular blocky very coarse, many roots, 85% stony.

Table 3. Physicochemical properties and texture of Profile 2

Horizon	Depth (cm)	pH H ₂ O	OM (%)	Texture			
				Sand	Silt	Clay	Class
Ah1/2	0–10	6.7	1.24	52.76	34	13.24	L
Ah3	10–15	6.8	1.28	50.76	34	15.24	L
Bw	15–50	5.8	0.59	50.76	24	15.24	L
2Bw	50–55	6.0	0.78	50.76	36	13.24	L
2BC1	55–90	6.9	0.69	74.76	16	9.24	SL
2BC2	90–111	7.0	0.15	70.76	22	7.24	SL

Table 4. Exchange cations of Profile 2

Horizon	Depth (cm)	Ca		Mg		K		Na		CEC (meq 100g ⁻¹)	BS (%)
		(meq 100g ⁻¹)	(%)	(meq 100g ⁻¹)	(%)	(meq 100g ⁻¹)	(%)	(meq 100g ⁻¹)	(%)		
Ah1/2	0–10	7.70	80.8	1.60	16.8	0.19	1.99	0.04	0.42	9.53	100
Ah3	10–15	7.73	79.0	1.81	18.5	0.16	1.64	0.08	0.82	9.78	100
Bw	15–50	4.46	72.3	1.22	19.8	0.15	2.43	0.03	0.49	6.17	100
2Bw	50–55	6.93	79.3	1.66	19.0	0.10	1.14	0.05	0.57	8.74	99.9
2BC1	55–90	15.2	88.9	1.44	8.42	0.10	0.58	0.31	1.81	17.1	100
2BC2	90–111	14.1	90.4	1.37	8.78	0.09	0.58	0.03	0.19	15.6	100

Profile 3 – Pantoskeletal Stagnic Endogleyic **Phaeozem** (Colluvic, Pantoloamic, Raptic)

Location: Saprolitized colluviums of granodiorite, squist, and gneiss, upper slope, inclination 35°, row-crop maize, 2,253 m a.s.l., San Francisco Ozolotepec Town **N** 16.11368°, **W** 96.21970°



Morphology:

- Ap** – 0–11 cm, humic plowed horizon, sandy loam, very dark brown (10YR 2/2), moderate granular very coarse, 50% stony, abrupt and wavy boundary;
- BA** – 11–33 cm, sandy loam, dark brown (10YR 3/3), moderate subangular blocky fine, 50% stony, clear and irregular boundary;
- 2C/B** – 33–60 cm, sandy loam, brown (10YR 4/3), moderate subangular blocky fine, 70% stony, abrupt and irregular boundary;
- 3BI** – 60–80 cm, sandy loam, brown (10YR 4/3), moderate angular blocky very coarse, 60% stony, gleyic properties, clear and irregular boundary;
- 3Blg** – 80–(110) cm, sandy loam, dark grayish brown (10YR 4/2), moderate subangular blocky very coarse, 60% stony, stagnic and gleyic properties.

Table 5. Physicochemical properties and texture of Profile 3

Horizon	Depth (cm)	pH H ₂ O	OM (%)	Texture			
				Sand	Silt	Clay	Class
Ap	0–11	6.3	6.45	72.76	20	7.24	SL
BA	11–33	5.4	1.69	68.76	22	9.24	SL
2C/Bb	33–60	4.9	1.04	70.76	18	11.24	SL
3Bl	60–80	4.8	0.32	60.76	28	11.24	SL
3Blg	80–(110)	5.2	0.39	60.76	24	15.24	SL

Table 6. Exchange cations of Profile 3

Horizon	Depth (cm)	Ca		Mg		K		Na		CEC (meq 100g ⁻¹)	BS (%)
		(meq 100g ⁻¹)	(% sat)	(meq 100g ⁻¹)	(% sat)	(meq 100g ⁻¹)	(% sat)	(meq 100g ⁻¹)	(% sat)		
Ap	0–11	6.8	78.7	1.16	13.4	0.64	7.41	0.03	0.35	8.64	99.9
Ah	11–33	4.4	74.6	0.71	12.0	0.40	6.73	0.02	0.34	5.94	93.6
2C/B	33–60	5.6	76.4	0.77	10.5	0.29	3.96	0.03	0.41	7.33	91.3
3Bl	60–80	7.9	71.1	1.06	9.4	0.16	1.43	0.05	0.45	11.2	82.4
3Blg	80–(110)	11.0	80.9	1.69	12.4	0.22	1.62	0.09	0.66	13.6	95.6

Profile 4 – Eutric Mollic Hyperskeletal **Leptosol** (Colluvic, Hyperhumic, Pantoarenic)

Location: Saprolitized colluviums of granodiorite and metamorphic conglomerate, middle slope, inclination 34°, coffee plantations with semi-evergreen forest as canopy cover, 1,903 m a.s.l., San Francisco Ozolotepec Town **N** 16.10995°, **W** 96.21886°



Morphology:

- Ap** – 0–21 cm, ploughed horizon, loamy sand, dark (10YR 2/1), granular structure, 80% stony, clear and smooth boundary;
- AB1** – 21–32 cm, loamy sand, dark brown (10YR 2/2), subangular blocky, 80% stony, gradual and irregular boundary;
- AB2** – 32–(70) cm, black brown (10YR 3/2), loamy sand, 80% stony.

Table 7. Physicochemical properties and texture of Profile 4

Hori -zon	Depth (cm)	pH H ₂ O	OM (%)	Texture			
				sand	silt	Clay	Class
Ap	0–21	6.5	15.5	80.76	12	7.24	LS
AB1	21–32	6.5	9.17	76.76	18	5.24	LS
AB2	32–(70)	6.2	5.02	78.76	16	5.24	LS

Table 8. Exchange cations of Profile 4

Hori -zon	Depth (cm)	Ca		Mg		K		Na		CEC (meq 100g ⁻¹)	BS (%)
		(meq 100g ⁻¹)	(%)	(meq 100g ⁻¹)	(%)	(meq 100g ⁻¹)	(%)	(meq 100g ⁻¹)	(%)		
Ap	0–21	13.4	81.7	2.16	13.2	0.79	4.82	0.05	0.30	16.4	100
AB1	21–32	12.4	82.7	2.03	13.5	0.52	3.47	0.03	0.20	15.0	99.9
AB2	32–(70)	9.68	83.4	1.39	12.0	0.46	3.97	0.05	0.43	11.6	99.8

Profile 5 – Rhodic Protovertic Stagnic **Luvisol** (Clayic, Colluvic, Cutanic, Humic, Profundic)

Location: Saprolitized colluviums of granodiorite and calcite, middle slope, inclination 20°, semi-deciduous tropical forest, 337 m a.s.l., San Miguel del Puerto Town, **N** 15.91168°, **W** 96.16608°



Morphology:

- Ah** – 0–18 cm, humus horizon, sandy loam, very dark brown (10YR 2/2), moderate subangular blocky very fine, 40% stony, gradual and irregular boundary;
- BA** – 18–40 cm, clay, dark reddish brown (2.5YR 2.5/4), moderate subangular blocky medium, 15% stony, gradual and irregular boundary;
- Btc1** – 40–70 cm, clay, dark red (2.5YR 3/6), strong subangular blocky medium, 35% stony, clay coatings, stagnic properties, protovertic properties, abrupt and irregular boundary;
- Btc2** – 70–115 cm, clay, dark red (2.5YR 3/6), strong subangular blocky very coarse, 15% stony, clay coatings, stagnic properties, gradual and irregular boundary;
- BC** – 115–139 cm, clay, dark red (2.5YR 3/6), strong angular blocky medium, 15% stony, gradual and smooth boundary;
- CB** – 139–(180) cm, sandy clay loam, dark red (2.5YR 3/6), strong angular blocky fine, 5% stony.

Table 9. Physicochemical properties and texture of Profile 5

Hori- zon	Depth (cm)	pH H ₂ O	OM (%)	Texture			Class
				Sand	Silt	Clay	
Ah	0–18	5.4	5.36	66.04	24	9.96	SL
BA	18–40	5.4	2.36	40.0	20	40.0	C
Btc1	40–70	4.6	0.86	44.04	10	45.96	C
Btc2	70–115	4.5	0.18	40.04	10	49.96	C
BC	115–139	4.3	0.02	36.04	18	45.96	C
CB	139–(180)	4.4	0.09	46.04	22	31.96	SCL

Table 10. Exchange cations of Profile 5

Hori- zon	Depth (cm)	Ca		Mg		K		Na		CEC (meq 100g ⁻¹)	BS (%)
		(meq 100g ⁻¹)	(%)	(meq 100g ⁻¹)	(%)	(meq 100g ⁻¹)	(%)	(meq 100g ⁻¹)	(%)		
Ah	0–18	5.3	58.1	3.1	34.2	0.68	7.36	0.03	0.32	9.24	97.7
BA	18–40	2.9	52.1	1.8	33.0	0.67	12.0	0.04	0.71	5.60	95.4
Btc1	40–70	1.7	41.3	1.1	28.3	0.57	13.5	0.05	1.19	4.21	82.1
Btc2	70–115	0.8	25.5	0.4	12.2	0.32	9.50	0.04	1.19	3.37	46.7
BC	115–139	0.6	18.0	0.2	7.61	0.29	8.17	0.04	1.13	3.55	32.6
CB	139–(180)	0.4	13.9	0.1	4.14	0.25	7.40	0.05	1.48	3.38	22.1

Profile 6 – Eutric Fluvic Arenosol

Location: Sandy fluvial sediments, plain, inclination 3°, row-crop maize with semi deciduous tropical forest, 197 m a.s.l., San Miguel del Puerto Town, **N** 15.89862°, **S** 96.17182°



Morphology:

- Ap** – 0–10 cm, humus ploughed horizon, sand, dark brown (10YR 3/3), weak subangular blocky medium, 10% stony, abrupt and wavy boundary;
- 2AB** – 10–19 cm, sand, dark yellowish brown (10YR 4/4), weak subangular blocky medium, 2% stony, abrupt and wavy boundary;
- 3A** – 19–28 cm, sand, very dark grayish brown (10YR 3/2), weak subangular blocky fine, 2% stony, clear and wavy boundary;
- 4BC1** – 28–48 cm, sand, dark brown (10YR 3/3), weak subangular blocky coarse, 2% stony, gradual and irregular boundary;
- 4BC2** – 48–67 cm, sand, dark brown (10YR 3/3), weak subangular blocky coarse, 2% stony, clear and irregular boundary;
- 5CB** – 67–84 cm, sand, dark brown (10YR 3/3), single grain structure, 2% stony, clear and smooth boundary;
- 6CB** – 84–97 cm, sand, dark brown (10YR 3/3), single grain structure, 2% stony, gradual and smooth boundary;
- 7CB** – 97–105 cm, sand, dark brown (10YR 3/3), single grain structure, 2% stony, gradual and smooth boundary;
- 8CB** – 105–112 cm, sand, dark brown (10YR 3/3), single grain structure, 2% stony, abrupt and irregular boundary;
- 9CB** – 112–130 cm, sand, dark brown (10YR 3/3), single grain structure, 40% stony.

Table 11. Physicochemical properties and texture of Profile 6

Horizon	Depth (cm)	pH H ₂ O	OM (%)	Texture			Class
				Sand	Silt	Clay	
A	0–10	7.7	0.13	-	-	-	S
2AB	10–19	7.4	3.48	-	-	-	S
3A	19–28	7.4	0.53	-	-	-	S
4BC1	28–48	7.5	1.67	-	-	-	S
4BC2	48–67	7.4	0.86	-	-	-	S
5CB	67–84	7.4	0.17	-	-	-	S
6CB	84–97	7.3	0.26	-	-	-	S
7CB	97–105	7.5	0.13	-	-	-	S
8CB	105–112	7.2	0.02	-	-	-	S
9CB	112–(130)	7.4	0.06	-	-	-	S

Table 12. Exchange cations of Profile 6

Horizon	Depth (cm)	Ca		Mg		K		Na		CEC (meq 100g ⁻¹)	BS (%)
		(meq 100g ⁻¹)	(%)	(meq 100g ⁻¹)	(%)	(meq 100g ⁻¹)	(%)	(meq 100g ⁻¹)	(%)		
A	0–10	4.7	81.3	0.95	16.3	0.12	2.05	0.02	0.34	5.84	100
2AB	10–19	8.0	78.6	1.82	17.8	0.28	2.75	0.04	0.39	10.2	99.6
3A	19–28	5.5	74.0	1.70	22.7	0.22	2.94	0.03	0.40	7.49	100
4BC1	28–48	6.5	76.6	1.84	21.5	0.14	1.64	0.02	0.23	8.56	100
4BC2	48–67	5.5	76.1	1.59	21.7	0.13	1.77	0.03	0.41	7.33	100
5CB	67–84	5.4	78.2	1.32	19.1	0.15	2.17	0.04	0.58	6.92	100
6CB	84–97	4.0	81.8	0.77	15.7	0.10	2.04	0.02	0.41	4.90	100
7CB	97–105	5.0	83.6	0.86	14.3	0.10	1.66	0.03	0.50	6.02	100
8CB	105–112	3.7	80.8	0.78	16.7	0.09	1.92	0.03	0.64	4.68	100
9CB	112–(130)	4.9	82.9	0.91	15.3	0.09	1.51	0.02	0.34	5.96	100

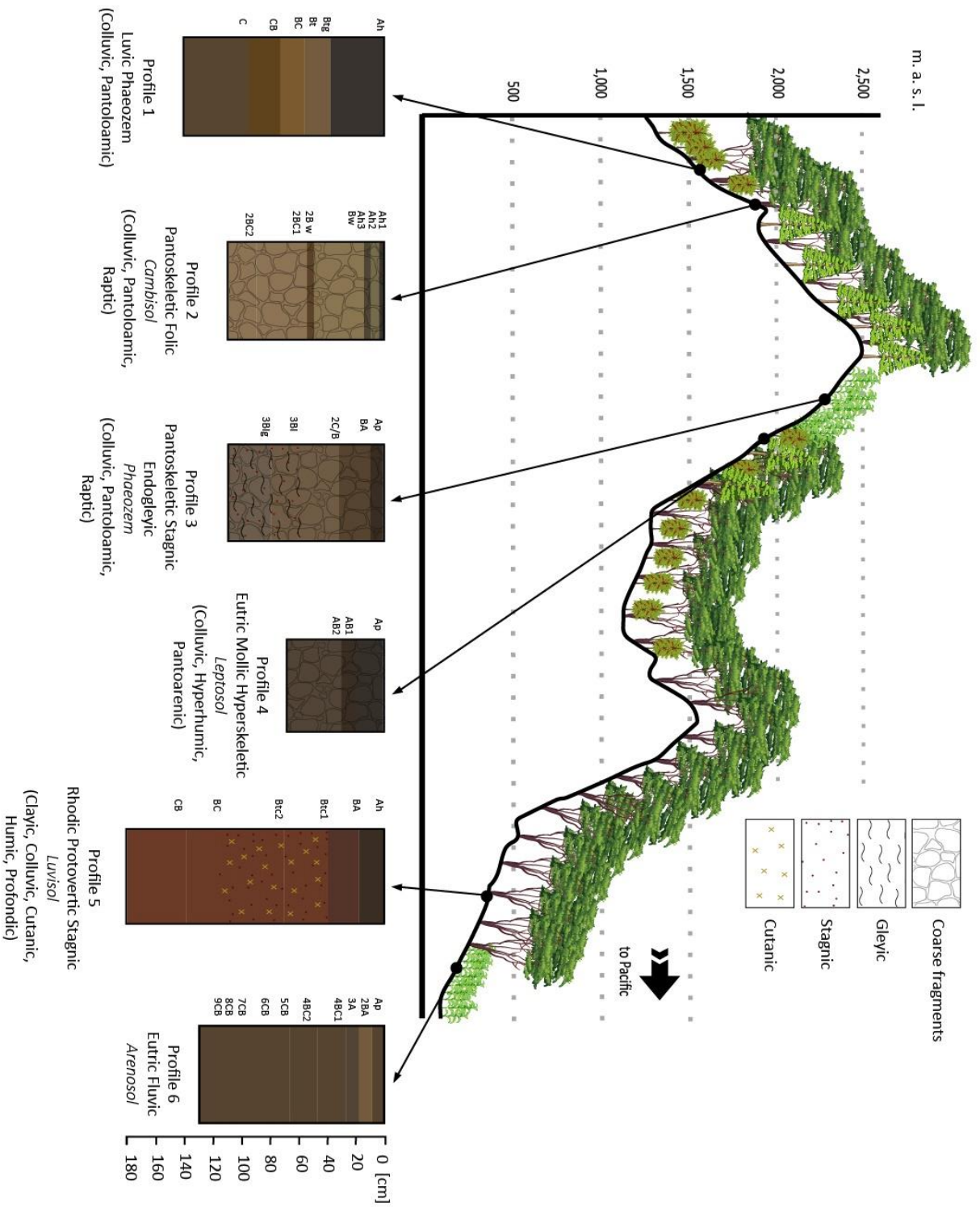


Figure 2. Toposequence of soils of coffee agroforestry systems in Southern Mexico

Soil genesis (discussion)

The Copalita basin is composed of a high lithological diversity with scraped slopes that allow active erosional and depositional processes. Furthermore, in the basin exists a climatic transition based on the altitudinal range. In this way, the communal organization for coffee agroforestry systems management depends more on climate and vegetation than on soil. These systems are found in the *climatic altitudinal range of coffee*, between 1.000 and 2.000 m a.s.l.

In order to understand the soil-forming processes and provide useful information to local farmers, the six soil profiles are located among different geomorphic positions in the topographic sequence; they also cover the principal climatic conditions in the basin including the climatic altitudinal range of coffee (Figure 2). Because of the high lithological diversity in the basin, the parent material varies between the soils.

Profile 1 is found in a micro-relief which promotes a relative environmental stability for pedogenetic processes with medium rates according to the characteristic times of soil formation (Targulian and Krasilnikov, 2007), specifically clay illuviation. This soil presents relative vegetation cover stability, clay coatings (**argic horizon**), soil organic carbon (**mollic horizon**), and colluvial materials especially on the bottom (**colluvic materials**). In this way, Profile 1 is classified as **Luvic Phaeozem (Colluvic, Pantoloamic)**.

Profile 2 is located at the top of the climatic altitudinal range of coffee and on a secondary upper slope. The erosional processes bring out colluvial materials from higher portions and deposit colluviums in the soil body constantly (**pantoskeletal qualifier** and **colluvic materials**). Nonetheless, there is a thick superficial organic layer related to the vegetation (**follic horizon**), it avoids soil erosion and it helps to incorporate the colluviums into the soil body. The colluviums also lead the soil by a polygenetical way with a lithic discontinuity (**raptic qualifier**). So, this soil is classified as **Pantoskeletal Follic Cambisol (Colluvic, Pantoloamic, Raptic)**.

Profile 3 represents one of the highest positions in the Copalita basin under maize crops. This soil profile shows three pedogenic cycles with a strong influence of colluviums (**Pantoskeletal qualifier** and **colluvic materials**), and hydromorphic changes as well. The first stage of this pedo-complex illustrates poorly drained conditions (**gleyic** and **stagnic properties**). The colluviums that buried the first stage and their soil-forming processes represent the second stage, with well-drained conditions. On the top of the soil profile can be found the third stage of the pedo-complex, characterized by another colluvial event and a relative stability thanks to the organic matter (**mollic horizon**). Thus, this soil is classified as **Pantoskeletal Stagnic Endogleyic Phaeozem (Colluvic, Pantoloamic, Raptic)**.

Profile 4 is found in the climatic altitudinal range of coffee. Nonetheless, it differs from **Profile 1** because of its higher content of coarse fragments and shorter thickness. The colluvial activity has affected this soil as well (**hyperskeletal qualifier** and **colluvic materials**). Nevertheless, Profile 4 does not show well-developed B-horizons like Profiles 1, 2, and 3. Instead, the organic matter and the litter (**mollic horizon** and **hyperhumic qualifier**) play an important role protecting the soil-forming process from erosion. This soil profile is classified as **Eutric Mollic Hyperskeletal Leptosol (Colluvic, Hyperhumic, Pantoarenic)**.

Profile 5 shows a long-term environmental stability which has allowed clay illuviation (**cutanic qualifier**) and strongly weathered parent materials on the bottom (**profundic qualifier**). This soil also presents a thick Ah horizon (**humic qualifier**). Even though there are some colluvial materials (**colluvic qualifier**), the soil-forming suitability is represented by an **argic horizon** with stagnic

conditions, and incipient vertic characteristics (**protovertic horizon**). In this way, Profile 5 is classified as **Rhodic Protovertic Stagnic Luvisol (Clayic, Colluvic, Cutanic, Humic, Profondic)**.

Finally, **Profile 6** is located in the Pacific plain under maize crops. This soil has a strong alluvial influence (**Fluvic**), and it is constituted by 9 principal pedogenic-sedimentary cycles with sandy texture. This soil is classified as **Eutric Fluvic Arenosol**.

In the Copalita basin, the colluviums work as parent materials for the soil-forming process; they re-start the pedogenic clock continuously. Furthermore, the addition of organic matter into soil thanks to the agroforestry systems prevents soil erosion from slope processes. In other words, on the mountainous portion of the Copalita basin, the colluviums and soil organic matter are facing a never-ending dispute to protect their own interests: to maintain the morphogenetical or pedogenetical process active.

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Soil Toposequence in the Busiljá Valley and its relationship with prehispanic anthropic activities (Chiapas, Mexico)

Karla Andrea Guillén Domínguez, Elizabeth Solleiro Rebolledo, Sergey Sedov, Charles Golden, Andrew K. Scherer, Axel Cerón González

The Busiljá Valley is located in the northeast of Chiapas State (Southeastern Mexico), where the tropical mountain karst landscape of the Sierra Madre de Chiapas is one of the most prominent features (Fig.1). This valley owes its name to the Busiljá River, a small tributary stream that joins the the Usumacinta River to flow northwest into the Gulf of Mexico. The Sierra Madre de Chiapas, which rises to its maximum heights far to the southwest of the Busiljá valley, is constituted by a thick sedimentary sequence of limestones, interbedded with evaporates (gypsum). The low hill ranges along the western edge of the valley, from which the water drains to form the Busiljá itself, is known as the Sierra Guiral. The soils which develop on this geofom consists of Leptosols, Luvisols, Cambisols, Vertisols, Nitisols, Gleysols and Arenosols (Bautista et al., 2011; INEGI 2017). However, some soils have been modified by anthropogenic processes since pre-Hispanic times, specifically for land use changes.



Fig. 1. Location

Lithology and topography

The study area lies over a calcareous bench due to the marine transgression of the early Cretaceous period (145–66 Ma), which resulted in the sedimentation of carbonates and evaporitic rocks, such as gypsum and anhydrites. After this event, this sedimentary sequence was strongly folded by the Chiapaneca Orogeny during the Miocene period (23.03 to 5.3 Ma), which created a set of NW-SE oriented ridges and alluvial plains (Burkart, 1983; Moran et al., 1984). Finally, during the Holocene period (beginning around 11.65 kya), the Sierra Madre de Chiapas was surrounded by fluvial and alluvial sediments, as a result of weathering and erosion of the rocks in the area.

Land use

Before the late 20th century, the Busiljá Valley was predominantly covered with tropical forest, including cedar and fruit trees. Beginning in the 1960s and 1970s, increasing human populations and a growing reliance on ranching, as well as the development of infrastructure to support these have led to significant deforestation in fluvial plains and valleys.

Climate and hydrology

According to INEGI (2017), the region is in a warm-subhumid climate, with an annual precipitation of 1200–4000 mm, distributed during the whole year. During summer, between June and September, the average temperature is 30°C, during winter the minimum is 17.5°C, with a marked increase in monthly precipitation. Additionally, one of the dominant landscape features is Usumacinta River, which drains the entire region and forms the modern political border between Guatemala and Mexico.

Profile 1 – Rendzic Phaeozem (Clayic, Colluvic, Hyperhumic)

Location: Inside of a karstic lens on the slope of a hill, 118 m a. s. l.,
N 17°7'6.94", W 91°22' 38.32"



Morphology:

- Ah1** – 0–30 cm, humus horizon, granular structure, very dark brown 7.5YR 2.5/2, loamy sand, 5% stony, many medium roots;
- Ah2** – 30–80 cm, humus horizon with less amount of organic carbon, granular structure, very dark brown 7.5YR 2.5/2, texture silty clay, less medium roots than Ah1. This horizon and Ah1, belong to a colluvium;
- Bw** – 80–130 cm, mineral horizon, subangular blocky structure, strong brown 7.5YR 5/6, fine roots. At the bottom of the horizon, there is a high proportion of cultural material, fragments of pottery, bones, snails, and charcoal;
- C** – 130–140 cm, limestone rock slabs and cultural material like bones;
- 2BC** – 140–(200) cm, calcareous parent material, poor pedological structure, strong brown 7.5YR 5/8, silty clay texture.

Table 1. Soil Texture

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural Class
Ah1	0–30	31.0	29.8	39.2	CL
Ah2	30–80	7.7	50.8	41.5	SiC
B	80–130	13.8	33.6	52.6	SiC
2BC	>130	50	25	35	SCL

Table 2. Physicochemical properties

Horizon	Depth (cm)	pH H ₂ O	EC (μS/cm)	OC (%)	N (%)	C/N	CEC (cmol(+)-kg)
Ah1	0–30	7.57	501.2	5.92	0.62	9.54	81.7
Ah2	30–80	8.01	394.1	4.12	0.38	10.84	71.0
B	80–130	8.33	248	1.26	0.13	9.69	26.8
BC	>130	8.47	202.8	-	-	-	-

Profile 2 – Leptic Luvisol (Clayic, Cutanic)

Location: on the top of a hill, 116 m a. s. l., **N** 17°07'29.3", **W** 91°23'16.7"



Morphology:

- A** – 0–4 cm, humus horizon, granular structure, dark red 2.5YR 3/6, clay texture, high medium-fine roots. With little fragments of charcoal.
- Bt1** – 4–24 cm, *argic* horizon, subangular blocky structure, dark red 2.5YR 3/6, clay texture, fine roots. With little fragments of coal, but less than horizon A.
- Bt2** – 24–(40) cm, *argic* horizon, hard subangular blocky structure, red 2.5YR 4/8, lower density of fine roots, stones 30–40%.

Table 3. Texture

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural Class
A	0–5	5.5	10.5	84.0	C
Bt1	5–14	7.4	11.6	81.0	C
Bt2	14–(32)	6.4	8.3	85.3	C

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	pH H ₂ O	EC (μS/cm)
A	0–5	6.8	517.2
Bt1	5–14	6.7	512.2
Bt2	14–(32)	7.4	574.5

Profile 3 – Eutric Gypsic Reductic **Gleysol** (Clayic, Protovertic, Ochric)

Location: Busiljá Valley, proximate to the river of the same name, 114 m a. s. l.,
N 17°07'15.9", W 91°22' 41.7"



Morphology:

- Ap** – 0–15 cm, humus horizon, compact granular structure, very dark brown 10YR 2/2, silty clay, high proportion of medium-fine roots;
- Cgiy** – 15–40 cm, gypsic horizon, angular blocky structure, dark grayish brown 10YR 4/2, clay, shows slickensides and a high proportion of gypsum crystals, size: medium sand;
- Cgy** – 40–(70) cm, gypsic horizon, subangular blocky structure, dark grayish Brown 10YR 4/2, clay, with a high proportion of gypsum crystals, size: coarse sand.

Table 5. Texture

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural Class
Ah	0–8	1.0	15.0	84.0	HC
Cgiy	8–26	0.86	43.04	56.1	SiC
Cgy	26–(55)	20.76	6.22	73.02	HC

Table 6. Chemical and physicochemical properties

Horizon	Depth (cm)	pH H ₂ O	EC (μS/cm)	OC (%)	N (%)	C/N	CEC (cmol(+).kg)
Ap	0–8	5.75	2445	11.7	12.1	0.97	81.7
Cgiy	8–26	7.2	2485	-	-	-	-
Cgy	26–(55)	7.6	2530	-	-	-	-

The next soil toposequence is shown in figure 2. Profile 1 is located in a karstic lens infilled by colluvial sediments. Profile 2 is formed in on the limestone in a more stable position. However, the thickness is small. Profile 3 is located at the lowest position, where the water table is close to the surface.

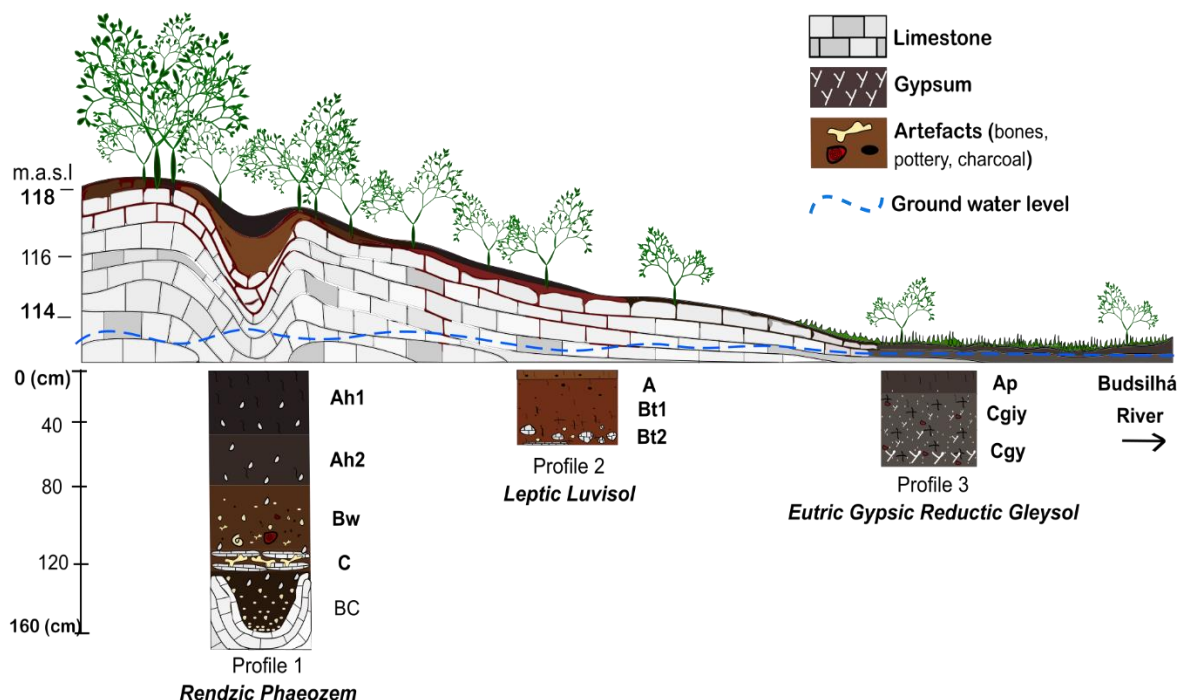


Fig. 2. Toposequence of soils in Busiljá Valley

Soil genesis and anthropic impacts

The morphology and classification of the soils of the Busiljá Valley are the result of pedogenetic processes influenced by the topographic position and hydrological conditions, as well as by the human impact in the last millennia. Natural resources have been used as raw materials for the creation of pottery, construction, and agriculture. The evidence of such impact can be clearly seen in profile 1, where there is anthropogenic material and the soil has not been disturbed for a long time.

Therefore, on top of the hills in depressions and karstic lenses, Phaeozems, which are rich in organic matter, are found. On slopes, Leptosols, which are reddish and with clay texture, are common. Meanwhile in the depressions, Gleysols appear showing greyish colors and neoformation of gypsum crystals, due to oxidation-reduction processes.

Genesis of soils with presence of gypsum

According to WRB 2015, soils demonstrating the presence of gypsum are commonly found in the arid climates. However, profile 3 has neoformation of secondary gypsum. There are two hypotheses about their genesis. The first considers gypsum precipitation from water enriched in sulfates, from the dissolution of surrounding rocks as evaporates. The second hypothesis proposes a more complicated process, in which the origin of the sulfate ions is due to the presence of minerals rich in sulfur, such as pyrite (FeS₂) in the parent material. Through weathering and oxidation, the sulfur of this mineral is

transformed into sulfuric acid, which interacts with the water of the environment, forming sulfuric acid, which in calcareous soils, reacts to form gypsum (FAO 1990; Poch et al., 2018; Rivera, 2020).

Conclusions

The studied soils show a variability in their formation processes, mainly depending on the geomorphological conditions. The position in the relief, plays an important role in the soil's evolution. Since, the parental material is conditioned by the relief, due to the high geomorphological dynamics in the area. Here karstic processes erode the soil surface cover, especially when the vegetation is altered, either by natural or anthropic processes, like deforestation.

Finally, the evolution of soils in a tropical karst landscape has been modified over the years due to the land use. However, nowadays soils and archaeological remains of the Busiljá Valley have been increasingly affected by deforestation and the excavation of rocks and soils as material banks for construction of nearby towns. The remains of the Pre-Hispanic Maya and their impacts on and engagement with ancient soils are better preserved in karstic lens and the more remote portions of the area.

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Megafan Soil Catena in The Guajira Semi-arid Zone

Juan Carlos Loaiza-Usuga, Tomasz Zaleski

The studied transect corresponds to the lowest part of the Guajira at the Barrancas village (Colombia) figure 1, under Tropical dry to really dry forest conditions, with a temperature average of 27,7°C and a maximum of 40°C, being the hottest months in July and August. The average rainfall is between 500 and 1000 mm and there are from 50 to 100 days of rain per year. Climatic conditions of high temperatures and low precipitations have preserved the parental materials (originated in high chemical weathering conditions), which is at present undergoing slow physical weathering that favors the conservation of the soil profile. There are conditions of a depositional environment and a colluvio-alluvial megafan presence.

The parental material is made by alluvial sediments of Rancheria river and by colluvio-alluvial sediments of the coalescent fans of the Sierra Nevada de Santa Marta oriental foothill. The abrupt change of topography (from steep to almost flat relief) is the consequence of an intense tectonic activity of the geological fault of Santa Marta. The soils are developed on quaternary deposits from Pleistocene – Holocene (Bürgl, 1960) with presence of stones layers and soil horizons rich in carbonates. There are Typic calciustepts, Udic Calciusterts, Vertic Calciustepts and Udic Caciustepts according to Soil taxonomy (2014). The studied soils of the Barrancas zone have had low pedogenetic development characterized by dry environment processes as low clay formation, low illuviation and long periods of water scarcity and high evapotranspiration. This megafan system was characterized by fresh colluvo-alluvial parental material and low weathering processes that formed a low developed calcic endopedons. Andean tectonic phenomena favor denudative process and fluvial torrential flows which rejuvenated soil profiles. Low precipitation, low illuviation and high evapotranspiration demand in combination with water irrigation make these soils highly susceptible to salinity affectation.

Lithology and topography

The study area is located in a depositional environment, influenced by the oriental slope foothill from the Sierra Nevada de Santa Marta, and the alluvial deposits from the Rancheria River, forming the Barracas Megafan between the Serrania de Perijá and Sierra Nevada of Santa Marta. These coalescent alluvial fans were originated under the influence of a fluvial system formed by rivers that come from the oriental slope of Sierra Nevada de Santa Marta towards the Ranchería river. This fan is formed mostly by granitic, highly altered with high number of gravels (Figure 2).



On the surface there is a layer of coarse sands above the strongly cemented gravels overlying a gray clayey cemented substrate rich in gravels and pebbles of variable diameter and shape (Bürgl, 1960; Cerrejon, 2010). There is a relief with slight inclinations; the sediments that conform to this fan have a well-defined pattern. In the apex coarse materials predominate and the sediments decrease in size and quantity until thin sediments predominate on the distal part of the fan. The terminal part of the fan on the foothill is sometimes confused with Rancheria river alluvial valley (IGAC, 2009). The floodplain of the foothill has a direct influence on the stream system that provides from the foothill range, hemmed in between the fan edge, where the permeable horizons of gravels and sands are combined with impermeable horizons of limes and clays (Bürgl, 1960; Cerrejon, 2010).

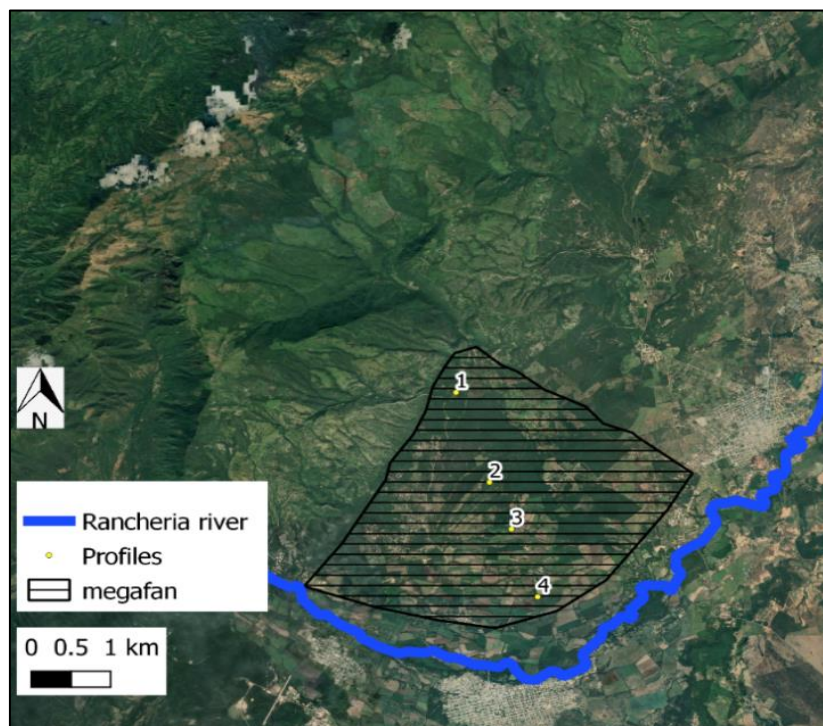


Fig. 2. Soil profiles position

Climatic conditions

The annual rainfall average is 837 mm, oscillating between 500 mm/year to 1000 mm/year, with 50 to 100 days of precipitation (EOT, 2018). The rainfall regime is bimodal with higher precipitation in April, June, July, August, September and December. The precipitation decreases during the last two months. The rainfall regime is directly influenced by the convergence intertropical zone (ZCIT). The average temperature is 27.7°C, with an absolute maximum temperature of 40.8°C and absolute minimum temperature of 16.4°C, and the warmest months are July and August (EOT, 2018; IDEAM, 2021). There is water deficit for most of the year as the evapotranspiration exceeds the contributions provided by rainfall with an ustic moisture regime and isohyperthermic temperature regime. The climatic and plant zone entails a transition from a dry tropical forest (Bs-T) to very dry tropical forest (bms-T) according to Espinal (1989).

Soil use

Nowadays soil use corresponds to forested pastures under extensive livestock farming, dense scrubland under protection and parcels of cassava, corn, muskmelon and watermelon crops. Some areas have a high degree of eroded soil cover with gully and furrows presence which makes vegetation growth impossible. The soil potential use is characterized by the presence of areas suitable for the development of highly technical agriculture, farming systems and forestry, with suitable zones for extensive grazing and silvopastoral systems (IGAC, 2019). In this area, there is 61% of the national goat stock, 46% of the national sheep stock and 0.22 cows per hectare (the lowest ratio in Colombia). The forestry plantations are 0.3% of the land and the most part of the land (65%) is destined mostly to banana crops for export markets (DANE, 2015). As dominant species there are *Prosopis juliflora*, *Quadrella odoratissima*, *Opuntia caracasana*, *Caesalpinia mollis*, *Guazuma ulmifolia*, *Crescentia cujete*, *Prosopis juliflora* (López et al., 2016); and pasture species for cattling such as *Panicum maximum*, *Pennisetum purpureum*, *Bothriochloa pertusa*, *Urochloa brizantha* y *Cynodon nlemfuensis*.

There are sodic and saline sodic soils, features associated with the soil parent materials, climatic conditions and the introduction of water irrigation from some of the water wells. Most of the area corresponds to arid and semi-arid regions, with a low productivity index and low capability of protection use, with severe hydric limitations.

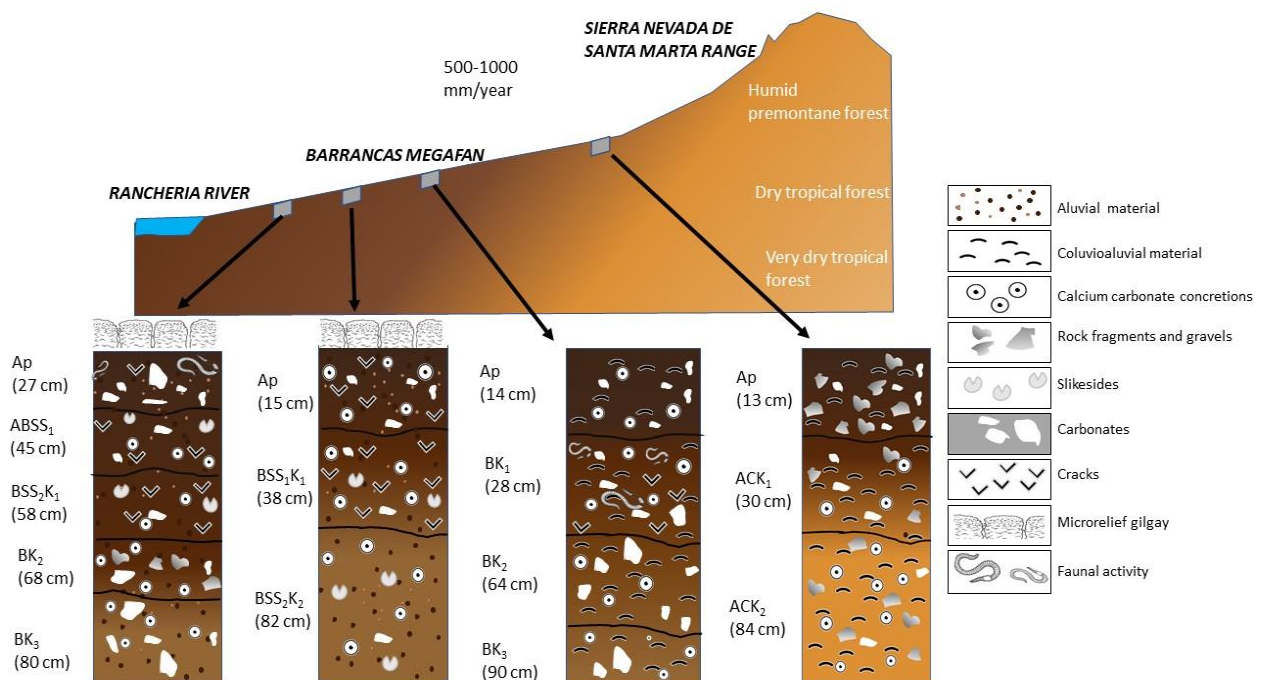


Fig. 3. Cross section of Barrancas Megafan with the studied soil sequence in colluvium-alluvial and alluvial deposits

Profile 1 – Petric Skeletic **Calcisol** (Loamic, Hypocalcic, Ochric)

Location: Barracas colluvial aluvial Megafan apex, Barrancas Municipality (Guajira), 220 m a.s.l.,
N 10°57'50.7"; W 72°51'34.0"



Morphology:

- Ap** – 0–13 cm, humus horizon with high organic matter content, brown (10YR 4/3) dry, dark brown (10YR3/3) moist, moderate granular very fine to subangular blocky structure, dry consistence soft, moist consistence friable, many fine to medium roots, abundant rock fragments, frequent carbonates, few shell fragments, strongly calcareous, clear and smooth boundary;
- ACk1** – 13–30 cm, *calcic* horizon rich in rock fragments inside fine soil matrix rich in carbonates (30%), pale brown (10YR 6/3) moist, fine and medium gravels (70%), medium crumbly very fine to fine structure, dry consistence soft, moist consistence friable, high porosity very fine and fine, many very fine to fine roots, abundant soft concretions brown (10YR 4/3) dry, dark yellowish brown (10YR 4/4) moist, accumulation of light yellowish brown (10YR 6/4) material in channels, strongly calcareous, clear and smooth boundary;
- ACk2** – 30–(84) cm, *calcic* horizon slightly hardened by calcium carbonates, very pale brown (10YR7/3) dry, fine and medium gravels (80%), medium to low fine porosity, strongly calcareous.

Table 1. Texture and physical properties

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class	COLE	BD [Mg·dm ⁻³]	Soil Moisture in Potential		
		> 2.0	2.0-0,05	0,05-0,002	< 0.002				0.3 Bar	1.0 Bar	15 Bar
Ap	0–13	0	50	30	20	L	0.07	1.23	18.7	20.2	7.1
ACK1	13–30	70	44	26	30	CL	--	1.38	24.4	19.1	12.5
Ck2	30–(84)	80	52	20	28	SCI	--	--	--	--	--

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	pH [H ₂ O 1:1]	OM [g·kg ⁻¹]	CEC	Exchange Cations				
					Ca ²⁺	Mg ²⁺	K ²⁺	Na ²⁺	Al ³⁺ +H ⁺
cmol(+)-kg ⁻¹									
Ap	0–13	8.0	55.0	36.48	34.6	1.2	0.58	0.10	0.00
ACK1	13–30	8.4	20.0	31.54	30.9	0.31	0.23	0.10	0.00
Ck2	30–(84)	8.0	7.40	33.85	32.8	0.35	0.23	0.37	0.00

Profile 2 – Petric Calcisol (Loamic, Hypocalcic, Ochric)

Location: Barracas Megafan body (high mid) colluvial-alluvial, Barrancas Municipality (Guajira), 180 m a.s.l., N 10°56'40.3", W 72°51'07.8"



Morphology:

- Ap** – 0–14 cm, humus horizon, very dark grayish brown (10YR 3/3, 10YR 3/2), moderate medium to fine subangular blocky structure, dry consistence very hard, moist consistence firm, few porosity fine to very fine, common fine to very fine roots, frequent calcium carbonates, abundant fine calcium carbonate concretions, clear and smooth boundary;
- Bk1** – 14–28 cm, *calcic* horizon, very dark grayish brown (10YR 3/2), moderate medium to fine subangular blocky structure, dry consistence very hard, moist consistence firm, medium porosity fine to very fine, fine porosity related to arthropofaunal activity (Earthworms), common very fine roots, irregular vertical cracks, abundant fine calcium carbonate concretions, clear and smooth boundary;
- Bk2** – 28–64 cm, *calcic* horizon, very dark grayish brown (10YR 4/2) in 60% and very pale brown (10YR 7/3) in 40%, moderate medium to coarse subangular blocky structure, dry consistence extremely hard, moist consistence very firm, few porosity fine to very fine, few very fine roots, common very fine calcium carbonate crystals, abundant fine calcium carbonate accumulations, very fine powder in the roots channels (pore infillings) and irregular concretions, clear and smooth boundary;
- Bk3** – 64–(90) cm, *calcic* horizon moderately hardened by calcium carbonates, yellowish brown (10YR 5/6, 10YR 5/3), moderate medium to coarse subangular blocky structure, dry consistence extremely hard, moist consistence very firm, few medium roots, common very fine calcium carbonate crystals, abundant fine calcium carbonate accumulations very fine to medium, strongly calcareous.

Table 3. Texture and physical properties

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class	COLE	BD [Mg·dm ⁻³]	Soil Moisture in Potential		
		> 2.0	2.0-0,05	0,05-0,002	< 0.002				0.3 Bar	1.0 Bar	15 Bar
Ap	0–14	0	16	46	38	SCL	0.12	1.07	27.2	23.38	14.79
Bk1	14–28	0	30	32	38	CL	0.14	0.94	27.3	17.7	14.04
Bk2	28–64	20	24	30	46	C	0.13	1.42	21.06	19.2	9.13
Bk3	64–(90)	20	24	38	38	L	0.13	1.48	19.16	18.36	9.25

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	pH [H ₂ O 1:1]	OM [g·kg ⁻¹]	CEC	Exchange Cations				
					Ca ²⁺	Mg ²⁺	K ²⁺	Na ²⁺	Al ³⁺ +H ⁺
cmol(+)·kg ⁻¹									
Ap	0–14	8.1	48	28.21	23.2	3.5	1.19	0.32	--
Bk1	14–28	8.6	27	38.07	30.4	4.8	0.47	2.40	--
Bk2	28–64	8.8	16	40.33	29.4	7.0	0.36	3.57	--
Bk3	64–(90)	8.0	08	56.77	48.3	3.3	0.30	4.87	--

Profile 3 – Calcic Vertisol (Hypereutric, Gilgaic, Ochric)

Location: Sencca between Ollachea and San Gabán municipality – Puno region; slope 98% northeast, land use rocoto chilli, cassava, coffee and corn; 1827 m a.s.l., S 13°39'54.838, W 70°28'29.666''



Morphology:

- Ap** – 0–15 cm, humus horizon, very dark grayish brown (10YR 4/3, 10YR 3/2), moderate fine to very fine crumbly to subangular blocky structure, dry consistence loose, moist consistence very friable, few channels fine to very fine, common fine to very fine roots, common cracks, presence of gilgai microrelief, abundant fine gravels, abundant to frequent calcium carbonates concretions (disperse powdery lime) fine to very fine, abundant fine yellowish red (5YR4/6) material, strongly calcareous, clear and smooth boundary;
- Bik1** – 25–38 cm, *calcic* and *vertic* horizon, yellowish brown (10YR 4/3, 10YR 4/2), moderate, coarse to moderate subangular blocky structure, dry consistence slightly hard, moist consistence firm, abundant porosity fine to very fine, few very fine roots, common cracks filled with very dark grayish brown (10YR3/2) material from Ap horizon, common distinct slickensides pedfaces, abundant fine subrounded gravels, abundant calcium carbonates concretions (disperse powdery lime) fine to very fine, abundant fine calcium carbonate powder, clear and smooth boundary;
- Bik2** – 38–(82) cm, *calcic* and *vertic* horizon, yellowish brown (10YR 4/3, 10YR 4/2) moderate, coarse subangular blocky structure, dry consistence hard, moist consistence very firm, abundant porosity fine to very fine, common shells (< 1 cm diameter), many distinct slickensides pedfaces, abundant fine and medium subrounded gravels, abundant calcium carbonates concretions (disperse powdery lime) very fine to medium, common fine calcium carbonate powder, strongly calcareous.

Table 5. Texture and physical properties

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class	COLE	BD [Mg·dm ⁻³]	Soil Moisture in Potential		
		> 2.0	2.0-0,05	0,05-0,002	< 0.002				0.3 Bar	1.0 Bar	15 Bar
Ap	0–15	0	34	30	36	CL	0.11	0.86	23.86	18.73	12.27
Bik1	25–38	0	24	32	44	C	0.10	1.25	22.78	21.26	13.26
Bik2	38–(82)	0	26	28	46	CL	0.16	1.1	23.97	22.6	15.06

Table 6. Chemical and physicochemical properties

Horizon	Depth [cm]	pH [H ₂ O 1:1]	OM [g·kg ⁻¹]	CEC.	Exchange Cations				
					Ca ²⁺	Mg ²⁺	K ²⁺	Na ²⁺	Al ³⁺ +H ⁺
cmol(+).kg ⁻¹									
Ap	0–15	8.1	4.8	30.94	26.7	3.8	0.33	0.11	--
Bik1	25–38	8.6	2.7	36.55	31	3.6	0.41	1.54	--
Bss2k2	38–(82)	8.0	0.8	37.69	27.5	4.7	0.45	5.04	--

Profile 4 – Calcic Vertisol (Mollic, Hypereutric, Gilgaic)

Location: Barrancas Megafan toe alluvial, Barrancas Municipality (Guajira), 145 m a.s.l.,
N 10°54'46.9", W 72°50'25.5



Morphology:

- Ap** – 0–27 cm, *mollic* horizon, very dark grey (10YR 3/1), moderate to coarse subangular blocky structure, dry consistence slightly hard, moist consistence firm, high porosity fine to very fine, few medium porosity from arthropofaunal activity (earthworm and ants), common fine to very fine roots, few medium and coarse roots, presence of gilgai microrelief, strongly calcareous, clear and smooth boundary.
- ABi** – 27–45 cm, transitional horizon, dark yellowish brown (10YR 4/4), moderate, coarse to moderate subangular blocky structure, dry consistence slightly hard, moist consistence firm, high porosity fine to very fine, few medium porosity, few very fine and medium roots, common fine calcium carbonate powder, common distinct slickensides pedfaces, common cracks filling with very dark gray (10YR3/1) material from Ap horizon, common very fine calcium carbonate powder in channels and pedfaces, common calcium carbonates concretions (disperse powdery lime) very fine, strongly calcareous, clear and smooth boundary.
- Bik** – 45–58 cm, *calcic* and *vertic* horizon, dark yellowish brown (10YR 4/6) in 80%, very pale brown (10YR 7/4) in 10%, dark brown (10YR3/3) in 10%, moist, moderate, moderate to fine subangular blocky structure, dry consistence hard, moist consistence firm, high porosity fine to very fine, few medium porosity, common very fine and few medium and coarse roots, common slickensides, few cracks filling with dark yellowish brown (10YR4/4) material from AB horizon, many very fine calcium carbonate powder in channels

and pedfaces and calcium carbonates concretions (disperse powdery lime) fine and very fine, strongly calcareous, clear and smooth boundary.

Bk1 – 58–68 cm, *calcic* horizon, dark yellowish brown (10YR4/6) moist (40%), fine and medium gravels (60%), moderate, moderate to fine subangular blocky structure, dry consistence hard, moist consistence firm, high porosity fine to very fine to medium porosity, few very fine roots, very few slickensides, abundant fine subrounded gravels, a lot of very fine calcium carbonate powder and calcium carbonates concretions (disperse powdery lime) very pale brown (10YR7/4) fine and very fine, strongly calcareous, clear and smooth boundary.

Bk2 – 68–(80) cm, *calcic* horizon, brownish yellow (10YR6/6) in 70%, very pale brown (10YR7/4) for very fine calcium carbonate concretions in 30%, moderate, moderate to fine subangular blocky structure, dry consistence very hard, moist consistence, extremely firm, low porosity fine to very fine, few very fine roots, many calcium carbonates, extremely calcareous.

Table 7. Texture and physical properties

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class	COLE	BD [Mg·dm ⁻³]	Soil Moisture in Potential		
		> 2.0	2.0-0,05	0,05-0,002	< 0.002				0.3 Bar	1.0 Bar	15 Bar
Ap	0–27	0	20	34	46	C	0.16	1.42	25.92	20.23	13.55
ABi	27–45	0	20	32	48	C	0.15	1.48	25.92	20.44	12.59
Bik	45–58	0	24	30	46	C	0.13	1.42	23.59	21.02	10.62
Bk1	58–68	0	30	30	40	CL	0.13	1.45	21.06	19.2	9.13
Bk2	68–(80)	0	26	34	40	CL	0.13	1.32	19.16	18.36	9.25

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	pH [H ₂ O 1:1]	OM [g·kg ⁻¹]	CEC	Exchange Cations				
					Ca ²⁺	Mg ²⁺	K ²⁺	Na ²⁺	Al ³⁺ +H ⁺
cmol(+).kg ⁻¹									
Ap	0–27	8.0	36	35.90	33.0	2.3	0.48	0.12	--
ABi	27–45	8.1	15	42.60	40.1	1.9	0.46	0.14	--
Bik	45–58	8.3	7.7	40.00	38.0	1.5	0.35	0.15	--
Bk1	58–68	8.3	6.1	42.63	40.2	1.9	0.38	0.15	--
Bk2	68–(80)	8.4	7.5	41.79	39.2	2.1	0.35	0.14	--

Soil genesis and systematic position

The Barracas megafan soils were formed in a pedo-sedimentary environment under dry seasonal conditions, for which alternation of pedological and geological processes is clear. The pedogenesis of deposition materials have a close relation to land surface stability when soil forming processes evolve in relation to sedimentation rates variation. The analyzed soils are morphologically diverse; developed from aggrading materials, transported and transformed from erosion and river sedimentation. The abrupt change of topography (from steep to flat relief) is the consequence of an intense tectonic activity of the geological fault of Santa Marta, the parental material is made by alluvial sediments of Ranchería river and by colluvium alluvial sediments of the coalescent fans of the Sierra Nevada de Santa Marta oriental foothill. This phenomenon is reported as another megafan in Andes Mountains by Loaiza et al. (2017).

The upper part or fan is predominated by coarse materials which decrease in size and amount gradually downslope, until being located at the distal part as thin sediments. Parental materials are composed of granitic materials, highly disturbed (sand-alteration of granite), sequence of coarse sands, highly cemented gravels, grey clay substrate cemented with gravel and rounded pebbles of variable diameters. The geomorphological environment suggests a combination of tectonic, denudative and fluvial sedimentary processes (plioquaternary) which gave rise to the existing geofoms. The parental materials are associated with Eocene marine dynamics as well as erosion, transport and deposition processes on drier conditions than actual ones. The soils are developed on quaternary deposits from Pleistocene-Holocene (IGAC 2009).

Climatic conditions of high temperatures and low precipitations have preserved the materials derived from chemical and intense physical weathering and its conservation of the soil profile. Since the 1950s, La Guajira has suffered a reduction of 6.3 mm of precipitation per decade; the duration and strength of the ENSO (El Niño Southern Oscillation) phenomenon has been increasing, which entails spatial and temporal alterations in the patterns of temperature, precipitation, insolation and winds (Le Houérou 1996, New et al., 2001). This has affected the pedogetic processes in the soils of this region, favoring the processes of movement and accumulation of carbonates, especially in the lower areas of the fan under microrelief conditions, where the seasonal humidity conditions favor the accumulation of calcium carbonates in the depth and processes of formation of hardened horizons (incipient Petrocalcic), in places where gilgai microrelief favors the accumulation of water in the most humid periods and where low percolation condition favors the occurrence of incipient vertization phenomena. Van der Hammen (1974) reports an arid period in Colombia, Venezuela and Mexico from 2100 to 13000 before present; similar results are reported by Lounejeva Baturina et al. (2006) suggesting a natural climatic change from relatively wet and cold conditions through the late Pleistocene to warmer and very dry conditions in the middle Holocene.

The amount of organic matter fluctuates between medium to very high. This behavior is associated with low rainfall, high temperatures, tropical dry forest vegetation, slope (0–3%) and drainage conditions favoring the accumulation of organic matter. The higher organic carbon content of the microbasins may partly be a result of admixtures of subsurface material into the microknoll area and slight erosion of organic-rich fines from the knolls to the basins (Templin et al., 1956). The Ca, Mg and K content is high. These results are coincident in regions where precipitation is lower than potential evapotranspiration (liberated cations by mineral weathering are accumulated due to low lixiviation). In the case of Zn, Cu, Fe, Mn, Metallic Micronutrients are easily available on acid soils and less soluble on pH > 7, which reduces their solubility. The soils developed have specific conditions of semi-arid environments, associated with water movement from the highest parts to low parts, and phreatic level fluctuation in conditions of low lixiviation favored the development of vertic properties

and accumulation of calcium carbonates under good drainage conditions. The studied soils of the Barracas zone have had low pedogenetic development characterized by dry environment processes as low clay formation, low illuviation and long periods of water scarcity and high evapotranspiration. In the past, the environment related to soils formation area was drier than actual conditions. This megafan system was characterized by fresh parent material and low weathering processes that formed a *calcic* endopedon. Andean tectonic phenomena favored denudative process and fluvial torrential flows which rejuvenated soil profiles. These soils are susceptible to salinity problems through the management of conditions and introduction of irrigation. Low precipitation, low illuviation and high evapotranspiration demand in combination with water irrigation makes these soils highly susceptible to salinity affectation. **Calcisols** or other calcareous soils are typical of tropical dry environments in the north of Colombia due to combination of parental materials and climatic conditions.

Soil sequence

The described pedons have various (two types) lithogeneses; they are formed from colluvial-alluvial deposits (heterogeneous texture) in the megafan upper part. The content of gravels diminished progressively to the medium part dominated by alluvial deposits (clay and clay loam). The main differences responsible for various pathways of the soil forming processes are associated with the landscape position, plant cover history, the influence of colluvial and alluvial processes (erosion, deposition, flood water) and ground water from the mid megafan. In figure 2, the presented spatial arrangement of pedons represents pedogenesis of the soil sequence. The typical indicators of colluvial-alluvial soil maturity are: (i) presence of a horization Ap-ACk1- ACk2 to Ap-Bk1-Bk2 sequence and the degree of stratification, (ii) formation of pedogenic structures and biological activity, (iii) chemical alteration of secondary carbonates formation and higher pH values. The maturity indicators of alluvial soils seem to be: (i) presence of a horization Ap-Bik1- Bik2 to Ap-ABi1-Bik1-Bk2-Bk3 sequence and the high stratification, (ii) formation of pedogenic structures like slickensides and vertic properties, gilgai microtopography, cracks and biological activity, (iii) chemical alteration of secondary carbonates and higher pH values.

Considering soil development stages within the analyzed deposition zones, the two main factors should be considered: (i) geomorphological processes of erosion and deposition of alluvial-colluvial materials and alluvial inputs by floods both rich in calcium carbonates, (ii) geomorphological position that favored the stability and soil development processes. The present transect (Fig. 3) reveals a simplified pattern in relation to lateral variability of soil development; shows the crucial role that distance from megafan apex plays as a main factor related to soil variability and the influence of river dynamics in the nature of low megafan soils. In other words, the greater the distance from the footslope, the higher degree of soil stability and low coarse materials inputs favoring fine sedimentation (clay and silt) by floods. The studied soils can be described as low to moderately developed. Weakly developed pedon was classified as *Petric Skeletic Calcisol* and *Petric Calcisol* located in the fan apex adjacent to footslope under low land surface stability conditions and high mid part of the fan. Sedimentation processes have significant influence on the soil pedogenesis when soil-forming processes cannot evolve completely. Moderately developed soils, such as *Calcic Vertisol* (*Mollic*, *Gilgaic*, *Ochric*) are present in the fan mid-position areas in alluvial materials deposited in flat areas with drainage limitations (slow permeability). The *mollic* horizons with well-developed structure are present under accumulation conditions (bioturbation), while less developed humus horizons (*Ochric*) are formed in erosion conditions.

The soil profile was deepened due to sediment accumulation from river regulation work. The horizons below the Ap have been transformed by pedogenesis to develop slickensides, gilgai

microrelief; the presence of microknolls and microbasins filled with water during the wet season favored microclimatic and changes at small-scale hydrology, causing differences in vegetative species and biomass production. Higher humidity due to moisture release from the cracks and water ponding during wet periods favored clay shrink and swell upon drying and wetting (argillic pedoturbation). This soil was developed under higher temperatures with greater calcium carbonate contents in erosional position, under dry variable seasonal condition and varied rainfall patterns under ustic conditions. The accumulation of carbonates was related to slickensides and cracks that intercept percolating water from microrelief structures where carbonates were accumulated; in this context soil processes are driven by microrelief at small-scale induced variations in hydrology and microclimatic condition, with direct results in soil pedoturbation. All the studied soils had high calcium carbonate contents and present high base saturation and high pH values. This confirms the presence of very young soils under low chemical alteration and weekly pedogenetical expression. In both colluvial and alluvial materials, lithogenesis operates with a variable rate of influence of pedogenesis in relation to geomorphological position and soil hydrological behavior.

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Soil catena in the Peruvian Amazon Basin

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The studied soil sequence is located in the southeast of Peru in the departments of Puno and Madre de Dios. This transect was carried out covering a linear extension of 310 km. The toposequence starts in the Peruvian plateau in the city of Macusani, crosses the Carabaya mountain range southeast of Peru in the Peruvian Oriental Andes and ends in the Amazon basin, West of the Puerto Maldonado City. Upper part of soil sequence is located in steeply mountain system with a strongly incised V shaped valleys in the vicinity of municipality of Ollachea. The transect crosses a hill piedmont system that precedes materials of alluvial origin in the zone corresponding to the Peruvian Amazon jungle between the municipality of San Gaban and Puerto Maldonado (Figure 1).



Fig. 1. Location

Lithology and topography

Soils show highly variable evolution, from incipient to evolved weathering. In the upper part, they are developed from organic materials and alluvial deposits; in the middle zone, sedimentary rocks (sandstones) and plutonic rocks (granite) dominate. In the lower zone, there are alluvial deposits. Due to its lithological characteristics this unit was accumulated in an ancient lagoon environment as a consequence of the extensive alluvium that came from the last glacial phase of the Pleistocene in the Andean mountain range. In the high transect part, the plateau is followed by a mountainous relief of long and inclined slopes with narrow valleys which have close bottoms of accumulation; the lower part of the transect has flat reliefs with small undulations due to a moderate past erosive activity.

Land use

Nowadays, the main land use in the low part of the toposequence is associated with pasture for cattle, papaya, watermelon, banana and cocoa crops with remaining primary forests and secondary forests such as pacal bamboo forest (*G. weberbaueri*, *G. sarcocarpa*, *G. angustifolia*), palm (*Gender Bactris spp*, *Geonoma spp*, *Attalea spp*, *Astrocaryum spp*) and lianas (*Philodendron spp*). In the middle part of the transect, the main land use is protection because they do not meet the relief conditions, followed by non-timber forest production, and few areas are used to cultivate hot pepper (rocoto) and corn. In the highland natural grasslands (*Stipa ichu*) under wetland areas (bofedal), ecosystems are conserved for the maintenance of productive livestock for breeding of such camelid species as llama (*Lama glama*), alpaca (*Lama pacos*), vicuña (*Vicugna vicugna*) and guanaco (*Lama guanicoe*).

Profile 1 – Skeletic-Fluvic **Phaeozem** (Amphiarenic, Epiloamic, Hyperhumic, Oxyaquic)

Location: Macusani plateau 2 km from Macusani city – Puno Region, slope 2 % west under native grasslands (bofedal), 4440 m a.s.l., **S** 14°02'49.488", **W** 70°23'26.111"



Morphology:

- Ah** – 0–14 cm, *mollic* horizon with high amount of fibrous organic material, black (10YR 2/1) moist, sandy loam, slightly acid, low infiltration, clear and smooth boundary;
- A** – 14–20 cm, *mollic* horizon, very dark brown (10YR 2/2) moist, loam, medium granular coarse structure, very friable, slightly acid, many fine, medium and coarse roots, high percolation, gradual and smooth boundary;
- A2** – 20–30 cm, *mollic* horizon, very dark brown (10YR 2/2) moist, loam, medium granular coarse structure, very friable, slightly acid, common medium and coarse roots, high percolation, clear and smooth boundary;
- 2C** – 30–(58) cm, grayish brown (2.5Y 5/2) in 80%, yellowish brown (10YR 5/8) mottles in 20% moist, sandy, fine single grain, common stones, slightly acid, few coarse roots, water table.

Table 1. Texture and physical properties

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class	BD [Mg·dm ⁻³]
		> 2.0	2.0-0,05	0,05-0,002	< 0.002		
Ah	0–14	0	63	24	13	SL	0.27
A	14–20	0	50	36	14	L	0.46
A2	20–30	0	48	36	16	L	0.95
2C	30–(58)	80	92	4	4	S	1.21

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	pH (1:1)	EC [ds·m ⁻¹]	CaCO ₃ [g·kg ⁻¹]	OM [g·kg ⁻¹]	P available	K available
						[mg·kg ⁻¹]	
Ah	0–14	6.38	0.11	0.00	321.2	39.2	312
A1	14–20	6.13	0.03	0.00	50.3	4.0	201
A2	20–30	6.09	0.07	0.00	47.7	3.8	196
2C	30–(58)	6.50	0.06	0.00	5.2	3.6	71

Table 3. Sorption properties

Horizon	Depth [cm]	CEC	Exchange Cations					BS [%]
			Ca ²⁺	Mg ²⁺	K ²⁺	Na ²⁺	Al ³⁺ +H ⁺	
cmol(+).kg ⁻¹								
Ah	0–14	41.28	30.30	5.03	0.67	0.46	0.00	88
A1	14–20	22.40	14.30	2.30	0.45	0.27	0.00	77
A2	20–30	21.28	12.30	2.25	0.43	0.24	0.00	72
2C	30–(58)	6.72	3.62	0.75	0.17	0.19	0.00	70

Profile 2 – Dystric Colluvic Skeletic Leptic **Regosol** (Humic, Loamic, Escalic)

Location: Pacaje site between Macusani and Ollachea municipalities – Puno region, slope 70% northeast, natural grasslands as land use (mountain grasslands and bunchgrass), 3979 m a.s.l., **S** 13°53'27.888", **W** 70°30'50.109"



Morphology:

- A** – 0–15 cm, humus horizon, very dark grayish brown (10YR 3/2) moist, brown (10YR 4/3) dry, sandy loam, medium granular moderate, slightly hard, strongly acid, common medium and coarse roots, many fine to coarse gravels (20%), moderate fast infiltration, gradual and smooth boundary;
- AC** – 15–30 cm, very dark gray (10YR 3/1) moist, dark grayish brown (10YR 4/2) dry, sandy loam, medium granular moderate to weak, more than 50% – rock structure, slightly hard, strongly acid, common medium to coarse roots, abundant medium to coarse gravels (50%) and few stones (5%), high permeability, abrupt and smooth boundary;
- R** 30–(90) cm, highly weathered rock fragments, fractured by tectonism.

Table 4. Texture and physical properties

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class	BD [Mg·dm ⁻³]
		> 2.0	2.0-0,05	0,05-0,002	< 0.002		
A	0–15	20	66	28	6	SL	0.76
AC	15–30	55	66	26	8	SL	1.47

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	pH (1:1)	EC [ds·m ⁻¹]	CaCO ₃ [g·kg ⁻¹]	OM [g·kg ⁻¹]	P _{available}	K _{available}
						[mg·kg ⁻¹]	
A	0–15	5.39	0.11	0.00	86.4	6.5	349
AC	15–30	5.31	0.02	0.00	54.1	13.4	236

Table 6. Sorption properties

Horizon	Depth [cm]	CEC	Exchange Cations					BS [%]
			Ca ²⁺	Mg ²⁺	K ²⁺	Na ²⁺	Al ³⁺ +H ⁺	
cmol(+).kg ⁻¹								
A	0–15	24.00	9.43	2.07	0.97	0.23	0.20	53
AC	15–30	21.44	6.63	1.95	0.49	0.18	0.30	43

Profile 3 – Haplic **Umbrisol** (Colluvic, , Hyperhumic, Loamic, Pachic)

Location: Sencca between Ollachea and San Gabán municipality – Puno region; slope 98% northeast, land use rocoto chilli, cassava, coffee and corn; 1827 m a.s.l, **S** 13°39'54.838, **W** 70°28'29.666''



Morphology:

- Ap** – 0–20 cm, *umbric* horizon, black (10YR 2/1) moist, sandy loam, medium subangular blocky moderate, friable, strongly acid, common fine and medium roots, fast infiltration, gradual and smooth boundary;
- A1** – 20–38 cm, *umbric* horizon, very dark brown (10YR 2/2) moist, sandy loam, medium subangular blocky moderate, very friable, strongly acid, few medium roots, few coarse gravels (5%), high permeability, gradual and smooth boundary;
- A2** – 38–79 cm, *umbric* horizon, black (7.5YR 2.5/1) moist, sandy loam, coarse subangular blocky moderate, friable, strongly acid, few medium roots, few coarse gravels (5%), gradual and smooth boundary;
- A3** – 79–(114) cm, *umbric* horizon, very dark brown (10YR 2/2) moist, sandy loam, coarse subangular blocky moderate, very friable, very strongly acid, few medium roots, few coarse gravels (5%).

Table 7. Texture and physical properties

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class	BD [Mg·dm ⁻³]
		> 2.0	2.0-0,05	0,05-0,002	< 0.002		
Ap	0–20	0	64	30	6	SL	0.74
A1	20–38	5	60	34	6	SL	0.93
A2	38–79	5	62	28	10	SL	0.92
A3	79–(114)	5	62	26	12	SL	0.69

Table 7. Chemical and physicochemical properties

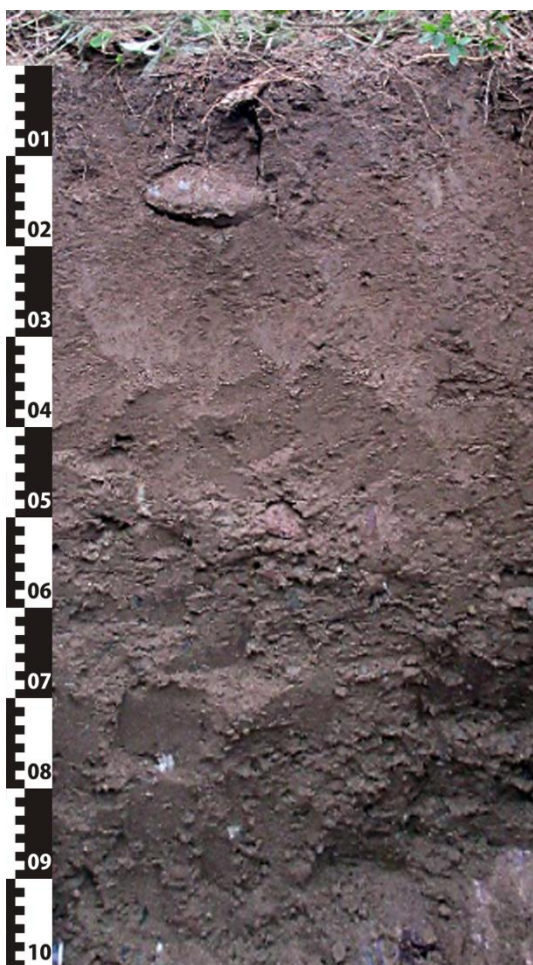
Horizon	Depth [cm]	pH (1:1)	EC [ds·m ⁻¹]	CaCO ₃ [g·kg ⁻¹]	OM [g·kg ⁻¹]	P available	K available
						[mg·kg ⁻¹]	
Ap	0–20	5.21	0.02	0.00	75.4	2.8	301
A1	20–38	5.37	0.03	0.00	50.9	4.0	206
A2	38–79	5.41	0.02	0.00	51.6	3.2	129
A3	79–(114)	5.00	0.02	0.00	45.8	2.9	71

Table 9. Sorption properties

Horizon	Depth [cm]	CEC	Exchange Cations					BS [%]
			Ca ²⁺	Mg ²⁺	K ²⁺	Na ²⁺	Al ³⁺ +H ⁺	
cmol(+).kg ⁻¹								
Ap	0–20	28.28	11.70	0.97	0.61	0.19	0.20	47
A1	20–38	25.60	9.21	0.75	0.42	0.21	0.15	41
A2	38–79	26.08	6.94	0.78	0.30	0.22	0.20	32
A3	79–(114)	27.52	3.56	0.88	0.18	0.18	0.55	17

Profile 4 – Dystric Fluvic **Cambisol** (Loamic, Humic)

Location: Pampa Hermosa near to San Gabán municipality – Puno region, slope 2% East, secondary forest cover (*Melostamaceae*, *Artocarpus altilis*, *Cecropia sp*, *Inga feuilleeipacay*), 611 m a.s.l., S 13°25'38.359, W 70°23'15.100'



Morphology:

- Ap** – 0–16 cm, humus horizon, dark brown (10YR 3/3) moist, loam, medium subangular blocky moderate, very friable, extremely acid, common fine and medium roots, moderate fast infiltration, clear and smooth boundary;
- Bw1** – 16–46 cm, *cambic* horizon, dark yellowish brown (10YR 4/4) moist, clay loam, medium subangular blocky moderate, very friable extremely acid, few medium roots, few medium gravels (5%), very high permeability, gradual and smooth boundary;
- Bw2** – 46–72 cm, *cambic* horizon, brown (10YR 4/3) moist, sandy clay loam, medium subangular blocky moderate, very friable, extremely acid, few medium roots, many medium gravels (40%), gradual and smooth boundary;
- BC** – 72–(110) cm, dark yellowish brown (10YR 4/4) moist, sandy clay loam, medium subangular blocky moderate (50%), very friable, extremely acid. fine/single grain structure, few iron concretions and segregations.

Table 10. Texture and physical properties

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class	BD [Mg·dm ⁻³]
		> 2.0	2.0-0,05	0,05-0,002	< 0.002		
Ap	0–16	0	46	30	24	L	0.71
Bw1	16–46	5	42	28	30	Cl	0.97
Bw2	46–72	40	46	26	28	SCI	1.19
BC	72–(110)	50	50	24	26	SCI	1.37

Table 11. Chemical and physicochemical properties

Horizon	Depth [cm]	pH (1:1)	EC [ds·m ⁻¹]	CaCO ₃ [g·kg ⁻¹]	OM [g·kg ⁻¹]	P _{available}	K _{available}
						[mg·kg ⁻¹]	
Ap	0–16	4.03	0.03	0.00	40.0	2.2	42
Bw1	16–46	4.27	0.02	0.00	23.8	2.5	24
Bw2	46–72	4.35	0.02	0.00	11.6	7.0	24
BC	72–(110)	4.39	0.02	0.00	07.1	2.2	21

Table 12. Sorption properties

Horizon	Depth [cm]	CEC	Exchange Cations					BS [%]
			Ca ²⁺	Mg ²⁺	K ²⁺	Na ²⁺	Al ³⁺ +H ⁺	
cmol(+)·kg ⁻¹								
Ap	0–20	16.96	0.85	0.25	0.13	0.19	1.95	8
Bw1	20–38	13.28	0.78	0.20	0.09	0.18	1.00	9
Bw2	38–79	11.20	0.84	0.22	0.10	0.18	0.50	12
BC	79–(114)	9.60	0.80	0.20	0.10	0.19	0.45	13

Profile 5 – Haplic Acrisol (Clayic, Cutanic, Ochric)

Location: Lechemayo between San Gabán and Mazuco municipality – Puno region, slope 25%, southwest, cocoa plantation (*Theobroma cacao*), *Erythroxylum coca*, banana (*Musa paradisiaca*), *Cecropia* sp, *Piper* sp, *Bauhinia picta*, 427 m a.s.l., S 13°15'49.150", W 70°19'23.150"



Morphology:

- Ap** – 0–10 cm, humus horizon, very dark grayish brown (10YR 3/2) in 80%, brown (10YR 5/3) in 20% moist, loam, medium subangular blocky moderate, friable, very strongly acid, common medium and coarse roots, very fast infiltration, clear and smooth boundary.
- Bt1** – 10–42 cm, *argic* horizon, yellowish brown (10YR 5/4) moist, clay, medium to coarse subangular blocky moderate, friable, very strongly acid, few medium and coarse roots, high permeability, diffuse and smooth boundary.
- Bt2** – 42–62 cm, *argic* horizon, yellowish brown (10YR 5/6) moist, clay, coarse subangular blocky moderate, friable, very strongly acid, few medium and coarse roots, gradual and smooth boundary.
- Bw** – 62–(105) cm, *cambic* horizon, yellowish brown (10YR 5/4) moist, clay, medium subangular blocky moderate, friable, very strongly acid, few coarse roots, high content of medium gravel (30%).

Table 13. Texture and physical properties

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class	BD [Mg·dm ⁻³]
		> 2.0	2.0-0,05	0,05-0,002	< 0.002		
Ap	0–10	0	40	34	26	L	0.91
Bt1	10–42	0	20	38	42	C	1.08
Bt2	42–62	0	20	32	48	C	1.11
Bw	62–(105)	30	22	32	46	C	1.05

Table 14. Chemical and physicochemical properties

Horizon	Depth [cm]	pH (1:1)	EC [ds·m ⁻¹]	CaCO ₃ [g·kg ⁻¹]	Organic Matter [g·kg ⁻¹]	P _{available}	K _{available}
						[mg·kg ⁻¹]	
Ap	0–10	4.68	0.18	0.00	54.8	4.4	118
Bt1	10–42	4.76	0.03	0.00	1.9	3.0	51
Bt2	42–62	4.64	0.03	0.00	3.9	2.2	57
Bw	62–(105)	4.56	0.04	0.00	2.6	2.2	67

Table 15. Sorption properties

Horizon	Depth [cm]	CEC	Exchange Cations					BS [%]
			Ca ²⁺	Mg ²⁺	K ²⁺	Na ²⁺	Al ³⁺ +H ⁺	
cmol(+).kg ⁻¹								
Ap	0–10	16.96	9.58	1.93	0.29	0.23	0.25	49
Bt1	10–42	13.28	6.93	1.85	0.18	0.29	1.90	47
Bt2	42–62	11.20	5.71	1.87	0.21	0.35	4.05	40
Bw	62–(105)	9.60	4.57	1.77	0.18	0.38	3.40	30

Profile 6 – Dystric Fluvic **Stagnosol** (Loamic, Drainic, Ochric)

Location: Santa Rita Baja Interoceanica road in the direction of Madre de Dios department, slope 1% south, secondary forest cover *Heliconia sp*, *Mauritia flexuosa*, *Uncaria tomentosa*, *Arecaceae sp* and Cucurbitaceae. 256 m a.s.l., S 12°54'39.967", W 70°12'23.112"



Morphology:

- Ap** – 0–14 cm, dark grayish brown (10YR 4/2) moist, loam, medium subangular blocky moderate, friable, extremely acid, common medium and coarse roots, moderate fast infiltration, clear and smooth boundary;
- Bwg1** – 14–32 cm, *cambic* horizon with *stagnic properties*, grayish brown (2.5Y 5/2) moist, loam, coarse subangular blocky weak, very friable, extremely acid, few medium and coarse roots, high permeability, gradual and smooth boundary;
- Bwg2** – 32–105 cm, *cambic* horizon with *stagnic properties*, olive gray (5Y 4/2) moist, loam, coarse subangular blocky weak, very friable, extremely acid, few coarse roots, gradual and smooth boundary;
- Bwg3** – 105–(152) cm, *cambic* horizon with *stagnic properties*, grey (GLEY 1 5/N) moist, loam, coarse subangular blocky weak, very friable, extremely acid, few coarse roots.

Table 16. Texture and physical properties

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class	BD [Mg·dm ⁻³]
		> 2.0	2.0-0,05	0,05-0,002	< 0.002		
A	0–14	0	48	34	18	L	0.97
Bwg1	14–32	0	46	36	18	L	1.28
Bwg2	32–105	0	44	44	12	L	1.52
Bwg3	105–(152)	0	30	48	22	L	1.53

Table 17. Chemical and physicochemical properties

Horizon	Depth [cm]	pH (1:1)	EC [ds·m ⁻¹]	CaCO ₃ [g·kg ⁻¹]	Organic Matter [g·kg ⁻¹]	P available	K available
						[mg·kg ⁻¹]	
A	0–14	3.94	0.02	0.00	2.96	4.0	42
Bwg1	14–32	4.11	0.02	0.00	0.52	8.6	26
Bwg2	32–105	4.27	0.02	0.00	0.26	6.9	21
Bwg3	105–(152)	4.43	0.02	0.00	0.19	30.9	19

Table 18. Sorption properties

Horizon	Depth [cm]	CEC	Exchange Cations					BS [%]
			Ca ²⁺	Mg ²⁺	K ²⁺	Na ²⁺	Al ³⁺ +H ⁺	
cmol(+)-kg ⁻¹								
A	0–14	12.00	0.85	0.37	0.13	0.23	2.30	13
Bwg1	14–32	7.52	0.84	0.38	0.10	0.24	1.80	21
Bwg2	32–105	6.72	0.90	0.53	0.08	0.23	2.15	26
Bwg3	105–(152)	9.60	0.99	1.08	0.08	0.30	2.50	26

Profile 7 – Dystric Fluvic Stagnic **Cambisol** (Loamic, Ochric)

Location: Florida Baja site near Puerto Maldonado city – Madre de Dios Department, slope 1% north, plant cover *Heliconia mathiasiae*, *Heliconia sp.*, *Arecaceae*, *Bambusoideae* and Lianas, 244 m a.s.l., S 12°43'09.058'', W 69°30'45.242''



Morphology:

- A** – 0–18 cm. pale brown (10YR 6/3) moist, clay loam, medium subangular blocky weak, firm, extremely acid, few medium and coarse roots, fast infiltration, clear and smooth boundary;
- Bwg1** – 18–45 cm, *cambic* horizon with *stagnic properties*, strong brown (7.5YR 5/8) in 95%, mottle yellowish brown (10YR 5/4) in 5% moist, sandy clay loam, coarse subangular blocky moderate, firm, extremely acid, few medium and coarse roots, very high permeability, gradual and smooth boundary;
- Bwg2** – 45–92 cm, *cambic* horizon with *stagnic properties*, strong brown (7.5YR 5/8) in 80%, mottle yellowish brown (10YR 5/4) in 20% moist, sandy clay loam, medium subangular blocky moderate, firm, extremely acid, few medium and coarse roots, gradual and smooth boundary;
- Bwg3** – 92–(140) cm, *cambic* horizon with *stagnic properties*, yellowish brown (10YR 5/4) in 50%, red (2.5YR 4/8) in 50% moist, sandy clay loam, medium subangular blocky weak, firm, extremely acid, few coarse roots.

Table 19. Texture and physical properties

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class	BD [Mg·dm ⁻³]
		> 2.0	2.0-0,05	0,05-0,002	< 0.002		
A	0–18	0	70	14	16	SL	1.37
Bwg1	18–45	0	62	18	20	SCL	1.39
Bwg2	45–92	0	58	20	22	SCL	1.50
Bwg3	92–(140)	30	54	16	30	SCL	1.52

Table 20. Chemical and physicochemical properties

Horizon	Depth [cm]	pH (1:1)	EC [ds·m ⁻¹]	CaCO ₃ [%]	Organic Matter [%]	P _{available}	K _{available}
						[mg·kg ⁻¹]	
A	0–18	3.70	0.08	0.00	0.58	5.9	29
Bwg1	18–45	3.94	0.03	0.00	0.39	4.2	20
Bwg2	45–92	4.02	0.02	0.00	0.52	3.4	21
Bwg3	92–(140)	4.03	0.02	0.00	0.45	3.5	26

Table 21. Sorption properties

Horizon	Depth [cm]	CEC	Exchange Cations					BS [%]
			Ca ²⁺	Mg ²⁺	K ²⁺	Na ²⁺	Al ³⁺ +H ⁺	
cmol(+).kg ⁻¹								
A	0–18	6.40	1.00	0.23	0.11	0.24	1.50	25
Bw1	18–45	6.40	0.89	0.22	0.08	0.23	1.50	22
Bw2	45–92	6.72	0.78	0.23	0.09	0.22	1.85	20
Bw3	92–(140)	7.20	0.79	0.22	0.08	0.20	2.30	18

Climate

The sequence of soils is located between 240 m a.s.l. to 4440 m a.s.l. The maximum annual mean air biotemperature in the lower part ranges is about 23.5°C and total annual precipitation fluctuates between 2550 mm and 3000 mm. In the high plateau situated at 4440 m a.s.l., the maximum annual average air biotemperature is 5.2°C with an average precipitation of 736 mm/year, the average for a 10-year period (INRENA, 1994).

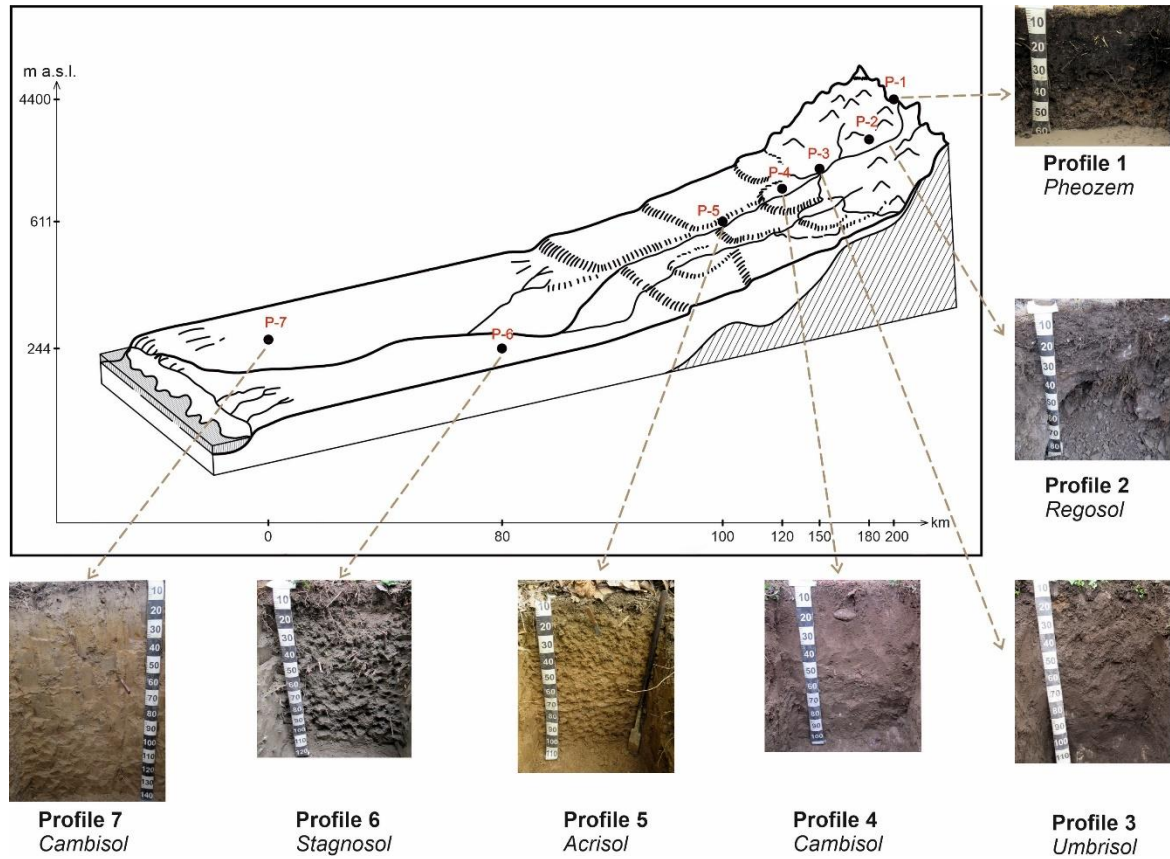


Fig. 2. Toposequence of the studied soils. From P-1 to P-7 approximate location of soil profiles

Soil genesis and systematic position

The soil profile 1 and 3 are classified as soils with well developed humus horizons – **Phaeozem** and **Umbrisol** respectively. They are developed from alluvial and colluvial materials; under plateau conditions they have high base saturation and slightly acid pH (**Phaeozem**), changing to low base saturation and strongly acidic pH in high mountain conditions (higher leaching, slope, climatic conditions and low weathering – **Umbrisol**). In both cases, the humus horizon is rich in organic matter which allowed to use *Hyperhumic* qualifier. In the plateau, organic matter (OM) content in A horizon is 85% higher than in the underlying horizons which have very low organic matter contents and low soil profile development. OM accumulation in surface horizons is due to wetland conditions typical of bofedal ecosystem when OM mineralization is slow. The presence of rounded sedimentary and volcanic rock fragments of alluvial origin is common in this soil profile and thin A horizon and low pedogenetic development of the soil profile at depth. For low mountain profile, bioclimatic and slope conditions favored medium OM accumulation and high soil horizonation.

Mollic horizon in the wetland areas as in profile 1 (bofedal) is shallower while the *umbric* horizon in the low mountain area is thick (*Pachic* qualifier) despite the sloping conditions and colluvial material accumulation (*Colluvic*). There are better soil developments of the underlying horizons and lower stone content in depth in spite of the presence of rock blocks on the surface. The presence of traditional prehispanic farm systems (chacras) in the middle mountain system favors the incorporation of organic matter and soil profile development. Cambisols (profile 4 and 7) are derived from alluvial deposit with extremely low pH and base saturation with loamy to sandy clay loam textures (*Loamic*) associated with recent formation conditions; these soils have low organic matter content which increases when vegetation is established in prolonged periods of time. The occurrence of inceptisols with a differentiation of horizons A, B and C is common in aguajales (humid forest ecosystems with swampy vegetation where the dominant species are aguaje “palm” (*Mauritia flexuosa*, *Mauritia vinifera*, *Mauritiella peruviana*) and in poorly drained areas (Aquentes), or well-drained, acid soils located in favorable topographies (Rodríguez, 1995; Ruiz and Leviestre, 2011). In low lands of this catena, seasonal water saturation conditions are favored and under terrace landform the soils have good drainage conditions, medium OM content and visible horizonation. The main feature in these profiles is the development of incipient cambic horizons. On very steep slopes the development of soils is incipient with high stoniness. The materials of moderately fine to fine textures of ancient alluvial origin are associated with landscape of middle terraces characterized by being free of floods (Rodríguez et al., 1991).

There are **Regosols** (profile 2) with shallow A horizons with high content of organic matter (*Humic*), strongly acid pH and low base saturation (*Dystric*). These soils are developed in high slope and exposed rocks with low chemical weathering and high instability and erosion. It is a shallow soil with low development of horizons and presence of lithic contact. Under conditions of hilly relief under highly weathered materials with clay textures **Acrisols** (profile 5) are developed. The soil has a medium content of organic matter in the A horizon (*Ochric*) higher than underlying horizons (96% more organic matter than the B horizons) which decreases abruptly in depth, with a very strong acid pH and low base saturation. There is presence of cutans (*Cutanic*) associated with high leaching conditions. These are soils with a low natural fertility subjected to high weathering processes in conditions of high percolation environment. The middle hill landscapes are characterized by the presence of fairly angular peaks and long slopes, with heights of 40–70 m, and slopes ranging between 25–50%, made up of consolidated clay material from the continental Tertiary with a higher degree of erosion (Rodríguez et al., 1991). From alluvial materials, loamy **Stagnosols** are derived. They have medium contents of OM, low base saturation, medium content of aluminium and extremely acidic

pH. Consequently, in the convex zones, the content of organic matter increases due to poor oxygenation, and soils are generally grayish and dark (Rodríguez, 1995). These soils have oxide reduction features associated with seasonal soil saturation under wet environmental conditions and fluctuating water table in a flat landscape in the low land zones. There are cambic horizons and redoximorphic colors. These zones are artificially drained for livestock management.

Soil sequence

Differentiation in the land cover of this toposequence is a result of differences in parental materials and ecological conditions, reflected in the morphological and soil groups diversity that reflected the differences between morphogenetic environments. In the upper part of the transect, surface soils are developed with a high content of organic matter in the first 10 cm depth and high gravel content inside soil profile, whose genesis is limited by climatic conditions and presence of thick alluvial deposits rich in gravels with a low slope on the plateau and very steep slope and exposed rocks surfaces in the high mountain environments where organic matter is accumulated in the A horizon; B horizons are not developed. In the middle mountain landscape, under warmer environments, soils are developed in steep slope conditions. These colluvial deposits created deep soils profiles with high organic matter content and a sequence of A horizons with thickness up to > 100 cm, despite the presence of rock blocks on the surface (rock fall phenomena). In the case of the foothills in warm environment of high weathering and gentle slope, clay soils have been developed with the presence of cutans which evidences high leaching conditions with a development of an incipient A horizon and developed Bt horizons. In the lower part of this toposequence, in the flat landscape, materials of alluvial origin are predominating with the presence of cambic horizons and loamy to sandy loam textures with a low to medium organic matter content in relation to the temporality of the establishment of the forest covers and presence of stagnic patterns in low lands associated with high seasonal humidity and hydromorphic conditions.

Acknowledgments

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Urban soils in Santiago de Compostela (Galicia, NW Spain)

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The city of Santiago de Compostela is located in the northwestern corner of the Iberian Peninsula (42°53'N, 8°32'W, Fig. 1). The history of the city dates back to the 9th century, but it has always been a small city. The municipality has an area of 222 km² and counts 97,000 inhabitants. It is the capital of the autonomous region of Galicia and an important political, administrative, religious and tourist center. In addition to the permanent residents, the city has over 20,000 University students and receives approximately one million visitors every year, many of them pilgrims of the Way of Saint James.

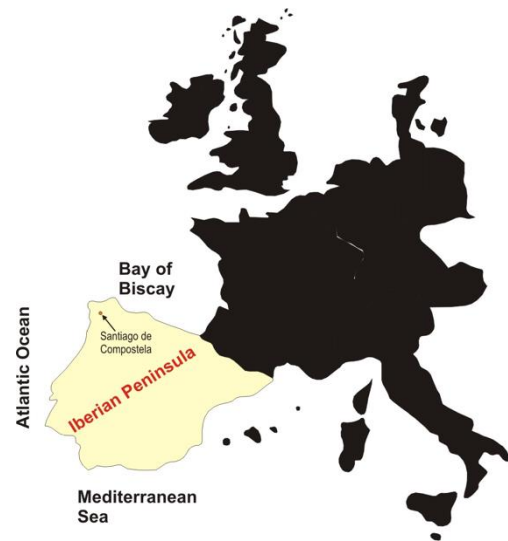


Fig. 1. Location of the study area

Lithology and topography

The city presents an accidented topography with a central elevation encircled by two small river valleys. The highest point is at 325 m a.s.l. and the lowest at 180 m a.s.l. The city is located in the contact zone between a geological unit composed by granites and the metamorphic massif known as the Ordes Complex, and therefore presents an important geological diversity. There are four main lithological units in the city, arranged approximately in parallel bands with a N-S direction: (1) granitic rocks, mostly medium- to coarse-grained two-mica granites; (2) Santiago schists, rich in micas and poor in quartz; (3) orthogneisses, with a similar composition to granites; and (4) amphibolites, composed mainly of amphibole and plagioclase (IGME, 1981; Martínez Catalán et al., 1984; Díaz-García, 1990; Arenas et al., 1995).

Land use and vegetation

In addition to typical urban infrastructures, including paved surfaces and buildings, which represent the main land use in the city, there is also an important surface of green areas. Santiago de Compostela ranks as the third Spanish city in managed green surface per capita, with over 5,000,000 m² of managed gardens and parks, from historical gardens established in the 19th century to green areas developed in the last decade. In the city center, there are 25 green areas with surfaces ranging from 1 to 40 hectares, including lawn areas and forest areas with *Quercus robur*, *Acacia melanoxylon* and *Eucalyptus globulus* (with presence of *Castanea sativa*, *Ilex aquifolium*, *Tilia sp.*, *Camelia japonica*). In addition, several agricultural areas exist within the city, including public and private urban gardens.

Climate

The city has an oceanic climate, warm and wet. According to the Köppen–Geiger Climate Classification, it is located in the temperate oceanic climate (Cfb) zone (Kottek et al., 2006). The mean annual air temperature is 13.0°C, with August as the warmest month (mean air temperature 19°C) and January as the coldest (mean air temperature 8°C). The average annual precipitation is 1787 mm.

Profile 1 – Leptic **Umbrisol** (Hyperdystric, Loamic)

Location: Public park in a hill in the city center, middle slope (moderately steep 16–30%), 250 m a.s.l., lawn with oaks (*Quercus robur*), N 42°52'44.14" W 8°32'56.70"



Morphology:

- Ah1** – 0–10 cm, organo-mineral, loam, common fine and medium schist fragments, very few artefacts (brick), very dark brown (10YR 2/2), fine subangular blocky structure, few roots, diffuse wavy boundary;
- Ah2** – 10–25/30 cm, organo-mineral, loam, many fine, medium and coarse schist fragments, very few artefacts (brick), dark brown (10YR 3/3), fine subangular blocky structure, few roots, clear wavy boundary;
- R** – 25/30–(100) cm, fragmented schist.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm						Textural class
		> 2.0	0.25-2.0	0.05-0.25	0.02-0.05	0.002-0.02	< 0.002	
Ah1	0–10	32	35	17	21	14	13	L
Ah2	10–25/30	56	33	17	23	14	12	L

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH	
					H ₂ O	KCl
Ah1	0–10	20.4	1.8	11	5.2	3.8
Ah2	10–25/30	9.7	1.0	10	5.4	3.9

Table 3. Base cations and CEC (1M AcONH₄, pH 7) and Al (1M KCl)

Horizon	Depth [cm]	Ca	Mg	Na	K	Al	CEC	BS [%]
		[cmol(+) kg ⁻¹]						
Ah1	0–10	0.35	0.27	0.05	0.22	2.5	16.9	5
Ah2	10–25/30	0.30	0.19	0.04	0.08	1.9	8.7	7

Table 4. Content of various forms of iron and aluminium

Horizon	Depth [cm]	Fe _d	Fe _o	Al _o	Al _o +0.5Fe _o
		[g·kg ⁻¹]			
Ah1	0–20	10.5	3.0	2.1	0.4
Ah2	20–40	9.4	2.5	1.9	0.3

Profile 2 – Endocambic **Umbrisol** (Hyperdystric, Loamic, Protoandic)

Location: cut in a street in a residential area, middle slope (moderately steep 16-30%), 240 m a.s.l., spontaneous vegetation, **N** 42°52'48.05" **W** 8°31'38.24"



Morphology:

- Ap1** – 0–20 cm, organo-mineral, loam, common medium and coarse fragments, very few artefacts (brick), dark reddish brown (5YR 3/3), fine subangular structure, plastic, common roots, clear wavy boundary;
- Ap2** – 20–40 cm, organo-mineral, loam, many medium and coarse fragments (stone line), very few artefacts (ceramics), dark reddish brown (5YR 3/3), fine subangular blocky structure, plastic, common roots, clear wavy boundary;
- 2Ah** – 40–60 cm, organo-mineral, silt loam, common fine and medium coarse fragments, without artefacts, dark reddish brown (5YR 3/3), granular structure, plastic, few roots, clear smooth boundary;
- 2Bw** – 60–100 cm, mineral, clay loam, common medium coarse fragments, without artefacts, yellowish red (5YR 4/6), few reddish brown mottles (5YR 4/4), fine subangular blocky structure, plastic, very few roots, gradual wavy boundary;
- 3Bw** – 100–140 cm, mineral, loam, very few fine and medium coarse fragments of weathered amphibolite, without artefacts, yellowish red (5YR 5/8), many reddish brown mottles (5YR 4/4), fine angular blocky structure, plastic, very few roots, clear wavy boundary;
- 3C** – 140–(200) cm, weathered amphibolite, loam, many medium and coarse fragments, without artefacts, strong brown (7.5YR 5/8), many Mn concretions (7.5YR 2.5/1), massive, plastic, without roots.

Table 5. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm						Textural class
		> 2.0	0.25-2.0	0.05-0.25	0.02-0.05	0.002-0.02	< 0.002	
Ap1	0–20	21	19	23	16	25	18	L
Ap2	20–40	58	18	23	14	28	17	L
2Ah	40–60	31	17	10	26	33	15	SiL
2Bw	60–100	18	11	20	11	24	34	CL
3Bw	100–140	2	2	16	15	32	34	L
3C	140–(200)	66	22	15	26	23	14	L

Table 6. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH	
					H ₂ O	KCl
Ap1	0–20	27.5	2.2	13	5.1	4.3
Ap2	20–40	27.1	2.2	12	4.9	4.3
2Ah	40–60	31.5	2.4	13	5.0	4.4
2Bw	60–100	5.2	0.3	15	4.9	4.0
3Bw	100–140	4.4	0.3	14	4.9	4.0
3C	140–(200)	3.5	0.4	10	5.3	4.7

Table 7. Base cations and CEC (1M AcONH₄, pH 7) and Al (1M KCl)

Horizon	Depth [cm]	Ca	Mg	Na	K	Al	CEC	BS [%]
		[cmol(+) kg ⁻¹]						
Ap1	0–20	0.27	0.08	0.06	0.13	1.01	15.3	4
Ap2	20–40	0.06	0.03	0.05	0.01	1.11	11.7	1
2Ah	40–60	0.04	0.06	0.05	0.07	0.83	9.8	2
2Bw	60–100	0.34	0.06	0.05	0.07	2.15	8.8	6
3Bw	100–140	0.65	0.14	0.06	0.15	1.73	12.4	8
3C	140–(200)	1.32	0.42	0.15	0.46	0.08	16.2	15

Table 8. Content of various forms of iron and aluminium

Horizon	Depth [cm]	Fe _d	Fe _o	Al _o	Al _o +0.5Fe _o [%]
		[g·kg ⁻¹]			
Ap1	0–20	42.5	6.5	7.0	1.0
Ap2	20–40	56.0	7.0	11.6	1.5
2Ah	40–60	53.0	6.8	8.1	1.2
2Bw	60–100	52.0	2.3	2.4	0.4
3Bw	100–140	62.7	1.3	1.5	0.2
3C	140–(200)	46.5	2.7	1.9	0.3

Profile 3 – Skeletic Regosol (Loamic, Ochric, Transportic)

Location: green area in the University Campus next to the Faculty of Chemistry, foot slope (gently sloping 2-5%), 240 m a.s.l., lawn, **N 42°52'33.47" W 8°33'7.77"**



Morphology:

- ^A** – 0–10/20 cm, organo-mineral, sandy loam, many medium and coarse fragments, very few artefacts (ceramics), dark yellowish brown (10YR 4/4), fine subangular blocky structure, slightly plastic, common roots, abrupt irregular boundary;
- ^C** – 10/20–50/60 cm, human transported material, sandy loam, many medium and coarse fragments, without artefacts, yellowish brown (10YR 5/6), fine subangular structure, slightly plastic, common roots, clear irregular boundary;
- 2^C1** – 50/60–70 cm, human transported material, sandy loam, common medium fragments, very few artefacts (bricks and ceramics), dark brown (10YR 3/3), fine subangular structure, slightly plastic, without roots, clear irregular boundary;
- 2^C2** – 70–90 cm, human transported material, sandy loam, many medium and coarse fragments, without artefacts, olive yellow (2.5Y 6/6), without structure, slightly plastic, without roots, diffuse irregular boundary;
- 2^C3** – 90–120 cm, human transported material, sandy loam, common medium and coarse fragments, without artefacts, olive yellow (2.5Y 6/6), without structure, slightly plastic, without roots, clear wavy boundary;
- 3Ab** – 120–(150) cm, organo-mineral, sandy loam, few fine and medium fragments, very few artefacts (ceramics), brown (10YR 4/3), fine without structure, no plastic, without roots.

Table 9. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm						Textural class
		> 2.0	0.25-2.0	0.05-0.25	0.02-0.05	0.002-0.02	< 0.002	
^A	0–10/20	35	28	43	7	12	10	SL
^C	10/20–50/60	43	22	43	16	12	7	SL
2^C1	50/60–70	24	28	38	7	14	13	SL
2^C2	70–90	48	26	39	9	14	11	SL
2^C3	90–120	34	25	40	8	15	12	SL
3Ab	120–(150)	46	29	34	8	15	14	SL

Table 10. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH	
					H ₂ O	KCl
^A	0–10/20	6.1	0.6	10	7.4	6.0
^C	10/20–50/60	2.9	0.3	9	7.0	5.1
2^C1	50/60–70	8.1	0.7	11	6.7	5.7
2^C2	70–90	4.3	0.5	9	7.1	5.6
2^C3	90–120	5.1	0.4	13	7.2	5.6
3Ab	120–(150)	11.5	1.0	11	6.8	5.5

Table 11. Base cations and CEC (1M AcONH₄, pH 7) and Al (1M KCl)

Horizon	Depth [cm]	Ca	Mg	Na	K	Al	CEC	BS [%]
		[cmol(+) kg ⁻¹]						
^A	0–10/20	3.6	0.24	0.05	0.23	0.01	5.3	78
^C	10/20–50/60	1.8	0.42	0.03	0.19	0.01	5.8	42
2^C1	50/60–70	3.7	0.50	0.05	0.23	0.02	10.0	45
2^C2	70–90	3.3	0.44	0.04	0.05	0.02	4.3	89
2^C3	90–120	2.9	0.21	0.05	0.11	0.02	4.6	71
3Ab	120–(150)	3.1	0.07	0.07	0.14	0.03	6.9	49

Table 12. Content of various forms of iron and aluminium

Horizon	Depth [cm]	Fe _d	Fe _o	Al _o	Al _o +0.5Fe _o
		[g·kg ⁻¹]			
^A	0–10/20	8.8	1.1	1.3	0.2
^C	10/20–50/60	8.4	0.3	0.4	0.1
2^C1	50/60–70	8.5	1.4	1.6	0.2
2^C2	70–90	11.0	0.9	1.0	0.1
2^C3	90–120	10.8	1.2	1.3	0.2
3Ab	120–(150)	13.4	3.0	3.2	0.5

Profile 4 – Urbic Technosol (Eutric, Humic, Loamic, Transportic)

Location: green area in the University Campus next to the Faculty of Politics, middle slope (moderately steep 16-30%), 230 m a.s.l., lawn with ornamental species, **N** 42°52'26" **W** 8°33'15"



Morphology:

- ^Ah1** – 0-8 cm, organo-mineral, sandy loam, common fine and medium fragments, very few artefacts (brick), very dark greyish brown (10YR 3/2), fine granular structure, slightly plastic, common roots, diffuse wavy boundary;
- ^Ah2** – 8-20 cm, organo-mineral, sandy loam, common fine and medium fragments, without artefacts, very dark greyish brown (10YR 3/2), fine subangular blocky structure, slightly plastic, few roots, gradual wavy boundary;
- ^AhCu** – 20-30 cm, organo-mineral, sandy loam, common fine fragments and construction sand, dark yellowish brown (10YR 4/4), fine angular blocky structure, slightly plastic, few roots, gradual wavy boundary;
- ^Cu** – 30-40 cm, construction sand, mineral, sandy with many coarse fragments, greyish brown (10YR 5/2), without structure, no plastic, without roots, abrupt wavy boundary;
- THM** – 40-50 cm, technic hard material (concrete);
- 2^C** – 50-(100) cm, rubble.

Table 13. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm						Textural class
		> 2.0	0.25-2.0	0.05-0.25	0.02-0.05	0.002-0.02	< 0.002	
^Ah1	0–8	14	35	11	18	18	18	L
^Ah2	8–20	15	35	25	8	21	12	SL
^AhCu	20–30	16	51	11	15	11	11	SL
^Cu	30–40	7	82	9	2	2	6	S

Table 14. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH	
					H ₂ O	KCl
^Ah1	0–8	61.8	4.8	13	5.8	4.9
^Ah2	8–20	37.0	3.1	12	5.6	4.6
^AhCu	20–30	11.4	1.0	11	5.8	4.8
^Cu	30–40	3.0	0.2	15	6.9	6.1

Table 15. Base cations and CEC (1M AcONH₄, pH 7) and Al (1M KCl)

Horizon	Depth [cm]	Ca	Mg	Na	K	Al	CEC	BS [%]
		[cmol(+) kg ⁻¹]						
^Ah1	0–8	4.8	1.05	0.13	1.02	0.15	12.3	57
^Ah2	8–20	2.4	0.50	0.07	0.23	0.50	5.0	65
^AhCu	20–30	2.2	0.44	0.03	0.14	0.14	4.2	67
^Cu	30–40	1.5	0.17	0.01	0.09	0.02	1.8	98

Table 16. Content of various forms of iron and aluminium

Horizon	Depth [cm]	Fe _d	Fe _o	Al _o	Al _o +0.5Fe _o [%]
		[g·kg ⁻¹]			
^Ah1	0–8	12.1	3.8	4.8	0.7
^Ah2	8–20	13.5	4.1	6.2	0.8
^AhCu	20–30	7.7	2.0	1.9	0.3
^Cu	30–40	1.5	0.9	0.7	0.1

Profile 5 – Ekranic Technosol (Humic, Loamic, Mollic, Endocambic)

Location: old agricultural terraces currently occupied by infrastructures in the University Campus, foot slope (strongly sloping 10–15%), 205 m a.s.l., **N** 42°52'24.23" **W** 8°32'42.68"



Morphology:

- THM** – 0–20 cm, technic hard material, concrete;
- Ap1** – 20–45 cm, organo-mineral, sandy loam, many medium and coarse fragments, very few artefacts (brick), dark brown (10YR 3/3), fine to medium subangular blocky structure, slightly plastic, common roots, clear smooth boundary;
- Ap2** – 45–60 cm, organo-mineral, sandy loam, abundant medium and coarse fragments, without artefacts, brown (10YR 4/3), fine to medium platy structure, slightly plastic, few roots, clear smooth boundary (stone line);
- 2Ap** – 60–75 cm, organo-mineral, sandy loam, common fine and medium fragments, very few artefacts (brick), dark brown (10YR 3/3), fine subangular blocky/platy structure, slightly plastic, few roots, abrupt smooth boundary;
- 2BC** – 75–(130) cm, mineral, sandy loam, many medium and coarse fragments, without artefacts, yellowish brown (10YR 5/6), very fine subangular blocky structure, slightly plastic, very few roots.

Table 17. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm						Textural class
		> 2.0	0.25-2.0	0.05-0.25	0.02-0.05	0.002-0.02	< 0.002	
Ap1	20–45	36	31	24	18	15	13	SL
Ap2	45–60	40	19	35	18	12	17	SL
2Ap	60–75	43	32	35	8	11	14	SL
2BC	75–(130)	41	28	48	6	8	9	SL

Table 18. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH	
					H ₂ O	KCl
Ap1	20–45	22.4	1.8	13	7.3	6.1
Ap2	45–60	13.9	1.2	12	6.9	5.5
2Ap	60–75	11.8	1.1	11	6.9	5.7
2BC	75–(130)	2.7	0.3	8	6.4	4.2

Table 19. Base cations and CEC (1M AcONH₄, pH 7) and Al (1M KCl)

Horizon	Depth [cm]	Ca	Mg	Na	K	Al	CEC	BS [%]
		[cmol(+) kg ⁻¹]						
Ap1	20–45	5.4	0.58	0.12	0.47	0.02	9.8	67
Ap2	45–60	3.7	0.34	0.22	0.60	0.03	11.1	44
2Ap	60–75	3.7	0.32	0.07	0.32	0.03	7.2	61
2BC	75–(130)	1.3	0.21	0.15	0.47	0.13	5.4	39

Table 20. Content of various forms of iron and aluminium

Horizon	Depth [cm]	Fe _d	Fe _o	Al _o	Al _o +0.5Fe _o
		[g·kg ⁻¹]			
Ap1	20–45	10.1	3.7	4.1	0.6
Ap2	45–60	10.6	2.7	3.5	0.5
2Ap	60–75	13.2	2.8	3.2	0.5
2BC	75–(130)	17.5	0.4	0.5	0.1

Profile 6 – Ekranic Technosol (Eutric, Transportic)

Location: street in the city center, upper slope (steep 30–60%), 250 m a.s.l., sidewalk without vegetation, N 42°52'36.69" W 8°32'31.37"



Morphology:

- THM** – 0–15 cm, technic hard material, concrete with paving stones;
- ^AC1** – 15–30 cm, mineral, sandy loam, abundant fine and medium fragments, very few artefacts (brick, concrete), dark yellowish brown (10YR 4/4), fine platy/angular blocky structure, slightly plastic, without roots, clear wavy boundary;
- ^AC2** – 30–35 cm, mineral, sandy loam, abundant fine, medium and coarse fragments, very few artefacts (brick), dark brown (10YR 3/3), fine angular blocky structure, slightly plastic, without roots, clear wavy boundary;
- ^AC3** – 35–55 cm, mineral, loamy sand, abundant fine, medium and coarse fragments, very few artefacts (brick), yellowish brown (10YR 5/4), fine angular blocky structure, slightly plastic, without roots, clear wavy boundary;
- ^AC4** – 55–75 cm, mineral, sandy loam, abundant fine, medium and coarse fragments, few artefacts (brick, ceramics), yellowish brown (10YR 5/4), without structure, non plastic, without roots, clear wavy boundary;
- ^ACu** – 75–90 cm, mineral, loamy sand, dominant coarse fragments, common artefacts (brick, ceramics), yellowish brown (10YR 5/4), without structure, non plastic, without roots, clear wavy boundary;
- ^AC5** – 90–115 cm, mineral, loamy sand, abundant fine, medium and coarse fragments, very few artefacts (brick), yellowish brown (10YR 5/4), without structure, non plastic, without roots, abrupt irregular boundary;
- 2R** – 115–(160) weathered schist.

Table 21. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm						Textural class
		> 2.0	0.25-2.0	0.05-0.25	0.02-0.05	0.002-0.02	< 0.002	
^C1	15–30	45	33	28	14	15	9	SL
^C2	30–35	48	36	33	11	12	8	SL
^C3	35–55	50	44	35	6	9	7	LS
^C4	55–75	46	54	21	13	6	5	SL
^Cu	75–90	90	-	-	-	-	-	LS
^C5	90–115	55	55	22	12	5	5	LS

Table 22. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH	
					H ₂ O	KCl
^C1	15–30	0.39	0.2	19	8.2	7.2
^C2	30–35	0.49	0.3	17	8.1	6.6
^C3	35–55	0.29	0.2	12	7.5	5.9
^C4	55–75	0.26	0.2	13	7.8	6.3
^Cu	75–90	0.33	0.3	11	7.5	6.1
^C5	90–115	0.25	0.2	11	8.3	7.5

Table 23. Base cations and CEC (1M AcONH₄, pH 7) and Al (1M KCl)

Horizon	Depth [cm]	Ca	Mg	Na	K	Al	CEC	BS [%]
		[cmol(+) kg ⁻¹]						
^C1	15–30	5.2	0.06	0.13	1.96	0.03	6.1	100
^C2	30–35	3.2	0.08	0.15	1.92	0.03	5.3	100
^C3	35–55	0.8	0.04	0.15	0.80	0.03	2.0	91
^C4	55–75	1.0	0.03	0.06	0.45	0.03	1.9	81
^Cu	75–90	1.1	0.05	0.06	0.39	0.03	1.6	100
^C5	90–115	2.1	0.03	0.02	0.14	0.01	2.6	90

Table 24. Content of various forms of iron and aluminium

Horizon	Depth [cm]	Fe _d	Fe _o	Al _o	Al _o +0.5Fe _o
		[g·kg ⁻¹]			
^C1	15–30	10.1	3.8	1.8	0.4
^C2	30–35	11.0	9.7	1.9	0.7
^C3	35–55	4.7	1.2	2.1	0.3
^C4	55–75	2.6	0.5	2.2	0.2
^Cu	75–90	3.0	0.8	2.9	0.3
^C5	90–115	2.3	1.1	2.0	0.3

Profile 7 – Ekranic Technosol (Dystric, Transportic)

Location: street in the city center, middle slope (strongly sloping 10–15%), 265 m a.s.l., road pavement without vegetation, **N 42°53'03" W 8°32'00"**



Morphology:

- THM** – 0–70 cm, technic hard material, several layers of asphalt and concrete;
- ^C1** – 70–130/140 cm, mineral, sandy loam, abundant coarse fragments, few artefacts (brick, plastic), yellowish brown (10YR 5/6), massive without structure, slightly plastic, without roots, clear wavy boundary;
- ^C2** – 130/140–150 cm, mineral, sandy loam, many medium and coarse fragments, without artefacts, brownish yellow (10YR 6/6), fine angular blocky structure, slightly plastic, without roots, abrupt smooth boundary;
- ^Cu** – 150–155 cm, construction sand, mineral, sandy loam, few fine fragments, pale brown (10YR 6/3), without structure, non plastic, without roots, abrupt smooth boundary;
- 2BC** – 155–(200) cm, mineral, loam, many medium and coarse fragments, without artefacts, yellowish brown (10YR 5/6) with Mn concretions (10YR 2/2), fine subangular blocky structure, slightly plastic, very few roots.

Table 25. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm						Textural class
		> 2.0	0.25-2.0	0.05-0.25	0.02-0.05	0.002-0.02	< 0.002	
^C1	70–130/140	43	26	32	14	15	12	SL
^C2	130/140–150	19	20	39	18	11	12	SL
^Cu	150–155	11	33	37	9	10	11	SL
2BC	155–(200)	31	22	31	14	17	16	L

Table 26. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH	
					H ₂ O	KCl
^C1	70–130/140	4.8	0.6	9	6.3	5.4
^C2	130/140–150	4.8	0.3	16	7.0	5.9
^Cu	150–155	3.9	0.4	11	6.5	5.7
2BC	155–(200)	6.2	0.7	9	5.5	4.5

Table 27. Base cations and CEC (1M AcONH₄, pH 7) and Al (1M KCl)

Horizon	Depth [cm]	Ca	Mg	Na	K	Al	CEC	BS [%]
		[cmol(+) kg ⁻¹]						
^C1	70–130/140	2.41	0.59	0.42	0.61	0.00	11.5	35
^C2	130/140–150	1.80	0.33	0.28	0.45	0.00	5.2	55
^Cu	150–155	1.44	0.24	0.26	0.42	0.00	4.5	52
2BC	155–(200)	1.66	0.39	0.29	0.34	0.08	11.3	24

Table 28. Content of various forms of iron and aluminium

Horizon	Depth [cm]	Fe _d	Fe _o	Al _o	Al _o +0.5Fe _o [%]
		[g·kg ⁻¹]			
^C1	70–130/140	15.6	2.6	1.1	0.2
^C2	130/140–150	10.9	2.0	1.3	0.2
^Cu	150–155	3.3	0.7	1.1	0.1
2BC	155–(200)	14.5	3.2	1.4	0.3

December is the wettest month with average precipitation around 260 mm and July the driest one, with average precipitation around 40 mm. The relatively low values for potential evapotranspiration (<300 mm in summer and 50–100 mm in winter) result in a positive water balance (600–800 mm) (Martínez Cortizas and Pérez Alberti, 1999).

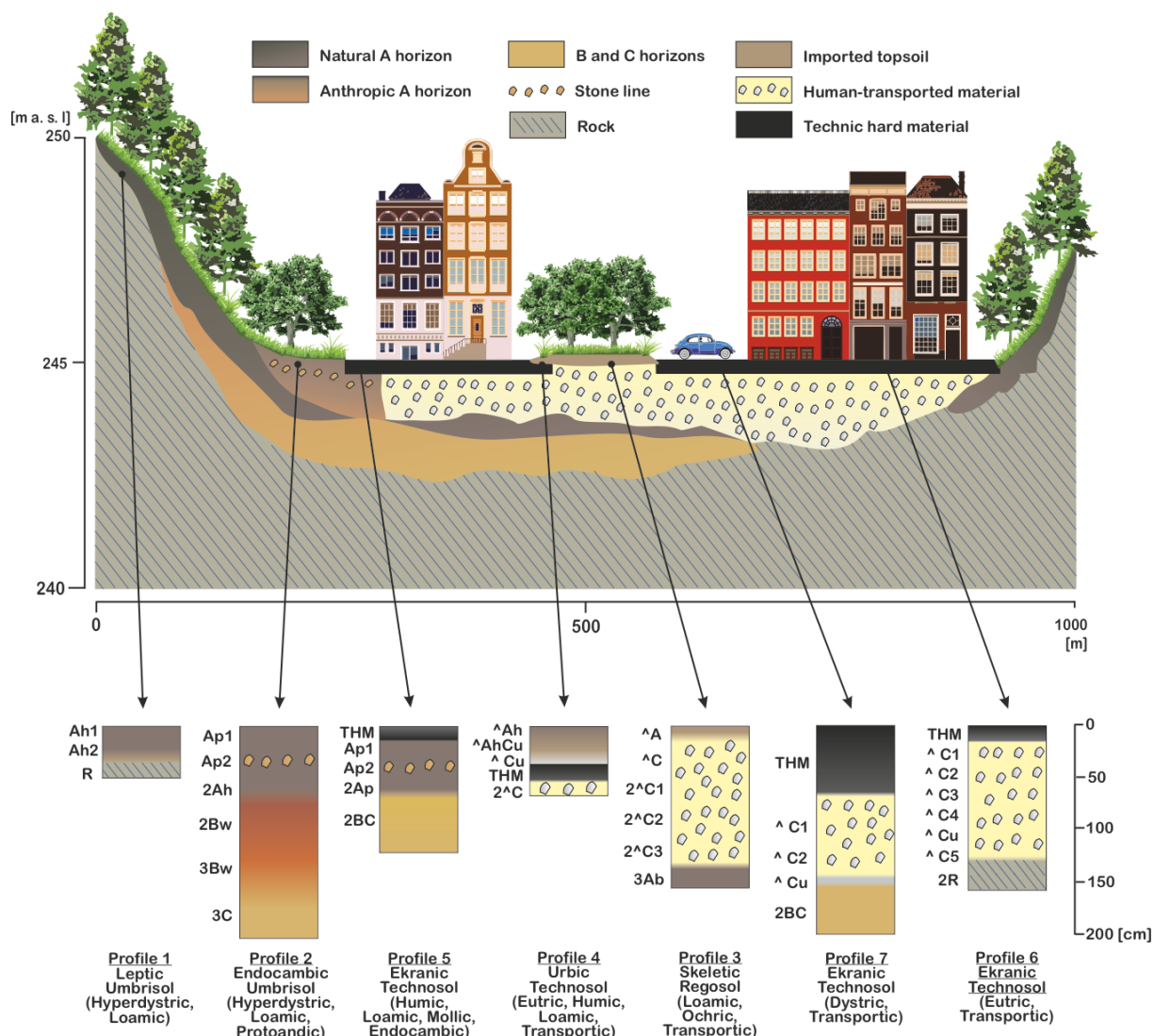


Fig. 2. Sequence of the soils of Santiago de Compostela

Soil genesis and systematic position

In urban areas, pedogenic processes are submitted to anthropogenic control to a much higher extent than soils in non-urban areas. In many cases, human decisions have impact on parent material, as urban planning activities determine whether previous soils (natural or agricultural) are preserved, disturbed, even removed or sealed. In addition, urban soils are characterized by a wide range of various activities over time and by a very frequent and often arbitrary change of use controlled almost exclusively by humans, who impose very rapid transformation cycles compared with those occurring in less disturbed areas (Norra and Stuben, 2003). Consequently, human influence leads to a great variety of soils on a limited surface area (compared to natural environments), with a lack of spatial logic, including deeply degraded soils, strongly transformed soils and pseudo-natural soils showing

only little changes with respect to natural soils (Burghardt et al., 2105; Morel et al., 2015; Levin et al., 2017; Hulisz et al., 2018).

The profiles studied here present examples of different urban soil typologies: three of the profiles correspond to soils developed on materials that have not been transported by humans (profiles 1, 2 and 5, the latter sealed by pavement) and the other four correspond to soil derived from human-transported material (profiles 3, 4, 6 and 7). The profiles presented variable amounts of artefacts, a typical feature of urban soils, even those less disturbed by human activities. These artefacts are mainly bricks and ceramics as well as layers of construction sand (horizons \wedge Cu in profiles 4 and 7). In profiles 1, 2 and 5, artefact contents represent less than 1% weight and they appear only on A horizons. In the rest of the profiles, those formed on human-transported material, artefacts are present in almost all horizons and with higher contents, although they are not dominant in any case.

Four profiles have layers of technic hard material (profiles 4–7), a circumstance that classified them as **Technosols**, even if not all are formed on human-transported materials. This *technic hard material* is at the surface in three of these soils (profiles 5–7), so they have been classified as **Ekranic Technosols**. Profile 4 is classified as **Urbic Technosol** because it is entirely composed of human-transported material, but its surface is not sealed. Profile 3 is also formed on human transported material, in this case excavated soils, but it has been classified as a **Regosol** because it is composed of material that has already been exposed to soil-forming processes (Rossiter, 2007); the qualifier **Skeletal** has been added because it has more than 40% coarse material in the first 100 cm. In turn, profiles 1 and 2 present thick unsaturated A horizons rich in organic mater, so they have been classified as **Umbrisols**, which are the most common soils in natural and agricultural areas in the region of Galicia (Carballas et al., 2016). The **Leptic** qualifier has been added to profile 1, because it has continuous rock at less than 100 cm from the surface, whereas profile 2 does not show the characteristics defining other qualifiers and is therefore classified as **Haplic Umbrisol**.

The first profile (**Leptic Umbrisol**) is a typical shallow soil of high slope areas in the region, with low edaphic development, an Ah horizon directly in contact with the rock (sometimes with presence of a C horizon), very acid and desaturated. Because of important limitations for agricultural use, these soils were traditionally reserved to forest or heath vegetation, whereas in the city they are currently public park areas. Soils in areas with lower slopes, with lesser limitations to crop growth, were traditionally used for agriculture, in many cases after terracing. Examples of these are the profiles 2 and 5, former agricultural soils that have been absorbed by urban sprawl, but with different degrees of artificialization. The two profiles present thick Ap horizons, rich in organic matter due to manuring, which was the traditional fertilization practice in the region, and stone lines separating different genetic cycles. Profile 2 (**Endocambic Umbrisol**) corresponds to a patch of soil developed over amphibolites that has not been disturbed by urbanization, although land use has changed and currently it presents herbaceous vegetation. It presents one cycle of cultivation and two cycles of natural edaphogenesis, differentiated by the presence of fresh amphibolite fragments in the most recent one. The subqualifier **Protoandic** has been added to this soil because the layer 2Ah has a value of $A_{lox} + \frac{1}{2}Fe_{ox} > 1.2\%$ and over 55% phosphate retention. *Andic properties* are common in soils developed over amphibolites in the region (García-Rodeja et al., 1987) although this andic character is less expressed in cultivated soils with respect to forest or shrubland soils (Verde et al., 2005). Profile 5 (**Ekranic Technosol**) is also a former agricultural soil from a terraced land, in this case developed over schist colluvium, with two cycles of cultivation separated by a stone line; the soil has been sealed with a concrete layer during urbanization.

The other four profiles correspond to soils formed on human-altered and transported material. The **Transportic** qualifier, indicating intentional human transport, has been added to the four soils, in

addition to *Dystric* or *Eutric* qualifiers, depending on base saturation, and *Ochric/Humic*, depending on OC contents. Profile 3 (Skeletal **Regosol**) is a soil consisting of several layers of excavated soil materials (>100 cm), burying a previous soil. It has been constructed during the urbanization of the University Campus in the 1960s–1970s. Since it has been reserved for establishment of a green area, it has not been sealed by pavement, having instead a surface layer of imported topsoil. It has two cycles of human-transported soil material with high amounts of gravel and stones: the upper cycle (horizons ^Au and ^Cu) is composed of materials from schist, whereas the inferior cycle (horizons 2^Cu1 , 2^Cu2 and 2^Cu3) consists of granitic material and shows signs of organic matter iluviation. Profile 4 (**Urbic Technosol**) also corresponds to the urbanization of the University Campus, and it is representative of a common practice for preparation of green areas that has been observed in several places of the city. In this case, the layers of rubble and other excavated materials (horizon 2^Cu) have been covered by a layer of concrete, maybe to homogenise and level the surface, above which a substrate for plant growth, consisting of a layer of sand and a layer of imported soil, has been added. Some edaphic development has taken place since the construction of this soil, as shown by the differentiation of two ^Ah horizons with different organic matter content and the apparition of a transitional horizon ^AhC .

Profiles 6 and 7 are those with the highest degree of artificialization. Profile 6 (**Ekranic Technosol**) corresponds to a sidewalk in an old street, whereas profile 7 (**Ekranic Technosol**) corresponds to a high capacity road. The two profiles consist of thick accumulations of human-transported materials, over a preexisting soil in the case of profile 7, and directly over excavated rock in profile 6. In both soils, these materials are covered by continuous technic hard material: a 15-cm layer of concrete with paving stones in profile 6, and three layers of asphalt concrete with a total thickness of 70 cm in profile 7. The human-transported materials in profile 7 are much more compacted than in profile 6, likely due to the use of heavy machinery for road construction.

Soil sequence

The seven profiles studied are representative of the different soil morphologies existing in the city of Santiago de Compostela and their diverse degree of artificialization, forming an anthroposequence of increasing human influence or Technosequence. They include former natural and agricultural soils that have been encircled within the city during urban growth, soils constructed with human-transported material and soils that have been sealed by pavement or concrete (Fig. 2). The first group includes natural or agricultural soils within the city preserved with little modification, represented by profiles 1 and 2. These soils are currently occupied by public parks and urban gardens. A second group includes soils formed on important amounts of human-transported materials, but not sealed, represented here by profiles 3 and 4. These are the typical soils of recently urbanized green areas, where the original soil has been removed and/or buried by excavated materials. Finally, there is a third group of soils that have been sealed for the construction of urban infrastructures. Within this group, most soils consist of human-transported material burying or replacing previous soils (profiles 6 and 7), but previous soils sealed directly without this layer of human-transported material also exist (profile 5). Overall, the morphological diversity of the profiles is illustrative of the high spatial heterogeneity that is typical of urban soils.

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Soil lithotoposequence in the catchment of the saline Gallocanta Lake (Northeast Spain)

Carmen Castañeda, Rafael Rodríguez-Ochoa, José Ramón Olarieta

The Gallocanta Lake is the largest and most undisturbed saline lake in Western Europe, covering 14.4 km² within the Iberian Mountains (Figure 1). It is 7.8 km long in the NW-SE direction and 2.8 km wide. The water level is heavily dependent on rainfall and may desiccate completely in low rainfall years while it covers some 1400 ha in wet years (Jiménez et al., 2015; Castañeda et al., 2020). But it is estimated that the lake occupied some 54 km² in its first stages and only became saline in relatively recent times (Gracia, 2009). The lake, its margins supporting natural vegetation, and the surrounding agricultural lands encompass a total of 6477 ha, are protected as a Natural Reserve, also by the EU Birds and Habitats Directives, and are included in the Ramsar list.



Fig. 1. Location

Lithology and topography

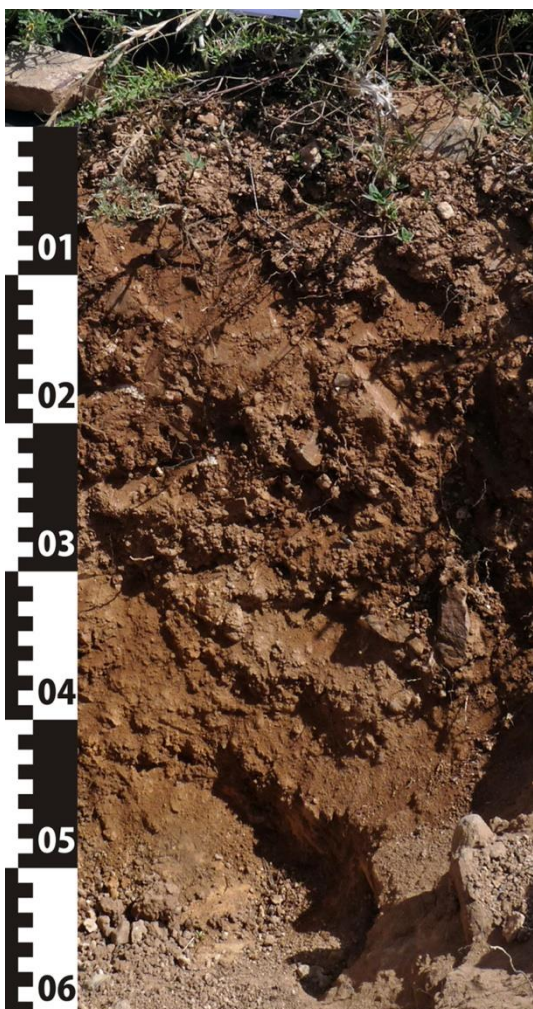
This endorrheic lake is located at an altitude of about 990 m a.s.l. in a polje that reached the impervious Triassic layers in the late Pleistocene (Gracia, 2014). The mountains on the NE side of the basin are constituted by Ordovician siliceous quartzites and slates and reach up to 1400 m a.s.l., while Mesozoic limestones and marls flank the basin on the southern side, which has a gentle relief. Impermeable Triassic lutites and evaporites lay at the base of the karstic polje, contributing to the high salinity of the lake (Gracia, 2014). Geomorphologically, the steep upper slopes on the northern side are followed by alluvial fans with siliceous material, while various types of deposits appear on the lake margins produced by the dynamics of the lake under the strong northwesterly winds prevailing in the area.

Land use

Most of the basin is used for rainfed agriculture, with winter rye as the main crop, while the steep (over 20–25%) slopes are covered by shrubs with scattered *Quercus ilex* subsp. *ballota* trees. Abandoned agricultural plots support species such as *Dactylis glomerata*, *Elymus* cf. *pungens*, *Medicago sativa*, and *Crepis pulchra*. The general distribution of vegetation around the lake is related to the gradients of soil moisture and salinity produced by the seasonal and interannual water level fluctuations in the lake (Castañeda et al., 2020). The lake bed supports the hydrogeophyte *Ruppia drepanensis* and microbial communities with high genetic and ecological diversity (Menéndez-Serra et al., 2019). Communities dominated by *Suaeda splendens*, *Suaeda spicata*, *Aeluropus littoralis*, *Salicornia patula*, and *Limonium costae* appear on the saline shores of the lake. Humid areas further away from the lake are covered by grasslands with *Bolboschoenus maritimus* and various *Juncus* species.

Profile 1 – Epileptic Calcisol (Loamic, Ochric)

Location: straight 5% slope, shrubs, 1033 m a.s.l., N 40°58'35" W 1°27'47"



Morphology:

- A** – 0–25 cm, humus horizon, sandy loam, 7.5YR 4/4, dry, fine to medium strong subangular blocky structure, compact, hard, frequent worm casts, frequent very fine and fine vertical roots, abrupt and smooth boundary;
- Bwk** – 25–45 cm, *calcic* horizon, sandy loam, 7.5YR 4/4, dry, fine moderate subangular blocky structure, compact, hard, few vertical roots, common nodules and pendants of calcium carbonate, abrupt and irregular boundary;
- R** – 45–(50) cm, quartzite.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class
		> 2.0	2.0-0.05	0.05-0.002	< 0.002	
		A	0-25	6-15	69	
Bwk	25-45	6-15	62	22	16	SL

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	EC (1:5) [dS·m ⁻¹ 25°C]	Gypsum [g·kg ⁻¹]	pH (sat.extr.)	CaCO ₃ [g·kg ⁻¹]
A	0-25	12	0.20	0	7.6	333
Bwk	25-45	7	0.17	0	7.7	410

Profile 2 – Epipetric Skeletic **Calcisol** (Loamic, Ochric)

Location: alluvial fan, 4% slope, winter grains, 1008 m a.s.l., N 40°58'17.7" W 1°28'43.17"



Morphology:

- Ap** – 0–28/31 cm, humus horizon, sandy loam, 7.5YR 3.5/3.5, dry, very fine to fine strong subangular blocky structure, compact, slightly hard, boundary;
- Bkm** – 28/31–(60) cm, *petrocalcic* horizon, strongly cemented by CaCO_3 , fragmented layer, 10YR 7.5/6 in the upper part and 2.5YR 5/8 in the lower part.

Table 3. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class
		> 2.0	2.0-0.05	0.05-0.002	< 0.002	
		Ap	0-28/31	50-70	73	

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	EC (1:5) [dS·m ⁻¹ 25°C]	Gypsum [g·kg ⁻¹]	pH (sat.extr.)	CaCO ₃ [g·kg ⁻¹]
Ap	0-28/31	21	0.2	0	8.3	230

Profile 3 – Calcic Kastanozem (Loamic, Raptic)

Location: lower flat-bottom valley, slope <5%, arable, water table at 170 cm depth, 997 m a.s.l., N 40°58'3.5" W 1°28'43.3"



Morphology:

- Ap** – 0–35/40 cm, *mollic* horizon, sandy loam, 10YR3/2, dry, coarse moderate subangular blocky, compact, very hard, abrupt and wavy boundary
- A** – 35/40–50/55 cm, humus horizon, sandy loam, 10YR 4/2, frequent mottles 10YR 5/5, dry, medium moderate subangular blocky, compact, very hard, frequent nodules of CaCO₃, gradual and wavy boundary;
- Bwk** – 50/55–100 cm, *calcic* horizon, clay loam, 2.5Y 6/3, few mottles 10YR 7/8, moist, medium moderate subangular blocky, compact, very hard, frequent worm channels, frequent nodules of CaCO₃, abrupt and smooth boundary;
- 2C** – 100–125/135 cm, loamy sand, 10YR 4/2, frequent mottles 10YR 5/8, moist, massive, slightly compact, abrupt and wavy boundary;
- 2Ck** – 125/135–(180) cm, sandy loam, 7.5YR 6/8, moist, massive, slightly compact, few Fe-Mn concretions, few nodules of CaCO₃.

Table 5. Texture

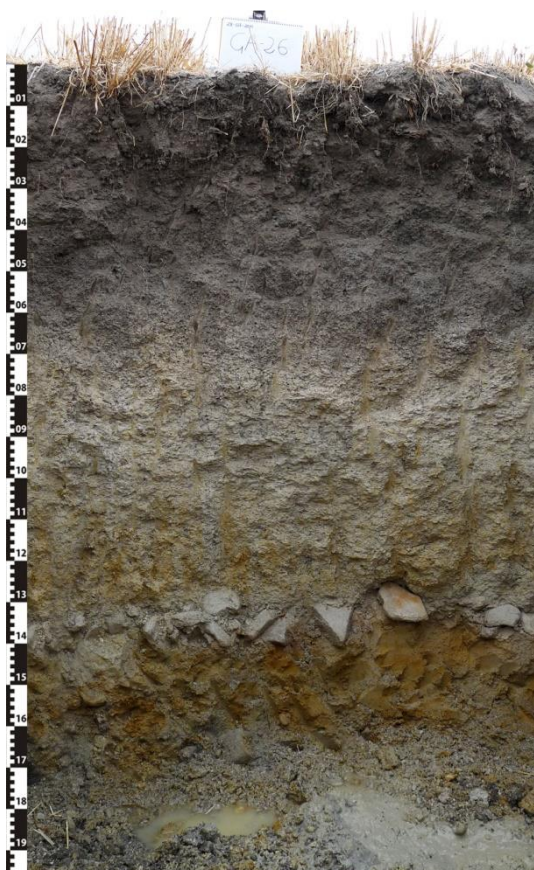
Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class
		> 2.0	2.0-0.05	0.05-0.002	< 0.002	
Ap	0-35/40	0	60	30	10	SL
A	35/40-50/55	1-5	55	25	20	SL
Bwk	50/55-100	1-5	40	26	34	CL
2C	100-125/135	16-35	86	11	3	LS
2Ck	125/135-180	6-15	67	26	8	SL

Table 6. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	ECe (sat.extr.) [dS·m ⁻¹ 25°C]	SAR	Gypsum [g·kg ⁻¹]	pH (sat.extr.)	CaCO ₃ [g·kg ⁻¹]
Ap	0-35/40	19	1.07	0.4	0	8.2	256
A	35/40-50/55	10	0.92	0.7	0	8.5	441
Bwk	50/55-100	3	0.42	0.4	0	8.5	497
2C	100-125/135	1	0.33	0.3	0	8.5	311
2Ck	125/135-180	1	0.41	0.3	0	8.1	385

Profile 4 – Gleyic Calcic **Kastanozem** (Aric, Amphiclayic, Endoloamic, Pachic)

Location: lower flat-bottom valley, slope <5%, arable, water table at 160 cm depth
994 m a.s.l., N 40°57'03'' W 1°28'54''



Morphology:

- Ap** – 0–29/33 cm, *mollic* horizon, sandy loam, 10YR 3/2, dry, medium strong subangular blocky, compact, hard, abrupt and smooth boundary;
- A** – 29/33–60 cm, *mollic* horizon, clay, 2.5Y 3/2, frequent mottles 10YR 5/4, dry, very fine strong subangular blocky, compact, hard, gradual and smooth boundary;
- Bwkl** – 60–131/136 cm, *calcic* horizon with *gleyic* properties, clay loam, 2.5Y 7/2, frequent mottles 10YR 7/6, slightly moist, medium moderate subangular blocky, compact, friable, frequent worm channels, abundant hard nodules of CaCO₃, soft Fe-Mn concretions, abrupt and wavy boundary with a stone line of angular-tabular quartzite rock fragments;
- 2Ckl** – 131/136–(165) cm, *calcic* horizon with *gleyic* properties, sandy loam, 2.5Y 6/4, abundant mottles 10YR 7/8, wet, medium weak layered, compact, very friable, very slightly cemented, frequent friable nodules of CaCO₃.

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class
		> 2.0	2.0-0.05	0.05-0.002	< 0.002	
Ap	0-29/33	0	61	30	9	SL
A	29/33-60	0	32	27	41	C
Bwkl	60-131/136	0	44	19	37	CL
2Ckl	131/136-165	6-15	69	22	9	SL

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Ece (sat.extr.) [dS·m ⁻¹ 25°C]	SAR	Gypsum [g·kg ⁻¹]	pH (sat.extr.)	CaCO ₃ [g·kg ⁻¹]
Ap	0-29/33	14	0.6	1.1	0	8.3	271
A	29/33-60	8	0.9	4.8	0	8.6	339
Bwkl	60-131/136	2	0.5	0.7	0	8.5	628
2Ckl	131/136-165	1	0.4	0.4	0	8.4	254

Profile 5 – Calcic Sodic Gleyic **Solonchak** (Chloridic, Evapocrustic, Loamic, Ochric, Amphiraptic, Hypersalic)

Location: sandbar on the lake fringe, slope <3%, halophytic communities, water table at 152 cm depth, 993 m a.s.l., **N** 40°57'42.43" **W** 1°28'33.33"



Morphology:

- Cz** – 0–0.2 cm, saline crust, 2.5Y 5/2, abrupt and smooth boundary;
- Ayz** – 0.2–12 cm, *salic* horizon, sandy loam, 10YR 5/2, slightly moist, fine strong granular, compact, loose, very few gypsum crystals, abrupt and smooth boundary;
- 2Czr** – 12–84/90 cm, *salic* horizon with *gleyic* properties, clay loam, 2.5Y 7/1, moist, massive, slightly compact to compact, friable, abrupt and wavy boundary;
- 3Czkr** – 84/90–115/120 cm, *salic* and *protocalcic* horizon with *gleyic* properties,, sandy loam, 2.5Y 5/2, abundant mottles 7.5YR 5/8, 2.5Y 6/2, and 5Y 7.5/2, wet, massive, slightly compact to compact, friable, abundant hard nodules of CaCO₃, soft Fe-Mn concretions, clear and wavy boundary;
- 4Czkr** – 115/120–(170) cm, *salic* and *calcic* horizon with *gleyic* properties, clay loam, 10YR 6/3, abundant mottles 7.5YR 5/8 and 2.5Y 6/2, moist, massive, slightly compact, frequent friable nodules of CaCO₃.

Table 9. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class
		> 2.0	2.0-0.05	0.05-0.002	< 0.002	
Ayz	0.2–12	<1	73	18	9	SL
2Czr	12–84/90	0	42	25	33	CL
3Czkr	84/90–115/120	0	76	17	8	SL
4Czkr	115/120–170	1–5	36	26	39	CL

Table 10. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	ECe (sat.extr.)		SAR	Gypsum [g·kg ⁻¹]	pH (sat.extr.)	CaCO ₃ [g·kg ⁻¹]
			[dS·m ⁻¹]	[dS·m ⁻¹ 25°C]				
Ayz	0.2–12	11	18	13	271	7.8	367	
2Czr	12–84/90	3	37	23	145	7.8	526	
3Czkr	84/90–115/120	1	21	15	170	8.2	134	
4Czkr	115/120–170	1	18	14	286	8.1	346	

Table 11. Some chemical properties of the saturation extract (meq·l⁻¹)

Horizon	Depth [cm]	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	CO ₃ ²⁻	Na ⁺	Ca ²⁺	Mg ²⁺	K ⁺
Ayz	0.2–12	155	57	3	0	98	55	54	5
2Czr	12–84/90	373	128	2	0	243	46	171	4
3Czkr	84/90–115/120	176	102	2	0	127	40	98	3
4Czkr	115/120–170	136	97	2	0	105	37	82	2

Profile 6 – Gypsic Sodic Gleyic **Solonchak** (Amphiclayic, Chloridic, Calcaric, Evapocrustic, Humic, Epiloamic, Amphiraptic, Hypersalic)

Location: lake bed, slope <1%, bare soil with salt crust and *Ruppia* communities, water table at 90 cm depth, 992 m a.s.l., N 40°57'34.67" W 1°28'44.87"



Morphology:

- Cz** – 0–0.5 cm, saline and biotic crust, N 6.5/1, abrupt and wavy boundary;
- Ay_{zr}** – 0.5–6/10 cm, *salic* and *gypsic* horizon, loamy sand, 10B 2.5/1, mottles 5Y 6/1, slightly moist, massive, slightly compact, common gypsum crystals, abrupt and wavy boundary;
- AC_{zr1}** – 6/10–14/16 cm, *salic* and *gypsic* horizon, sandy loam, 10B 2.5/1, wet, coarse moderate layered, slightly compact, slightly sticky, slightly plastic, common gypsum crystals, abrupt and wavy boundary;
- AC_{zr2}** – 14/16–24 cm, *salic* and *gypsic* horizon, loam, 10B 5.5/1, mottles 10B 5.5/2, very coarse very weak layered, slightly compact, sticky, plastic, silt coatings in crack faces, common gypsum crusts, very abrupt and smooth boundary;
- 2AC_{zr1}** – 24–42 cm, *salic* and *gypsic* horizon, clay loam, 10B 5.5/1, mottles 10B 4.5/1, wet, massive, slightly compact, sticky, plastic, silt coatings in vertical galleries, common gypsum crystals, abrupt and smooth boundary;
- 2C_{zr}** – 42–90/106 cm, *salic* and *gypsic* horizon, silty clay, 2.5GY 6/1, wet, massive, slightly compact, sticky, plastic, common gypsum crystals and nodules, abrupt and smooth boundary;
- 3C_{zr}** – 90/106–(110) cm, *salic* and *gypsic* horizon, clay, 7.5GY 6/1, wet, massive, common gypsum crystals, abrupt and smooth boundary.

Table 12. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm				Textural class
		> 2.0	2.0-0.05	0.05-0.002	< 0.002	
Ayzz	0.6–6/10	0	80	16	5	LS
ACyzz1	6/10–14/16	0	62	25	12	SL
ACyzz2	14/16–24	0	44	32	24	L
2ACyzz1	24–42	0	45	26	29	CL
2Cyzz2	42–90/106	0	15	40	45	SIC
3Cyzz	90/106–110	0	16	38	46	C

Table 13. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	ECe (sat.extr.) [dS·m ⁻¹ 25°C]	SAR	Gypsum [g·kg ⁻¹]	pH	
						(sat.extr.)	CaCO ₃ [g·kg ⁻¹]
Ayzz	0.6–6/10	34	182	113	271	7.9	184
ACyzz1	6/10–14/16	36	145	69	145	8.5	293
ACyzz2	14/16–24	23	105	50	170	8.6	366
2ACyzz1	24–42	20	100	41	286	8.2	280
2Cyzz2	42–90/106	7	98	40	57	7.9	520
3Cyzz	90/106–110	6	82	38	43	7.7	360

Table 14. Some chemical properties of the saturation extract (meq·l⁻¹)

Horizon	Depth [cm]	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	CO ₃ ²⁻	Na ⁺	Ca ²⁺	Mg ²⁺	K ⁺
Ayzz	0.6–6/10	5172	819	11	0	3537	8	1950	86
ACyzz1	6/10–14/16	1995	373	3	0	1426	40	806	42
ACyzz2	14/16–24	1173	377	3	0	910	43	631	26
2ACyzz1	24–42	1051	436	2	0	784	37	682	24
2Cyzz2	42–90/106	795	299	1	0	567	25	383	14
3Cyzz	90/106–110	788	299	2	0	609	38	469	20

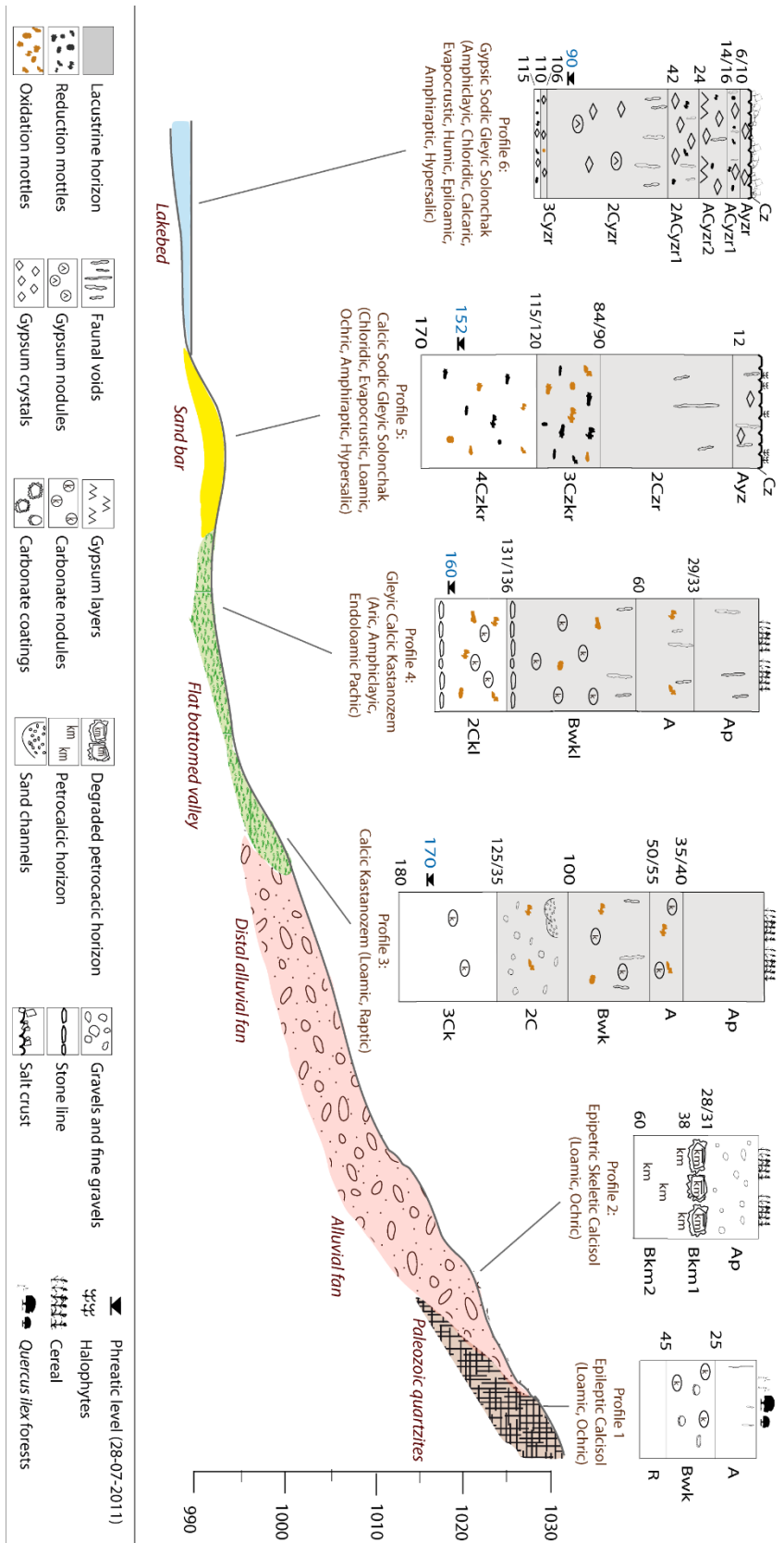


Fig. 2. Lithotoposequence of the soils of the northeastern side of the Gallocanta Lake basin

Climate

The region has a mean annual temperature of 11.2°C, with the minimum mean monthly temperature of 2.7°C occurring in January and the maximum of 21.6°C in July. Mean annual rainfall is 488 mm, but yearly values in the period 1944–2014 have varied from a minimum of 232 mm to a maximum of 760 mm (Luna, 2017). Winter is the driest season with a mean rainfall of 92 mm. Annual reference evapotranspiration (ET_0) is over 1100 mm (García-Vera and Martínez-Cob, 2004). According to the IPCC (2006) the climate may thus be classified as Warm Temperate Dry.

Soil genesis and systematic position

Profile 1 is a *Epileptic Calcisol (Loamic, Ochric)* with a strongly structured A horizon. Quartzite strata appear at depths shallower than 50 cm (*Leptic* qualifier). The sparse vegetation of shrubs and scattered trees does not provide enough litter to produce a significant organic horizon or a dark A horizon, therefore showing just an *Ochric* horizon with low concentrations of organic carbon (OC) (less than 15 g · kg⁻¹). Common (5–15% in volume) secondary accumulations of CaCO₃ appear as nodules and pendants beneath the rock fragments in the B horizon, providing the argument for the *Calcic* horizon.

A *Petric Calcisol (Loamic, Ochric)* with a *Petrocalcic* horizon at shallow depths, usually less than 30 cm, is shown in Profile 2. This *Petrocalcic* horizon is strongly cemented but fragmented, probably by agricultural practices, and these fragments eventually appear in the surface horizon, fulfilling the requirement for the *Skeletal* qualifier. The agricultural use in this semiarid environment has only allowed the development of surface horizons fulfilling the requirements for the *Ochric* qualifier.

Profile 3 is a *Calcic Kastanozems (Loamic, Pachic)* with a 50 cm-thick A horizon that meets the requirements for *Mollic* horizon and *Pachic* qualifier. This *Mollic* horizon has nevertheless relatively low concentrations of OC, less than 20 g · kg⁻¹. Frequent nodules of CaCO₃ appear in the Bwk horizon providing the argument for the *Calcic* qualifier. The presence of mottling from very shallow depths (40 cm) and Fe-Mn concretions at depths of about 100 cm agrees with the requirements for gleyic color pattern, but the absence of reducing conditions does not allow the use of the *Gleyic* qualifier for these soils. Profile 4, *Gleyic Calcic Kastanozem (Aric, Amphiclayic, Endoloamic Pachic)*, on the other hand, qualifies for *Gleyic* as the Bwk horizon has a color of 2.5Y 7/2, and also shows frequent mottles with a color of 10YR 7/6 and Fe-Mn concretions. Nodules of CaCO₃ are more frequent in the *Calcic* horizons of this profile (Bwk and 2Ck) than in that of Profile 3. The A horizon provides the *Amphiclayic* qualifier because it has 41% clay and a thickness of 30 cm at the depth 29–60 cm. The Ap and A horizons combine for a 60 cm-thick *Mollic* horizon but with a low mean OC concentration of 11 g · kg⁻¹.

Profile 5 is a *Calcic Sodic Gleyic Solonchak (Chloridic, Evapocrustic, Loamic, Ochric, Amphiraptic, Hypersalic)* with no development of soil structure below the 12 cm-deep Ayz horizon. This is a highly saline soil with a thin (less than 1 cm thick) saline crust on the surface (*Evapocrustic* qualifier) and values of the EC_e higher than 17 dS · m⁻¹ throughout the profile and reaching up to 37 dS · m⁻¹ in the subsurface horizon (*Hypersalic* qualifier). Similarly, the *Sodic* qualifier is granted as the values of SAR are higher than 13 throughout the profile and reach a maximum of 23 in the subsurface horizon. The *Calcic* qualifier is granted due to the presence of abundant nodules of CaCO₃ that appear at depths over 84 cm. *Gleyic* properties with dominant hues of 2.5Y appear between 12 and 120 cm depth and abundant mottles below 84 cm depth. The Ayz and 2C horizons also fulfill the requirements for the *Chloridic* qualifier, but this is not the case for the horizons deeper in the profile,

in which the concentration of SO_4^{2-} is 60–70% of the Cl^- concentration. Although the extreme salinity conditions only allow the development of a sparse vegetation cover of *Puccinellia sp.* and *Salicornia sp.*, the surface horizon has an OC concentration higher than $10 \text{ g}\cdot\text{kg}^{-1}$. The profile shows two abrupt textural changes from sandy loam to clay loam between the first and second horizons and between the third and fourth horizons, but the ***Abruptic*** qualifier is not considered in Solonchaks (IUSS Working Group WRB, 2015).

Profile 6 is similar to Profile 5 but shows very little development of structure even in the surface horizon and is classified as ***Gypsic Sodic Gleyic Solonchak (Clayic, Chloridic, Calcaric, Evapocrustic, Humic, Hypersalic)***. The EC_e of this soil is even higher than in the previous profile, with values over $100 \text{ dS}\cdot\text{m}^{-1}$ in the upper 40 cm and over $80 \text{ dS}\cdot\text{m}^{-1}$ in the first 100 cm. SAR values decrease from 113 in the surface horizon to 40 at a depth of 100 cm. ***Gleyic*** properties are reflected in the dominant hue of the soil color, which ranges from 10B in the horizons down to 40 cm to hues of 2.5GY and 7.5GY in the deeper horizons. Common accumulations of gypsum appear throughout the soil profile, mostly as crystals but also as nodules in the lower part of the profile. The concentration of OC carbon in the surface horizons is higher than $20 \text{ g}\cdot\text{kg}^{-1}$ in the surface 40 cm, therefore satisfying the requirement for the ***Humic*** qualifier. Silt coatings appear at a depth between 14 and 40 cm, but this feature is not considered in anyway in the classification, as also happens with other systems of soil classification such as Soil Taxonomy (SSS, 1999). The texture of the profile shows an increasing content of clay with depth, with three abrupt textural changes that, again, cannot be introduced in the classification of this Solonchak.

Soil sequence

The soils described in this sequence on the northeastern side of the Gallocanta Lake reflect the conditions of different environments: those related to the siliceous mountains on the northeastern side of the lake (the mountain sides and the alluvial fans at the lower slopes of these mountains), those related to the lake itself and the area influenced by its dynamics, and the flat-bottom valley that acts as the transition between those two. These environments involve different soil parent materials, geomorphological positions, microclimatic conditions, and as a result, different land uses both present and in the past.

Shallow soils developed from quartzites (***Leptic Calcisols***) appear on the slopes of the mountain. These soils share a complex pattern with ***Calcaric Lithic Leptosols*** with very incipient development of soil horizons, probably as a result of past processes of soil erosion under the pressure of grazing animals and the associated fires and the extraction of firewood.

Petric Skeletic Calcisols have developed from the coarse siliceous deposits on the alluvial fans at the footslope of these mountains. The high level of CaCO_3 throughout the soil profile cannot be therefore attributed to the parent material but has been produced from the calcium present in feldspars in the Ordovician slates and from CO_2 in rainfall and produced by plant roots. This fraction of the CaCO_3 in the soils represents a very significant sink of atmospheric CO_2 . This profile may therefore be considered as part of an “accumulation catena” (Sommer and Schlichting, 1997).

The two ***Calcic Kastanozems*** (Profiles 3 and 4) show a mixture of lacustrine materials on the upper part of the profile and detrital materials from the upper slopes of the basin on the deeper horizons. The former show very small proportions of rock fragments and/or matrix colors with hue of 2.5Y or chroma of 2 or less (Castañeda et al., 2015). The genesis of these soils is heavily influenced by their proximity to the lake, as their location is only 2–5 m above that of the lake bed in that area. They differ in that coarser-textured horizons (loamy sand to sandy loam) predominate in Profile 3, which is

located further away from the lake, whereas finer-textured horizons (clay to clay loam) make up most of Profile 4, which is closer to the lake. Nevertheless, both soils show horizons with contrasting textures throughout their profiles, with clay-loam horizons also appearing in Profile 3 and sandy loam horizons also appearing in Profile 4. The stone line at a depth of 130 cm in Profile 4 reflects the complex conditions of erosion/sedimentation under which these soils have developed.

The development of A horizons up to 50–60 cm-thick in these two soils seems to be related to the increased moisture availability in this valley due to the common springs that appear in the lithological contacts (between the Paleozoic and more recent materials) in the slopes and the higher biomass productivity under these conditions. This also allows an intensive agricultural use which is limited nevertheless by the high soil water content in the autumn-spring period.

The influence of the lake water level is reflected in the presence of mottling at a depth of 30 cm and Fe-Mn concretions further down the profile. Similarly, the abundant nodules of CaCO_3 that appear at depths over 84 cm seem to be related to precipitations from the fluctuating water table.

Profile 5 – *Calcic Sodic Gleyic Solonchak* – has developed on the sand bar formed at the lake shore and shows two abrupt textural changes, in both cases from sandy loam to clay loam horizons, that show the changing sedimentary conditions at the edge of the lake. Gleyic conditions with soil color hue of 2.5Y appear already at a depth of 12 cm reflecting the strong influence of the lake water table, which is also expressed in Fe-Mn concretions and CaCO_3 nodules. Soils in this environment show similar concentrations of available nutrients to the previous cultivated profiles as a result of the downward movement of those nutrients in the landscape (Luna et al., 2019). These soils support habitats protected under the European Habitats Directive, especially annual and perennial halophytic formations (of intermittent flooded areas and saline soils) which include Iberian endemisms such as *Puccinellia pungens* and other catalogued flora.

The *Gypsic Sodic Gleyic Solonchak* (Profile 6) described at the lake bed shows strongly reducing conditions, with dominant soil color hue of 10B in the surface horizon, estimated E_H values below 100 mV and a sulphidic redox status according to the Bartlett and James (1995) classification (Castañeda et al., 2017). These reducing conditions are not prevented by the high salinity and carbonate concentration of these soils.

Accumulations of gypsum crystals and nodules appear throughout the profile and substitute in this wetter soil for the CaCO_3 accumulations that appear in all the other profiles of the sequence. Another specific feature of this profile is the presence of silt coatings at a depth between 14 and 42 cm that result from the translocation of precipitated carbonatic silt that cannot be retained in the upper horizon due to the absence of soil structure.

The surface horizon shows the highest concentration of OC in the soil sequence studied. This OC may have various sources: deposition of dissolved and particulate OC in the lake waters, plant residues from the *Ruppia* communities, accumulation of wind-blown plant material in the periods when the lake is dry, and recalcitrant OC remaining from the vegetation present in first stages of the lake when it was still filled with freshwater.

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Soils with andic properties on alkaline basalt in Mediterranean climate. A toposequence study in the Marghine district (Sardinia, Italy)

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The study area is located on Mt. Sant'Antonio (808 m a.s.l.) This is a basaltic (basanite) formation, part of the volcanic complex of Montiferru in the Marghine sub-region, in the central-west part of Sardinia, Italy (Capra et al., 2009)(Fig. 1).

Lithology and topography

The formation was formed in the late Pliocene–Early Quaternary by intense magmatic activity leading to the accumulation of alkaline basaltic lava, such as basanite, from different emission centers (Vernia et al., 1977). Mt. St. Antonio represents an

emission center of an old shield volcano. It is characterized by the presence of a series of trachybasaltic taps that extended to the west and north-west. The general structures are represented by: “two dikes formed by trachybasaltic lava characterized by a grain size rougher than that of gaining rocks, with large plagioclastic elements that detach in the phenocrystalline association” (Vacca et al., 2009; Carmignani et al., 2001).

Land use

The landscape is characterized by the intense activity of reforestation during the last part of the 19th century. Currently, the vegetation is composed of autochthonous species such as oaks (*Quercus Pubescens* Q. *Ilex* and *Suber*), and exotic species such as pine (*Pinus* spp.), eucalyptus (*Eucalyptus camaldulensis*), locust tree (*Acacia saligna*). Several perennial herbaceous species are present (*Luzula forsteri*, *Viola alba subsp. dehnhardtii*, *Brachypodium sylvaticum*, *Cyclamen repandum* and *Ornithogalum pyrenaicum*). Historically, this area has been affected by wildfires and intense agricultural activities. Currently, parts of the areas are occupied by forests and plantations. The agricultural activities are limited to semi-extensive farming.

Climate

The climate is typical for the inland area of Sardinia: continental, warm and sub-humid. The average annual rainfall is 905 mm and temperature of 14.6°C (Ente Autonomo Flumendosa, 1998). The Köppen Climate Classification subtype for this climate is ‘Csb’ (Warm-summer Mediterranean climate). The average annual potential evapotranspiration (Thorntwaite and Mather, 1957) is 806.9 mm. Soil temperature and soil moisture regimes are estimated as thermic and xeric.

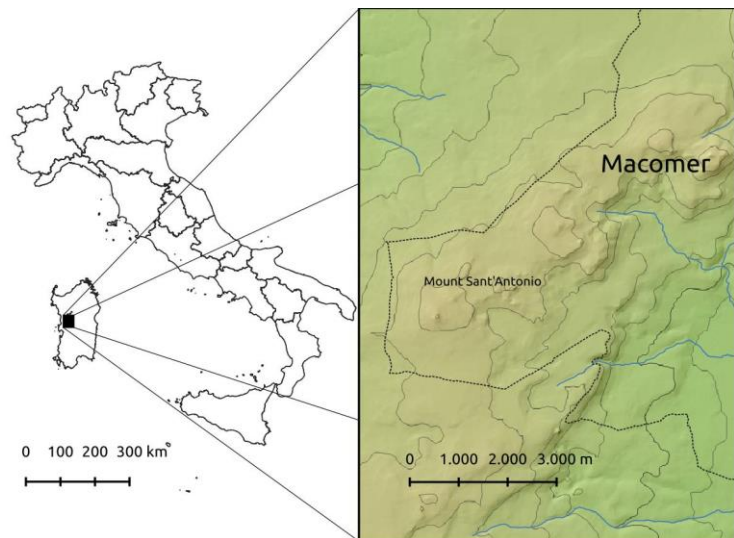


Fig. 1. Location

Profile 1 – Mollic Katogleptic Andosol (Protoandic, Thixotropic)

Location: Alkali basalts, Vulcanic flow in hillslope, lower slope (2,6%), east aspect (125°N), Eucaliptus plantation (burnt in 1996) undergrowth, 640 m a.s.l., N 40°14'15.9" E 8°32'53.7"



Morphology:

- Oi** – 0,5–0 cm, slightly decomposed organic material, leaves;
- Ah1** – 0–5 cm, *mollic* horizon, dark gray color (5YR 2.5/2), wet, silt loam, gravel 10/15%, moderate lumpy and polyhedral subangular structure with fine-sized top-down trend, brittle from wetness, abundant small (<1mm) to very small (1–2 mm) pores, normal drainage, abundant oblique and vertical roots of small dimensions; intense biological activity;
- Ah2** – 5–25 cm, *mollic* horizon, dark gray (2.5YR 3/2), wet, loam, gravel 10%, common pores ranging in size from small (1–2mm) to medium (2–5mm); moderate subangular polyhedral type aggregation of fine to medium; crumbly when wet; normal drainage; common roots running from horizontal to vertical and oblique, mostly small but also medium in size; medium biological activity;
- Bw** – 25–45 cm, reddish brown (7.5R 3.5/6), wet, loamy sand, skeleton 10%, small (1–2mm) to medium (2–5mm) common pores, moderate fine to medium sized subangular polyhedral aggregation; crumbly when wet; normal drainage; common roots running from horizontal to vertical and oblique, mostly small but also medium in size; medium biological activity;
- R** – 45–(60) cm, weak altered Pliocenic Basalts.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm							Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.2	0.2-0.05	0.05-0.002	<0.002	
Ah ₁	0-5	7.2	12.0	2.0	2.0	29.1	46.2	8.7	SiL
Ah ₂	5-25	15.3	7.0	1.5	1.8	37.6	44.3	7.8	L
Bw	25-45	36.0	6.0	1.0	1.0	55.4	32.0	4.6	LS
R	45-(60)	-	-	-	-	-	-	-	-

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH		CaCO ₃ [g·kg ⁻¹]
					H ₂ O	KCl	
Ah ₁	0-5	63	7,1	9	7.4	6.8	
Ah ₂	5-25	55	5,9	9	6.2	5.2	
Bw	25-45	31	3,0	10	6.1	6.1	
R	45-(60)	-	-	-	-	-	-

Profile 2 – Endoskeletal **Umbrisol** (Protoandic, Amphiarenic, Colluvic, Pachic)

Location: not altered Alkali – Basalts covered by colluvial materials in hillslope, 2–6% slope, aspect SE (105° N) deciduous coppice (Nuts and Chestnut), 655 m a.s.l., **N** 40°13'23.22" **E** 8°42'22.18'



Morphology:

- Ah1** – 0–8 cm, *umbric* horizon, *colluvial* material, dark gray (5YR 2.5/2), wet, loam, gravel <5%, moderate polyhedral and subangular to angular fine structure; crumbly when wet; abundant pores of very small (<1mm) and small (1–2 mm) sizes; normal drainage; common roots with oblique and vertical course of small dimensions; intense biological activity;
- Ah2** – 8–30 cm, *umbric* horizon, *colluvial* material, dark gray (5YR 2.5/2) wet, loamy sand, gravel <5%, moderate angular and polyhedral medium structure, crumbly when wet, abundant pores of very small (<1mm) and small (1–2 mm) sizes, normal drainage, common small roots with oblique and vertical course and in smaller quantities of medium size, intense biological activity;
- Ah3** – 30–50 cm, *umbric* horizon, *colluvial* material, dark gray (5YR 2.5/2), loamy sand, gravel <5%, angular polyhedral type aggregation of medium to coarse size with a strong degree of aggregation; crumbly when wet, common pores of small size (1–2 mm), normal drainage, roots from common to sparse with oblique and vertical course of small size and in smaller quantities of medium size, average biological activity;
- Ah4** – 50–70/75 cm, *umbric* horizon, *colluvial* material, dark gray (5YR 2.5/2), loamy sand, gravel 5–10%, strong angular polyhedral medium to coarse structure, crumbly when wet, common small pores, normal drainage, scanty medium and small roots with oblique and vertical course, average biological activity;
- 2C** – 70/75–(90) cm, gravels 60/70% of rounded type of coarse size (10–25 cm).

Table 3. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm							Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.2	0.2-0.05	0.05-0.002	<0.002	
Ah ₁	0-8	4.1	1	5	1.2	44.3	33.1	15.4	L
Ah ₂	8-30	12.1	2	7	1.6	47.0	33.2	9.2	LS
Ah ₃	30-50	6.6	1	6	2.1	50.3	31.7	8.9	LS
Ah ₄	50-70/75	3.3	2	1	4	55.6	29.7	7.7	LS
2C	70/75-(90)	70.0	-	-	-	-	-	-	-

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH		CaCO ₃ [g·kg ⁻¹]
					H ₂ O	KCl	
Ah ₁	0-8	114	8,4	14	6.1	5.1	-
Ah ₂	8-30	42	3,5	12	5.6	4.4	-
Ah ₃	30-50	31	2,1	15	5.9	4.6	-
Ah ₄	50-70/75	30	2,0	15	6.1	4.6	-
2C	70/75-(90)	-	-	-	-	-	-

Profile 3 – Haplic Umbrisol (Protoandic, Chromic, Colluvic, Anoloamic)

Location: Hillslope/ basaltic plateau, slope 2–6% , mixed forest with *Quercus Pubescens* and *Quercus Suber*, aspect SE (160° N), 725 m a.s.l., N 40°13'25.5" E 8°42'06.6"



Morphology:

- Ah1** – 0–10 cm, *umbric* horizon, dark gray (7.5YR 3/2), wet, sandy loam, gravel 5–10%, moderate subangular polyhedral fine structure, crumbly when wet; common pores of small (1–2 mm) and medium size (2–5 mm); normal drainage, common roots with vertical and oblique course of small dimensions, intense biological activity;
- Ah2** – 10–35 cm, *umbric* horizon, dark gray (7.5YR 3/2), wet, sandy loam, gravel 5–10%, moderate to strong subangular polyhedral medium structure, crumbly when wet; common pores of small (1–2 mm) and medium size (2–5 mm); normal drainage; roots from common to scarce with vertical and oblique course of small dimensions; average biological activity;
- BC** – 35–60 cm, transitional horizon, reddish brown (5YR 4/6), wet, sandy loam, gravel 25%, moderate subangular polyhedral medium to coarse structure, crumbly when wet, few pores of small size (1–2 mm) and very small (<1 mm), normal drainage, roots from scarce to absent with vertical and oblique course of small dimensions, absent biological activity;
- C** – 60–(70) cm, parent material, sandy loam.

Table 5. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm							Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.2	0.2-0.05	0.05-0.002	<0.002	
Ah ₁	0–10	4.2	2.8	2.2	12	41.0	28.5	13.5	SL
Ah ₂	10–35	2.7	0.9	1.2	12	45.2	30.3	10.4	SL
BC	35–60	-	-	1	1	71.2	11.3	15.5	SL

Table 6. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH		CaCO ₃ [g·kg ⁻¹]
					H ₂ O	KCl	
Ah ₁	0–10	57	4.4	13	6.3	4.3	-
Ah ₂	10–35	30	2.8	11	6.1	4.7	-
BC	35–60	3	0.6	5	6.3	4.6	-

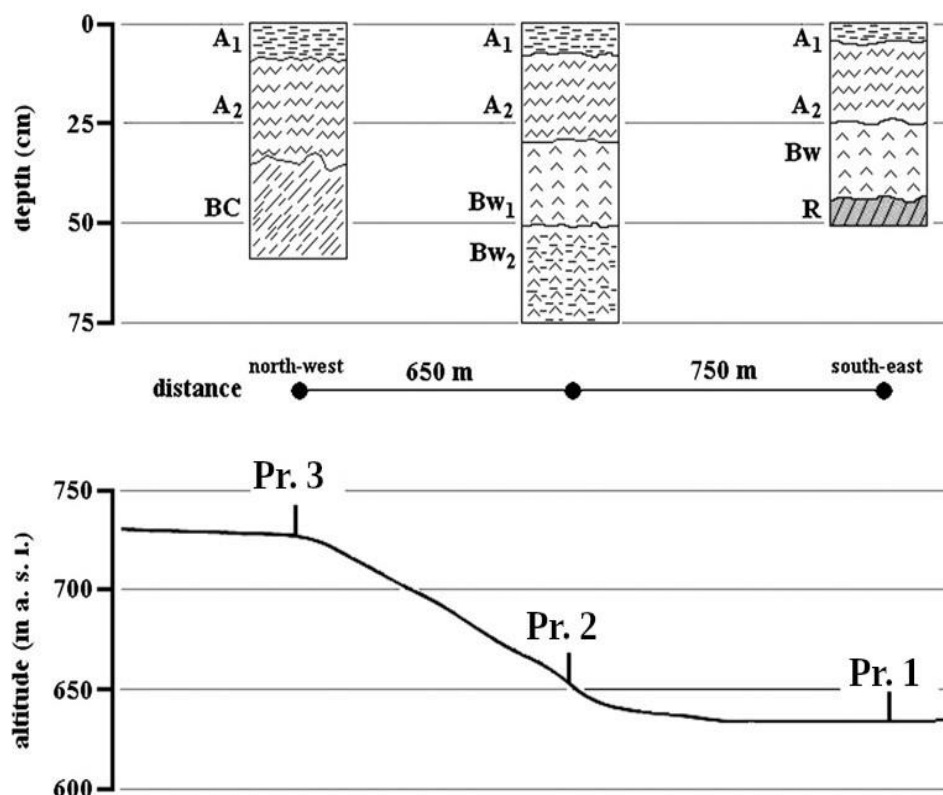


Fig. 2. Schematic representation of the soil profiles (Vacca et al., 2009)

Soil genesis and systematic position

The main morphological features of the selected toposequence profiles are represented in Fig. 2. The soil in Profile 1 (Ah1–Ah2–Bw) is shallow and it is located on the toe slope of Mt. St. Antonio. The geomorphic surface is characterized by high stability and insignificant erosion processes. This soil presents a well-expressed horizon differentiation; the solum shows a dark reddish brown A1, a very dusky red A2 horizon (*Mollic*) and a dark red Bw horizon with a higher hue (Vacca et al., 2009). Profile 2 is located in the foot of the slope; in these morphological conditions, a deep soil can develop. In fact, the profile shows (Ah1–Ah2–Ah3–Ah4) horization, with scarcely differentiated horizons and with the same dark reddish brown color from top to bottom with accumulation of slope material (*Colluvial*). The last profile 3 is located between the summit and the shoulder of the slope. This area is characterized by a relatively unstable (truncation) condition. The solum with thickness of 60 cm shows a simpler horization (Ah1–Ah2–BC). In this profile, it can remark the absence of a Bw horizon, although it is registered the color variation from dark brown in A1 and A2, to red (*Chromic*) in BC (Vacca et al., 2009).

Overall, the A horizons in all profiles show a granular-subangular blocky type structure, with a moderate grade, fine size and high aggregate stability (Vacca et al., 2009). These characteristics may be related to the high OC content (Shoji et al., 1993). This condition is a consequence of the prevalence of forest land cover in the area. The darkness of A horizons, all showing a chroma of 2, is strictly correlated to the high level of OC. Furthermore, features characterized by a dark granular A horizons, Bw horizons with subangular blocky structure, very friable moist consistence, high permeability and

high structure stability are common to volcanic soils (Lulli et al., 1988; Shoji et al., 1993; Vacca et al., 2003; Fauzi and Stoops, 2004). Soil data and geomorphological conditions justify the absence of water-logging conditions. In fact, the soils investigated present no evidence of iron pan, horizontal Fe segregation or significant content of Fe coatings (Chen et al., 1980; Vepraskas et al., 1994). Another important issue is the clay content that is not adequate to sustain shallow water tables (Malucelli et al., 1999).

Soil sequence

The allophanic **Andosol** (Profile 1) is located in the lower site of the toposequence. This topographic position shows well-defined conditions: lower surface runoff, greater water infiltration rate, absence of significant erosion and colluvial movement which may have increased the impact of weathering processes (Vacca et al., 2009). These conditions create the situation where the prolonged soil moistness avoids the transformation of short-order components. In general, the results are evidence of the role of the morphology of the slope and the importance of Al-, Fe-amorphous compounds in expressing soil andic properties and allophane content versus the volcanic origin of the parent material.

Profiles 2 and 3 are developed on a slope, and they present common significant characteristics. They are both characterized by a low content of short-order secondary minerals (allophane content 3%) and the lack of andic properties in any horizon. In fact, these non-allophanic **Umbrisols** (Profile 2 and Profile 3) are characterized by a lower weathering degree a poor expression of *Protoandic* properties, a larger amount of Fe-humus complexes together with a lower Al_o and Si_o content and a predominance of Al-humus complexes that results in an anti-allophanic effect (Vacca et al., 2009).

In general, this toposequence shows the co-existence of both allophanic, non-andic, dystric rich in humus **Umbrisols** and andic, non-allophanic **Andosols** in a small geographical frame. They are characterized by two important issues: they are developed from the same volcanic material and evolved under the same climate. In this context, the expression of andic properties is sustained by the abundance of short-range ordered Al and Fe compounds more than volcanic glass (Vacca et al., 2009).

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Marine tidal /subaqueous soil sequence at the coast of Slovenia

Blaž Repe, Alja Pristovšek

The study area (Fig. 1) is located exactly at the intersection of two provincial plains of Slovenia. The land part is represented by the Sub-Mediterranean Slovenia, the marine part by the Slovenian Sea. The coastline is almost entirely composed of flysch. Steep, rugged cliffs (Debeli rtič, coast between Izola and Strunjan, Piran) and intervening low, levelled parts filled with sediments by larger watercourses alternate along 46.6 km of the coastline (the Rižana, Badaševica, Drnica, Dragonja). This region also includes the sea, i.e., the most north-eastern part of the Adriatic Sea or approximately one-third of the Gulf of Trieste (180 km²) (Radinja, 1990) between Italy and Croatia. By far the largest areas of subaqueous soils can be found in this region (Repe and Pristovšek, 2011).



Fig. 1. Location

Lithology and topography

Flysch is a mechanically quite unstable rock, so the cliff areas are exposed to strong lateral processes. Large boulders and coarse material quickly accumulate directly on the shore and underwater, so the chances of soil formation are very low. Fine material is carried away by sea currents or waves or accumulates under stone blocks. The shallow coastal bottom is rocky and dominated by underwater vegetation that adheres directly to the rocks. On the other side, the accumulative and levelled part of the land continues into the sea like a shallow underwater coastal shelf. The abrasion shelf between Ankarana and Debeli Rtič is about 150 meters wide and between Debeli Rtič and the state border with Italy, in the bay of St. Bartholomew, about 100 meters wide (Fig. 2). The most extensive abrasion shelf in the Slovenian Sea is located off Debeli Rtič, where it is 300 meters wide (Natek et al., 2012).

The coast is the boundary between sea and land and is the result of geomorphological processes in the sea and on land. The Slovenian coast belongs to the Rias type of coast, where rivers and streams carry material inside the bays and create extensive coastal plains. On the shores of the flysch peninsulas, cliffs have formed due to abrasion. Only a small part of the coast, in the area of the town Izola, has a special type of coast made of limestone (Natek et al., 2012). Today's Slovenian coast is extremely dynamic, being mainly the result of intense geomorphological processes of abrasion and accumulation, on the one hand, and climatic changes in the Holocene, which caused the sea transgression, on the other (Orožen Adamič, 2002; Radinja, 1973; Šifrer, 1965; Žumer, 1990). The coast, or sea level, at the time of the peak of the Würmian glaciation 18,000 years ago was about 120 meters lower than today and extended approximately to the Zadar-Ancona line. The rise in sea level at the end of the Pleistocene was initially rapid, as sea level rose by an average of more than 10 meters within 1,000 years. Later, the rise slowed considerably; in the last 2,000 years, the sea has risen only about 2 meters, an average rise of 1 mm per year (Ogorelec et al., 1997). Rivers have risen faster than sea level over the past 5,000 years, so parts of the coasts where rivers carry material are slowly

migrating into the sea. This is particularly evident at the mouths of the Po, Timent and Soča rivers, and in Slovenia at the mouths of the Rižana, Dragonja and Drnica rivers.

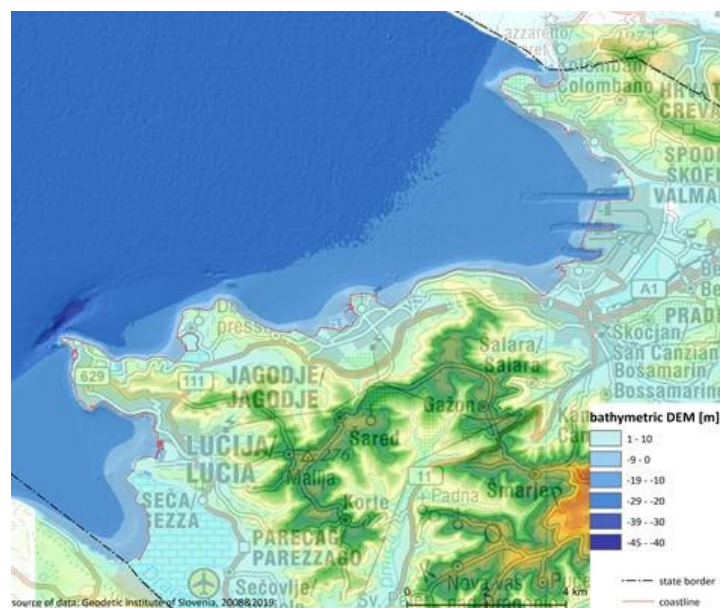


Fig. 2. Bathymetric model of the studied area showing the shallowness of the Trieste bay (25 m resolution).

The rapid transgression of the sea lasted up to 5,000 years before our era and filled almost the entire depression of the present-day Slovenian Sea. The dynamics of river accumulation did not follow the sudden rise of the sea level, so the mouths of the rivers were withdrawn deeper into the river valleys (Ogorelec et al., 1987). In the Piran Bay, the situation was similar, as in the northern part of the Sečovlje salt pans, at a depth of about 100 meters, there are fine-grained sediments, most likely from the marine sedimentary environment (Šifrer, 1965). The rapid rise of the sea level until about 5,000 years before our era was followed by a period of slow rise. At that time, the Slovenian coastline was similar to today's, except that the steep cliff parts of the coast reached deeper into the sea and the low accumulation plains at the river mouths were shifted deeper into the land. This was followed by a period of abrasion of the cliff sections and accumulation in submerged river valleys (Orožen Adamič, 1981).

Climate

According to the Köppen climate classification, the coastal zone up to an altitude of 350 m is classified as a temperate warm-humid climate with hot summers (Cfa). Compared to the Mediterranean climate (Cs), there is more precipitation more evenly distributed throughout the year, less pronounced dryness in summer and generally lower temperatures throughout the year. In the coastal zone there is a so-called moderate Mediterranean coastal climate (locally known as the climate of the olive tree, *Olea europaea*) or sub-Mediterranean climate. Average temperatures are over 4 °C in January and over 22 °C in July. Precipitation is distributed throughout the year according to a moderate Mediterranean precipitation pattern, i.e., most of it falls in autumn (about 30 %) and a little more than 20% in the other seasons. The average annual rainfall is between 1000 and 1200 mm. The highest amount of precipitation usually falls in November or October, with a second peak in June, at the transition from spring to summer. The lowest precipitation usually falls at the end of winter and beginning of spring, with a second low point in July and August, when droughts usually occur (Ogrin, 2012; 1996; 1993).

Land use and land soil types

Today's coastline is characterized by an interplay of natural and built coastal sequences (Bricelj, 2004) and represents a synthesis of hydrological, landscape, and anthropogenic factors (Gabrijelčič et al., 2005). Historically, the coastline has been largely reinforced by various land uses to provide efficient access to the sea or to limit the impact of the sea on the urban environment. Traditional spatial interventions include the provision of technological conditions for maritime transport (Ažman Momirski, 2015), fishing, and defense, while in modern times planning interventions follow the needs of natural and cultural heritage protection, tourism, and recreation (Ažman Momirski, 2017; Miculinič, 2018). The abundance of preclusive activities (tourism, transport, industry, and settlements) leads to land use conflicts at the expense of the natural environment and soil degradation. The flora of Slovenian Istria differs in many respects from that of the rest of Slovenia. Climate is the natural factor that changes the composition of forest communities in almost every way, and most plants that are distinctly heat-loving, light-loving, or drought-tolerant, even those that exhibit all three characteristics simultaneously, are found here. The vegetation, although still thermophile and drought tolerant, is not evergreen, but deciduous of downy oak (*Quercus pubescens*), manna ash (*Fraxinus ornus*), and hop hornbeam (*Ostrya carpinifolia*). Also unique to Slovenian conditions are the saline habitats and the natural salt-loving species found in the more or less narrow coastal strip (Repe, 2012).

The dominant land soil types on limestone are Leptosols (Eutric, Rendzic, etc.), Cambisols (Chromic, Eutric, etc.) and Luvisols (Rhodic – Terra Rossa). Eutric Cambisols on flysch are of great importance and are known as Slovenia's best agricultural soil. Marshes with Gleysols commonly appear on the bottoms of the flysch valleys. Fluvisols form along rivers and on wider and mostly gravely floodplains. Directly on the coast, a limited area of salt-affected soils (Solonchaks) can also be found (Vrščaj et al., 2017).

The sea and the sea water characteristics

Shalowness is an important feature of the Slovenian sea (Bat et al., 2003; Ogrin and Plut, 2009; Radinja, 1990). The Gulf of Trieste descends rapidly and irregularly along the Slovenian coast. Seawater temperatures in the Gulf of Trieste typically reach their lowest point in February (8-9°C) and their highest point in August (about 24°C). Therefore, the average annual amplitude is 15–16°C. The average annual water temperature is about 16°C, 2–3°C higher than the average annual air temperature. The sea never freezes. The Gulf of Trieste has a salinity of 37–38 ‰, which is higher than in the oceans. During winter it never freezes. The salinity varies according to the season and the freshwater inflow into the bay. During the rainy season, the salinity of the water at the mouths of rivers and streams can fall below 20 ‰ (Kolbezen, 1998a; Ogrin and Plut, 2009). The Slovenian Sea is characterized by high turbidity (poor transparency) due to its muddy and fine sandy bottom, shallow water depth, and high nutrient and plankton loading. Many dead particles and transitions between water layers with different temperatures and salinities also contribute to higher turbidity and lower visibility in the lower layers. Typical visibility at the surface is 6–8 m (Ogrin and Plut, 2009). The currents in the Gulf of Trieste are rather weak and already turn mostly to the west along the southern coast of Istria. The current that reaches the Gulf of Trieste flows north and northwest along the Slovenian coast before returning to the southern Adriatic along the Italian coast. The current speed is generally not more than 1.5 km/h. The tidal range off the Slovenian coast is a mixed type, with two tides alternating on a lunar day (24 hours and 50 minutes). The average tidal range is 66 cm in Koper and 88 cm in the Gulf of Trieste. Very high waves with destructive force are generated by strong local winds (especially storms) (Maček et al., 2002).

Profile 1 – Fluvic Gleyic **Solonchak** (Clayic, Calcaric)

Location: Coastal area (50 m from the upper tide line), inclination 0°, reed and salt tolerant *Limonium angustifolium*, 1 m a.s.l., N 45°34'08.8" E 13°44'34.5"



Morphology:

- Oi** – 7–0 cm, poorly decomposed organic material, clear and smooth boundary, moist, 1/3 of the year saturated with water;
- AC** – 0–8 cm, poorly developed humus horizon, clear and smooth boundary, silt clay loam, dark grey (2.5Y 4/1), very strongly calcareous, weak subangular blocky, wet, common fine and medium roots;
- Cr** – 8–32 cm, parent material, clear and smooth boundary, silt clay, grey (2,5YR 6/1) and reddish-brown mottles (2,5YR 4/4), very strongly calcareous, weak subangular blocky to massive, wet with reducing conditions, common fine and medium roots;
- 2Cl** – 32–40 cm, parent material, clear and smooth boundary, silt clay, grey (N6) and reddish-brown mottles (5YR 4/3), extremely calcareous, cloddy to massive, wet with reducing conditions, few fine roots;
- 3Cr** – 40–(60) cm, parent material, silt clay, grey (N6) and reddish-brown mottles (5YR 4/3), very strongly calcareous, cloddy massive, wet with reducing conditions, very few fine roots.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class	
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002		
Oi	7-0	-	-	-	-	-	-	-	-	-	-	-	-
AC	0-8	0.7	0	0	0	0	4	17	26	18	35	SCL	
Cr	8-32	0.6	0	0	0	0	2	10	24	20	44	SC	
2Cl	32-40	0	0	0	0	0	10	8	20	18	44	SC	
3Cr	40-(60)	0.4	0	0	0	0	4	7	21	21	47	SC	

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH		CaCO ₃ [g·kg ⁻¹]
					H ₂ O	KCl	
Oi	7-0	32.8	1.25	26.2	7.5	7.2	7.0
AC	0-8	3.53	0.15	23.2	8.4	7.6	29.8
Cr	8-32	-	-	-	9.2	7.9	28.9
2Cl	32-40	-	-	-	8.6	8.0	51.9
3Cr	40-(60)	-	-	-	8.5	7.8	26.7

Profile 2 – Anocalcaric Amphistagnic Mollic Tidalic **Gleysol** (Epiloamic, Humic, Hypersalic, Sodic, Sulfidic)

Location: Tidal plane, inclination 0°, reed and sea rush (*Juncus maritimus*), 0 m a.s.l.,

N 45°35'28.3" E 13°43'14.8"



Morphology*:

- Hi1** – 0–23 cm, poorly decomposed, rotting organic material (very strong and distinct odor of rotten eggs), plant tissue is clearly visible (fig. 3), gradual and wavy boundary, sandy loam, N 3/, structureless;
- Hi2** – 23–40 cm, poorly decomposed, rotting organic material (very strong and distinct odor of rotten eggs), plant tissue is less, but still clearly visible, gradual and wavy boundary, root channels filled with organic matter, sandy loam, 2.5Y 4/2, structureless;
- HiC** – 40–48 cm, poorly decomposed, rotting organic material, mixed with parent material, diffuse and wavy boundary, silt loam, 2.5Y 5/8, weakly developed granular; very few worm channels, few hard shells of crustaceans and snail remains, few fine roots;
- C** – 48–(60) cm, parent material, silt loam, 2.5Y 5/8, nearly single grain, very few hard shells of crustaceans and snail remains, very few fine roots.

* When collected, entire sample was in liquid state; soil is completely saturated with sea water for 8-12 hours per day; the sample on the picture has been slowly drained in the period of two weeks without disturbing the profile and without access of air; all the samples are extremely calcareous and saline.

Table 3. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm			Textural class
		Sand	Silt	Clay	
		2-0,5	0,5 - 0,002	< 0,002	
Hi1	0–23	66.3	28.0	5.7	SL
Hi2	23–40	55.2	37.4	7.4	SL
HiC	40–48	34.6	53.3	12.1	SiL
C	48–(60)	26.4	58.7	14.9	SiL

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	pH KCl	EC (dS·m ⁻¹)	OM [g·kg ⁻¹]	OC [g·kg ⁻¹]	CaCO ₃ [g·kg ⁻¹]	Color (wet)
Hi1	0–23	7.43	22.53	108.4	63.0	66.67	N 3/
Hi2	23–40	7.40	28.80	73.9	43.0	50.00	2.5Y 4/2
HiC	40–48	7.39	55.30	29.7	17.3	65.00	2.5Y 5/8
C	48–(60)	7.41	65.92	25.5	14.8	46.67	2.5Y 5/8

Table 5. Sorption properties

Horizon	Depth [cm]	Ca	Mg	K	Na	H	S	CEC	BS	Ca	Mg	K	Na (ESP)	H
		[cmol(+)·kg ⁻¹]								[%]				
Hi1	0–23	17.4	5.55	0.88	15.8	0.15	39.7	39.9	99.5	43.7	13.9	2.2	39.6	0.4
Hi2	23–40	18.6	6.44	0.94	19.5	0.20	45.4	45.6	99.6	40.7	14.1	2.1	42.8	0.4
HiC	40–48	22.2	12.9	1.61	39.8	0.55	76.6	77.1	99.4	28.9	16.7	2.1	51.7	0.7
C	48–(60)	24.1	17.5	2.21	49.3	2.10	93.1	95.2	97.8	25.4	18.4	2.3	51.8	2.2

**Fig. 3. Poorly decomposed, rotting organic material at the soil surface**

Profile 3 – Anocalcaric Reductigleyic Histic Tidalic **Gleysol** (Humic, Anoloamic, Salic, Sodic, Sulfidic)

Location: Tidal plane, inclination 0°, salt tolerant plants predominantly *Arthrocnemum macrostachyum* and sea rush (*Juncus maritimus*), -0.5 m a.s.l., **N** 45°35'28.8" **E** 13°43'14.8"



Morphology*:

- Hi** – 0–5 cm, poorly decomposed, rotting organic material (very strong and distinct odor of rotten eggs), plant tissue is clearly visible, gradual and wavy boundary, sandy loam, 5Y 3/1, structureless;
- HiC** – 5–12 cm, poorly decomposed, rotting organic material, mixed with parent material, gradual and wavy boundary, sandy loam, 5Y 3/2, weakly developed granular, very few worm channels, few fine roots;
- C1** – 12–32 cm, parent material, diffuse and wavy boundary, silt loam, 2.5Y 6/2, single grain, very few hard shells of crustaceans and snail remains (fig. 4);
- C2** – 32–(60) cm, parent material, silt loam, 2.5Y 6/3, single grain.

* When collected, entire sample was in liquid state; soil is completely saturated with water for 14–16 hours per day; the sample on the picture has been slowly drained in the period of two weeks disturbing the profile and without access of air; all the samples are extremely calcareous and saline.

Table 6. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm			Textural class
		Sand	Silt	Clay	
		2-0,5	0,5 - 0,002	< 0,002	
Hi	0-5	62.3	31.3	6.4	SL
HiC	5-12	55.4	41.7	2.9	SL
C1	12-32	42.7	51.5	5.8	SiL
C2	32-(60)	34.3	60.1	5.6	SiL

Table 7. Chemical and physicochemical properties

Horizon	Depth [cm]	pH KCl	EC (dS·m ⁻¹)	OM [g·kg ⁻¹]	OC [g·kg ⁻¹]	CaCO ₃ [g·kg ⁻¹]	Color (wet)
Hi1	0-23	7.81	22.46	42.1	24.5	500.0	5Y 3/1
Hi2	23-40	7.70	24.45	31.1	18.1	550.0	5Y 3/2
HiC	40-48	7.67	31.62	22.8	13.3	433.3	2.5Y 6/2
C	48-(60)	7.70	40.19	15.9	09.2	366.7	2.5Y 6/3

Table 8. Sorption properties

Horizon	Depth [cm]	Ca	Mg	K	Na	H	S	CEC	BS	Ca	Mg	K	Na (ESP)	H
		[cmol(+)·kg ⁻¹]								[%]				
Hi1	0-23	17.2	4.97	0.88	15.3	0.10	38.4	38.5	99.7	44.7	12.9	2.3	39.7	0.3
Hi2	23-40	18.6	5.79	1.12	16.8	0.15	42.3	42.4	99.8	43.8	13.7	2.6	39.6	0.4
HiC	40-48	18.9	7.23	1.21	22.2	0.15	49.5	49.7	99.6	38.0	14.5	2.4	44.6	0.3
C	48-(60)	20.6	9.78	1.64	30.0	0.15	62.0	62.2	99.7	33.1	15.7	2.6	48.3	0.2



Fig. 4. Remains of the hard shells of crustacean

Profile 4 – Anocalcaric Sodic Epigleyic Subaquatic Arenosol (Ochric, Nechic)

Location: Underwater shelf (20 m from the low tide line), inclination 0°, marine vegetation, predominantly see grass (*Cymodocea nodosa*), -1 m a.s.l., N 45°35'30.1" E 13°43'15.8"



Morphology:

- HaC1** – 0–3 cm, decomposed organic material, mixed with parent material, clear and irregular boundary, loamy sand, 2.5Y 2.5/1, nearly single grain, few fine roots;
- HaC2** – 3–16 cm, decomposed organic material, mixed with parent material, clear and irregular boundary, sandy loam, 2.5Y 4/1, some oxymorphic mottles (Fig. 5) around root and worm channels (2.5Y 6/4), nearly single grain, very few fine roots;
- C1** – 16–44 cm, parent material, diffuse and irregular boundary, sandy loam, 2.5Y 6/2, single grain, few hard shells of crustaceans and snail remains;
- C2** – 44–(50) cm, parent material, loamy sand, 2.5Y 7/6, single grain, few hard shells of crustaceans and snail remains.

* When collected, entire sample was in liquid state; soil is completely saturated with water 24 hours per day; the sample on the picture has been slowly drained in the period of two weeks disturbing the profile and without access of air; all the samples are extremely calcareous and saline

Table 9. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm			Textural class
		Sand	Silt	Clay	
		2-0,5	0,5 - 0,002	< 0,002	
HaC1	0–3	74.2	21.7	4.1	LS
HaC2	3–16	73.7	22.2	4.1	SL
C1	16–44	73.3	22.6	4.1	SL
C2	44–(50)	78.4	17.9	3.7	LS

Table 10. Chemical and physicochemical properties

Horizon	Depth [cm]	pH KCl	EC (dS·m ⁻¹)	OM [g·kg ⁻¹]	OC [g·kg ⁻¹]	CaCO ₃ [g·kg ⁻¹]	Color (wet)
HaC1	0–3	7.79	19.71	13.1	7.6	400.0	2.5Y 2.5/1
HaC2	3–16	7.63	21.95	20.7	12.0	600.0	2.5Y 4/1 2.5Y 6/4
C1	16–44	7.65	25.22	13.1	7.6	400.0	2.5Y 6/3
C2	44–(50)	7.99	57.28	12.4	7.2	333.3	2.5Y 7/6

Table 11. Sorption properties

Horizon	Depth [cm]	Ca	Mg	K	Na	H	S	CEC	BS	Ca	Mg	K	Na (ESP)	H
		[cmol(+)·kg ⁻¹]								[%]				
HaC1	0–3	16.5	4.37	0.81	12.4	0.05	34.1	34.2	99.7	44.7	12.9	2.3	39.7	0.3
HaC2	3–16	17.3	4.48	0.76	15.1	0.05	37.6	37.7	99.8	43.8	13.7	2.6	39.6	0.4
C1	16–44	17.8	4.35	0.76	16.8	0.05	39.7	39.8	99.6	38.0	14.5	2.4	44.6	0.3
C2	44–(50)	17.7	10.2	1.44	40.8	0.05	70.2	70.3	99.7	33.1	15.7	2.6	48.3	0.2



Fig. 5. Oxymorphic mottles around the root and worm channels

Soil sampling

For the study we selected underwater soils along the coast of the Slovenian Sea. We were looking for an accumulative, lagoon coastal type (Bat et al., 2003; Radinja, 1990), which gradually descends below the water surface. The field work was carried out at four locations near the city of Ankaran and Debeli Rtič peninsula, near to the Slovenian-Italian border crossing. The sites were selected based on observing the tidal line and the vegetation adapted to this process. The first site is located above the coastline, influenced by saline underground water. The second one is located directly on the coastline, where the flooding with saline water occurs for less than half of the day. The third location lies lower, where the ground is flooded for most of the day. Both locations are characterized by a predominantly terrestrial and/or halophytic vegetation. The fourth location is permanently submerged, and underwater vegetation thrives on it. At the time of sampling, the three out of four soils (the first one is an exception) were completely flooded with water. The locations differed in water depth, with the first being 10 cm, the second 20 cm and the third 50 cm below sea level. For underground soils we performed the field work and sampling twice (October 2010), using improvised equipment to take samples. During the work we used sewer pipes (Fig. 6). The pipes containing samples were cut in the laboratory to obtain half of the content, observing the horizons, their thickness, and other morphological characteristics. The samples separated by horizons were dried, ground, and analyzed in two laboratories of the University of Ljubljana (Faculty of Arts and Biotechnical Faculty). The first profile was examined and sampled in May 2017, using standard protocols. Laboratory analysis was performed by the laboratory at The Faculty of Earth Sciences and Spatial Management, Torun.



Fig. 6. Improvisational sampling, using drainage pipes

Formation of subaqueous soils

Soils can be located mostly on land but also in shallow waters. Subaqueous soils are formed below the water level, especially at the bottom of shallow, stagnant waters, e.g., in bogs, swamps and lakes (Bufon et al., 2005) and are poorly studied. There are several reasons for this. Research is extremely difficult; these soils have hardly any economic value, and there are differences of opinion if this material is soil at all. Although some researchers (Goldschmidt, 1958; Kubiëna, 1953; Mückenhausen, 1965) as early as in the middle of the last century recognized the material as soils, most of the researchers (geologists, biologists) consider them to be merely underwater sediment (Demas et al.,

1996). The ground-breaking study of underwater material in the Maryland area (Demas, 1998) led to a change of definitions in Soil Taxonomy in 1999 (Payne, Turenne, 2009). Research have continued, although rarely (Balduff, 2007; Turenne, 2010). Some pedologists believed that the upper limit of the soil should be the atmosphere (Foth, 1978; Nikiforoff, 1959; Simonson, 1959), others believed it should be shallow waters (Demas, 1993; Demas and Rabenhorst, 1999; Goldschmidt, 1958; Kubiěna, 1953; Mückenhausen, 1965; Ponnampuruma, 1972; Soil Science Division Staff, 1993; Soil Survey Staff, 1975). The International WRB Classification included underwater soils with the definition that any material within 2 m of the Earth's surface that is in contact with the atmosphere, excluding living organisms, areas with continuous ice not covered by other material, and water bodies deeper than 2 m (in tidal areas, the depth of 2 m is to be applied at mean low water springs.) (IUSS Working Group WRB, 2015).

In 1972, Folger described the primary factors that influence the composition and distribution of estuarine sediments. Together, the factors of Jenny (1941) and Folger thus form a new equation (Balduff 2007):

$$p_e = f(p, cl, o, t, B, F, W, E) + H$$

in which subaqueous soils (p_s) are a function (f) soil forming factors: climate (cl), organisms (o), bathymetry (B), waterflow properties (F), parent material (p), time (t), chemical properties of water (W) and extreme events (E). The latter two factors were added later (Balduff, 2007) and human (H) influences were added separately.



Fig. 7. Flysch. The most common parent material at the coast, that provides mineral material for the studied soils

The study area is located in the Slovenia's littoral region, where the Eocene carbonate flysch predominates (Pleničar et al., 1973) (fig. 7), from which material is deposited on the coastal bottom. Parent material is mainly a coarse-grained, sandy remnant of the weathering of hinterland flysch material brought into the bay by watercourses and erosion processes (Natek et al., 2012; Repe, 2012). On land, the relief determines the local hydrology, and in underwater environments the opposite can happen, so that the hydrological conditions (water balance) become a decisive factor in the formation of underwater relief forms. Altitude in underwater environments is replaced by the depth. This influences the development of subaqueous soil profiles and allows to explain the effects of internal/external waves and wind induced waves (Demas and Rabenhorst, 2001). The hinterland is hilly, steeply sloping towards the sea. Where local watercourses flow into the sea, shallow coastal plains have formed (Ogrin and Plut, 2009; Repe, 2012) with sandy-silty sediments from which the soils studied have developed. Selected sites have an accumulation type of coastline, and its bottom is rather flat. About 50 meters from the shore there is a strip of land with occasional flooding (Kolbezen, 1998b; Natek et al., 2012).

The sites also differ in vegetation. The first two sites are located within the predominant reed belt. The third site is under water most of the time, and various halophyte plants grow there. The fourth is strongly dominated by seaweed. As was later found out in the laboratory, the soils also differ in

physical and chemical properties, in the stage of development and thus in the reference group. Subaqueous soils receive organic matter from the macroflora, such as macroalgae. The activity of underwater plants can change the chemical structure of the soil. For example, seaweed releases oxygen into the soil, which oxidizes to compounds such as reduced iron and sulphides (Holmer et al., 2005). The macroflora can physically stabilize the surface. However, its effectiveness depends on the density of plants (Koch, 2001). We have observed that root and underwater wormholes (fig. 8) allow the transfer of oxygen and organic matter to greater depths. A large number of shells helps to increase the amount of carbonates and basic cations and also raise the pH. Most subaqueous soils are relatively young and resemble to some extent young alluvial soils in flood plains (Demas and Rabenhorst, 2001). They have poorly developed profiles and an oxidized horizon on the surface (Stolt and Rabenhorst, 2010), which is also true for our soils. Extremes include events that occasionally affect the stability of the underwater surface (Demas and Rabenhorst, 2001), which was not observed in our case. We have also not observed a major human influence, except for a smaller amount of artifacts (bricks, shards) dumped by bathers or passers-by.



Fig. 8. Living organism in the soils (worms)

The soil forming processes of subaqueous soils can be divided into four groups (Demas and Rabenhorst, 2001; Repe and Pristovšek, 2011; Stolt and Rabenhorst, 2010; Turenne, 2010). Along the Slovenian coast, we discovered the following processes:

- Transformation: humification, formation of fine soil particles and sulphurization.
- Vertical translocation: oxygen diffusion, bioturbation, vertical translocation of base cations.
- Inputs: mineral material from land and through waves and from shells; dead plant and animal organic material.
- Outputs: erosion of mainly mineral material by waves, during storms and stronger winds, and decomposition of organic material.

Systematic position

Based on observations and measurements (Tables 1–11), we first determined diagnostic horizons, properties and materials in accordance with the WRB classification, all the qualifiers and final name (IUSS Working Group WRB, 2015). All the studied soils have the following common characteristics: the parent material of all is strongly carbonate, weathered flysch residue; all are strongly influenced by seawater, either as groundwater or predominantly or permanently flooded with it; accumulation of poorly weathered organic material, also strongly influenced by saline seawater (Fig. 9).

The first soil has a saline surface part, strongly influenced by underground seawater, with sufficient thickness (≥ 15 cm) and can be recognized as a diagnostic *salic* horizon. Although present, the thickness of the organic material was insufficient for Histosols. Therefore, the soil is classified as **Solonchak**. There were clearly visible layers of organic and mineral material, possibly formed by fluvial or tidal waters (*Fluvic*). Beneath the poorly decomposed organic material was a clayey horizon (*Clayic*) with gleyic properties (*Gleyic*), high pH, and an abundance of primary carbonates (*Calcaric*). Further investigation was hampered by groundwater that rapidly flooded the profile pit. All horizons also exhibited the Hypereutric properties but were omitted because of the use of *Calcaric*.

The next three soils all meet the criteria for Solonchaks, but since they mostly occur underwater, we must look further in the WRB key. The second and the third soil are quite similar. They both belong to the **Gleysol** RSG. The difference is mostly attributed to the amount of organic material, which is obviously higher in the second profile. Soil has a surface layer of virtually undecomposed plant remains. The organic carbon content is insufficient for Histic and therefore Histosols, but *Mollic* can be added. The soils are under the daily influence of saline tidal water (*Tidalic*). The appearance of stagnic properties (combination reducti- and oxymorphic colors) below the surface adds the *Amphistagnic* qualifier. As with all soils studied, the presence of primary carbonates adds the supplementary qualifier *Calcaric* (Most likely this is *Pantocalcaric*, but due to the limited ability to excavate the sufficient thickness soil, we cannot confirm this). At a depth of about 50 cm, the soil becomes completely mineral and would eventually turn to sandy material. There is loamy material at the surface (*Epiloamic*). Due to the presence of saline water and high electrical conductivity, we can also add the qualifiers *Hypersalic* and *Sodic*. The analysis has not been carried out, but due to the extremely strong and unpleasant smell of rotten eggs when soil is exposed to oxygen in the laboratory, we have also taken the liberty of adding the classifier *Sulfidic*.

As mentioned, there are many similarities between the third and second soil (*Calcaric*, *Tidalic*, *Salic*, *Sodic*, and *Sulfidic*). Grey Munsell colors and reducing conditions (*Reductigleyic*) of sufficient thickness assign the soil to **Gleysol** RSG. The significant amount of poorly decomposed organic material also adds the principal qualifier *Histic* and supplementary *Humic*. Unlike Histosols, Gleysols also use the qualifier for texture and in the third soil Loam is a predominant class (*Loamic*). Similar to the previous soil, the profile would likely become completely sandy with increasing depth.

The last soil is under water all year round (*Subaquatic* and *Sodic*). The only diagnostic feature recognized is *Calcaric* and Mineral material that has a texture of loamy sand and coarser. Only a few coarse fragments (shell remains) were recognized. Therefore, we can classify the soil as **Arenosol** (in some parts there is also gleyic pattern present but very weakly expressed and visible, therefore, we believe the Arenosol describes the soil properties better). The organic matter is poorly developed and of light color (*Ochric*). There is also a layer, more than 25 cm thick, with *Gleyic* properties (grey color pattern) and reducing conditions in some parts, less than 50 cm from the surface. Only traces of oximorphic features were also found in the root channels. *Nechic* is a typical feature for Podzols, but since uncoated grains occur in the darker matrix, this supplementary qualifier was also added.

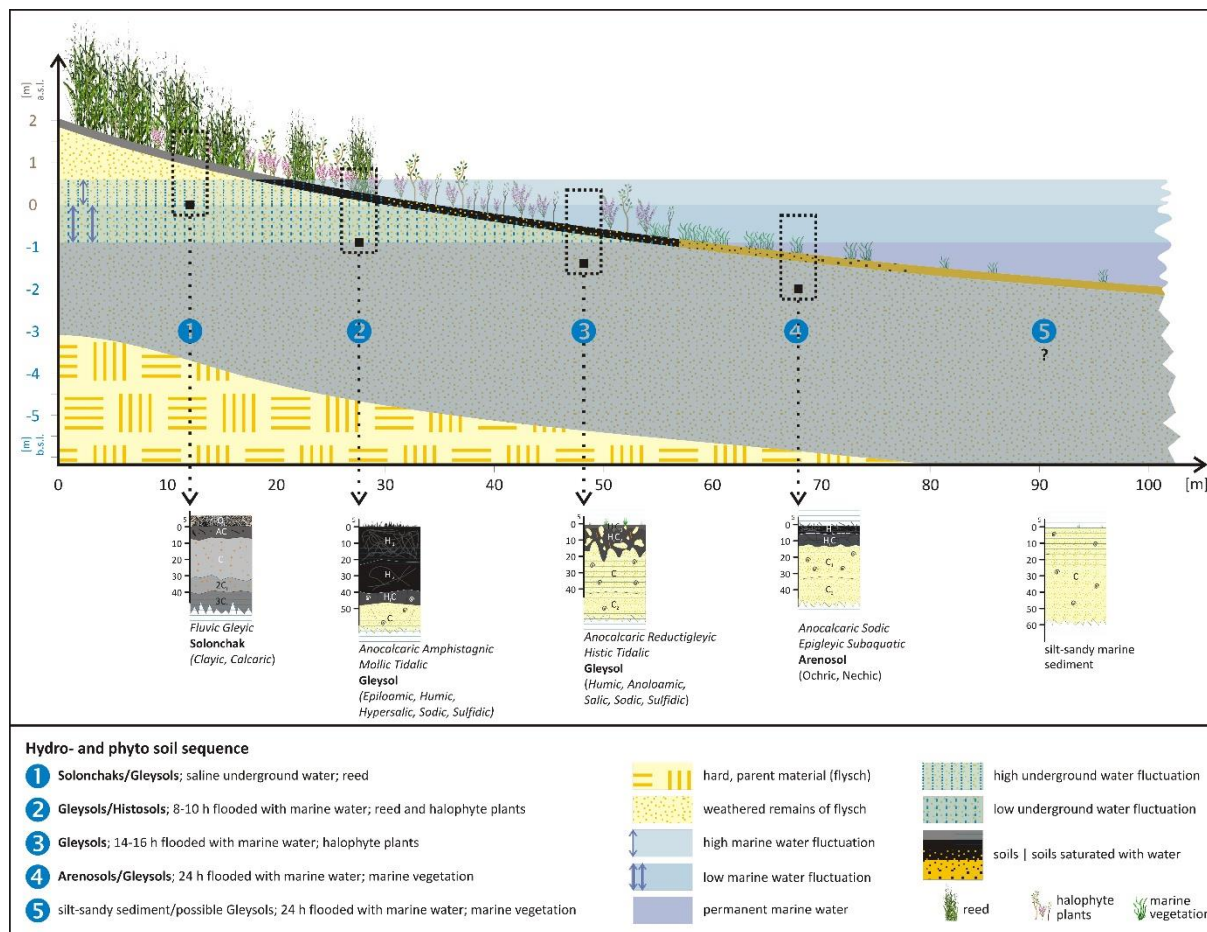


Fig. 9. Hydro- and phytosequence of the soils at the marine coast of Slovenia

Soil sequence

On the coastal part of Slovenia, with a very shallow and muddy bottom, different soil groups occur on weathered (predominantly sandy), carbonate parent material, although they have quite similar origin and characteristics. The depth of the soil before the impact with parent material varies between 40 and 65 cm, which means that there are medium-deep soils in the area under study. Coarse fragments are of mixed form and their percentage is around 20% or less, which decreases with increasing depth. Their size is between 2 and 6 mm. Many skeletons are of biogenic origin (shells of crustaceans and snail). In all soil horizons, the proportion of sand is relatively high, and the proportion of clay is low, i.e., these are relatively young, poorly developed soils, which are exposed to soil forming factors and processes for short periods of time. Due to the flooding with seawater, the soils are slightly saturated with hydrogen and strongly saturated with sodium ions (more than 40%), the electrical conductivity is high (higher than 15dS/m). The soils are saline (Brady and Weil, 1996), the sodium content and the salinity increase with depth as a result of vertical displacement of cations. The calcium carbonate content in the profiles is very high. In addition to the topsoil, the percentage is further increased by carbonate shells. As a result, the soils are almost 100% saturated with basic cations and slightly alkaline. On average, the amount of organic matter decreases with depth, as mineral material fills the soil surface and is displaced by bioturbation. The proportion of organic matter in the upper part

decreases significantly away from the coast, due to the lower density of vegetation that contributes organic material.

During the field research and subsequent laboratory analysis we noted that among all sites many soil forming factors (parent material, topography, water flow characteristics, chemical properties of water) and processes (runoff: decomposition of organic matter; vertical translocation: bioturbation and oxygen diffusion; transformation: humidification, sulfidation) are very similar if not entirely the same. However, some differences occur within the distance from the coastline towards the sea. The seawater gets deeper, but more than that, the main factor is the increasing time of flooding with seawater. This, in turn, initially has a decisive influence on the type and density of vegetation and the resulting amount of dead organic matter. This decreases in the direction mentioned above, while in the opposite direction the influx of mineral material to the surface increases with the waves. Also, in the same direction, seaward, the intensity and expression of stagnic and gleyic properties decreases. Slowly, however, the sandy fraction of the parent substrate dominates completely (becoming merely a sediment). Based on these results, we can conclude that the studied soil sequence can be determined mainly as **hydrosequence**. But on the other hand, there is also **phytosequence** present since the addition and type of organic matter (and therefore soil properties and type) is heavily influenced by the type and density of vegetation. The sequence can be at least partially determined visually, only by observing the plant cover (Fig. 10).

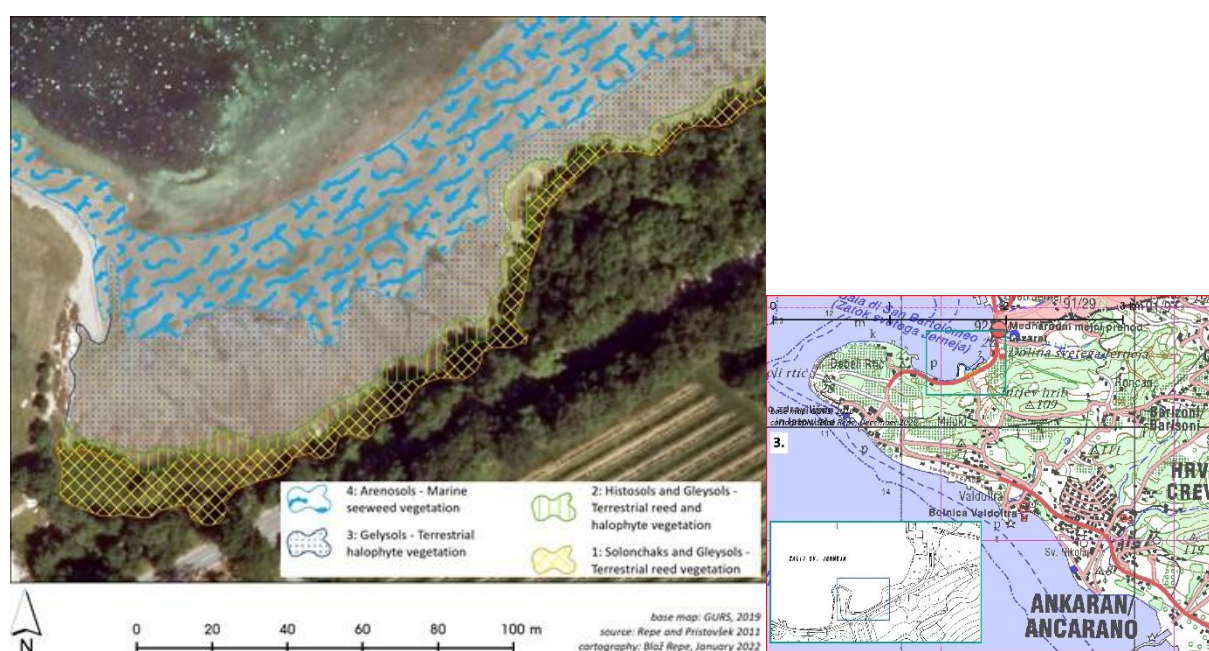


Fig. 10. An approximation of the soil and vegetation zones (the case of the St. Bartholomew Bay, location of the right)

The terrestrial part consists mainly of reeds (*Phragmites sp.*). The substrate is a combination of **Solonchaks** and **Gleysols**, inundated in the lower part by saline groundwater. Similar belt (**Gleysols** and somewhere possible **Histosols**) with reed and some halophyte, terrestrial vegetation appears in places of occasional tidal floodings. With prolonged tide, reed is completely replaced by halophyte, terrestrial vegetation (*Salicornia europaea*, *Arthrocnemum glaucum*, *Crithmum maritimum*, *Limonium angustifolium*, *Juncus maritimus* etc.), where the soil is more saline but gleyic properties are expressed to lesser extent. Nevertheless, since the density of vegetation drops significantly (and therefore the addition of organic material) Gleysols contain less and less organic material. There are

still enough fine particles (silt and clay), so the gleyic properties are more pronounced. Distancing from the shoreline, there is more sand and less clay fractions present. Where soils are completely flooded with water, underwater marine vegetation (*Cymodocea nodosa*) is present. The gleying process is still present, but is not intense enough, therefore, sandy fraction and **Arenosols** predominate in this zone.

From field observations and laboratory analyses of selected soil examples on the Slovenian coast, we can conclude that the soils were influenced by similar factors and processes and that the soils are also quite similar to each other, with similar properties. All soils are young and weakly developed. All soils show accumulation of the organic material at the surface, signs of displacement (diffusion and bioturbation), gleying and oxidation of the surface horizons. The differences are more pronounced from the coast to the sea, which is due to the duration of flooding. The flooding heavily influences vegetation, which in return also heavily influence soil properties.

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Lithosequence of calcareous soils in Tunisia

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The study area is located in the northwest of the governorate of Sfax in the delegation of Menzel Chaker. The delegation of Menzel Chaker covers an area of 1620 km², it is delimited by the delegations of Sakiet Ezzit, Sfax Sud and Hencha, the delegations of Agareb and Bir Ali Ben Khalifa in the South, the governorate of Mahdia in the North and the governorates of Kairouan and Sidi Bouzid in the west.

Lithology and topography

The study area is characterized mainly by outcrops of continental middle and upper Pleistocene, as well as lower Pleistocene, limnic sabkhas (coastal plateau deposits proposed to periodic flooding and evaporation), recent and current alluvial deposits. Most of the wadis are endorheic, leading to closed depressions of the Sebkhass and Garâas type. According to their morpho-structural conditions, these closed depressions take the form of synclinal basins (Menzel Chaker area) or the form of sands of Sebkhass Garâas (Bou Jmal, Karafita). In dry regions, wind processes also play an important role, especially in areas with less than 150 mm of precipitation per year (Previtali et al., 2014). The accumulation of aeolian materials leads to the formation of primitive or slightly developed sandy soils (Driessen et al., 2001).

Most of the wadis are endorheic, opening into closed depressions of the sebkhass and garâas type. According to their morpho-structural conditions, these closed depressions take the form of synclinal basins (region of Menzel Chaker) or the form of sebkhass and garâas (Bou Jmal, Karafita) (Missaoui et al., 2013).

Land use

The study area is marked by sandy soils that are easy to work, especially by plowing. This successive plowing facilitates the mobilization of the soil, especially by wind deflation. It is very widespread in the vast olive groves of Menzel Chaker. The work was carried out within the agro-combinat 'Essalema' Farm which is located 50 km north-west of the Sfax region (34°59'15"N – 10°20'03"E). The 'Essalema' Farm covers 18 670 ha, it is composed of 7 sub-farms, each farm has different plots, these plots are characterized by different soil types, different cultivation methods.

Climate

The climate is arid Mediterranean, characterized by high temperatures and scarce rainfall. The average temperature was 19.5°C between 1966 and 2019 (Temperature data provided by the National Institute of Metrology (NIM, 2020) and the average annual rainfall was 169 mm between 2008 and 2019 (rainfall data provided by the agricultural station of Salama, 2020). According to the Köppen Geiger climate classification (Kottek et al., 2006), it is a warm steppe and arid climate.



Fig. 1. Location

Profile 1 – Haplic Calcisol (Aric, Pantoloamic, Ochric, Endoraptic)

Location: Olive trees plantation, almost flat - terraced, 198 m a.s.l., N 35°07'18.7" E 10°15'26.6"



Morphology:

- Akp** – 0–55 cm, humus and *calcic* horizon, sandy loam, strong brown (7.5YR 6/6; 7.5YR 5/6), slightly moist, subangular / granular structure, few calcareous nodules, shell fragments fine and medium few roots, clear and smooth boundary;
- 2Ck** – 55–(130) cm, *calcic* horizon, sandy clay loam, light brown (7.5YR 8/4; 7.5YR 6/4), slightly moist, massive structure, concentrations of secondary carbonates, medium very few roots;

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm					Textural class
		Coarse sand	Fine sand	Coarse silt	Fine silt	Clay	
		2-0.2	0.2-0.05	0.05-0.02	0.02-0.002	<0.002	
Akp	0-55	25.0	44.5	5.5	7.4	17.6	SL
2Ck	55-(130)	16.8	34.6	6.6	12.3	29.7	SCL

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	EC [ds m ⁻¹]	OC [g·kg ⁻¹]	OM [g·kg ⁻¹]	pH		CaCO ₃ [g·kg ⁻¹]
					H ₂ O	KCl	
Akp	0-55	0.09	3.9	6.8	8.9	7.8	171.3
2Ck	55-(130)	0.10	3.0	5.7	8.8	7.8	354.1

Profile 2 – Haplic Calcisol (Aric, Pantoloamic, Ochric)

Location: Olive trees plantation, almost flat, 160 m a.s.l., N 34°55'35.4" E 10°18'42.5"



Morphology:

- Akp** – 0–45 cm, humus horizon, sandy loam, strong brown (7.5YR 4/4; 7.5YR 3/4), dry, subangular / granular structure, very few calcareous nodules, fine shell fragments fine and medium few roots, clear and smooth boundary;
- Ck** – 45–(130) cm, *calcic* horizon, sandy clay loam, light brown (7.5YR 8/4; 7.5YR 6/4), dry, massive structure, concentrations of secondary carbonates, medium very few roots;

Table 3. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm					Textural class
		Coarse sand	Fine sand	Coarse silt	Fine silt	Clay	
		2-0.2	0.2-0.05	0.05-0.02	0.02-0.002	<0.002	
Akp	0-45	26.8	47.1	3.6	9.4	13.1	SL
Ck	45-(130)	19.4	44.1	3.1	11.4	22.0	SCL

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	EC [ds m ⁻¹]	OC [g·kg ⁻¹]	OM [g·kg ⁻¹]	pH		CaCO ₃ [g·kg ⁻¹]
					H ₂ O	KCl	
					Akp	0-55	
Ck	55-(130)	0.12	2.3	3.9	9.0	7.9	219.7

Profile 3 – Calcaric Regosol (Aric, Aridic, Pantoloamic, Ochric)

Location: Olive trees plantation, almost flat – terraced, 139 m a.s.l., N 35°03'43.9" E 10°09'37.4"



Morphology:

- Akp** – 0–30 cm, humus horizon with *calcaric* material, sandy loam, strong brown (7.5YR 5/6; 7.5YR 4/6), dry, subangular / granular structure, very few calcareous nodules, fine shell fragments fine and medium few roots, clear and smooth boundary;
- Ck** – 30–(100) cm, parent *calcaric material*, sandy loam, light brown (10YR 4/6; 10YR 3/6), dry, subangular / granular structure, concentrations of secondary carbonates, medium very few roots;

Table 5. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm					Textural class
		Coarse sand	Fine sand	Coarse silt	Fine silt	Clay	
		2-0.2	0.2-0.05	0.05-0.02	0.02-0.002	<0.002	
Akp	0-30	13.3	64.3	0.1	12.4	9.9	SL
Ck	30-(100)	13.8	58.2	0.1	11.0	16.9	SL

Table 6. Chemical and physicochemical properties

Horizon	Depth [cm]	EC [ds m ⁻¹]	OC [g·kg ⁻¹]	OM [g·kg ⁻¹]	pH		CaCO ₃ [g·kg ⁻¹]
					H ₂ O	KCl	
Akp	0-30	0.14	4.3	9.6	8.9	8.0	107.1
Ck	30-(100)	0.13	4.0	7.1	8.6	7.8	116.3

Profile 4 – Calcaric Arenosol (Aric, Ochric)

Location: Olive trees plantation, middle slope, inclination 2°, 163 m a.s.l., N 35°07'40.7" E 10°11'26.8"



Morphology:

- Ap** – 0–30 cm, humus horizon with *calcaric* material, loamy sand, brown (7.5YR 6/4; 7.5YR 4/4), moist, very weak subangular / single grain structure, fine shell fragments fine and medium few roots, clear and smooth boundary;
- BC** – 30–(80) cm, parent *calcaric material*, sand, light brown (10YR 6/8; 10YR 5/8), moist, single grain structure, small shell fragments, fine very few roots;

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm					Textural class
		Coarse sand	Fine sand	Coarse silt	Fine silt	Clay	
		2-0.2	0.2-0.05	0.05-0.02	0.02-0.002	<0.002	
Ap	0-30	45.1	43.7	3.1	2.2	5.9	LS
BC	30-(80)	56.5	38.8	0.6	0.7	3.4	S

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	EC [ds m ⁻¹]	OC [g·kg ⁻¹]	OM [g·kg ⁻¹]	pH		CaCO ₃ [g·kg ⁻¹]
					H ₂ O	KCl	
Ap	0-30	0.08	2.9	4.9	8.8	7.9	30.3
BC	30-(80)	0.08	0.9	1.6	8.7	7.8	26.3

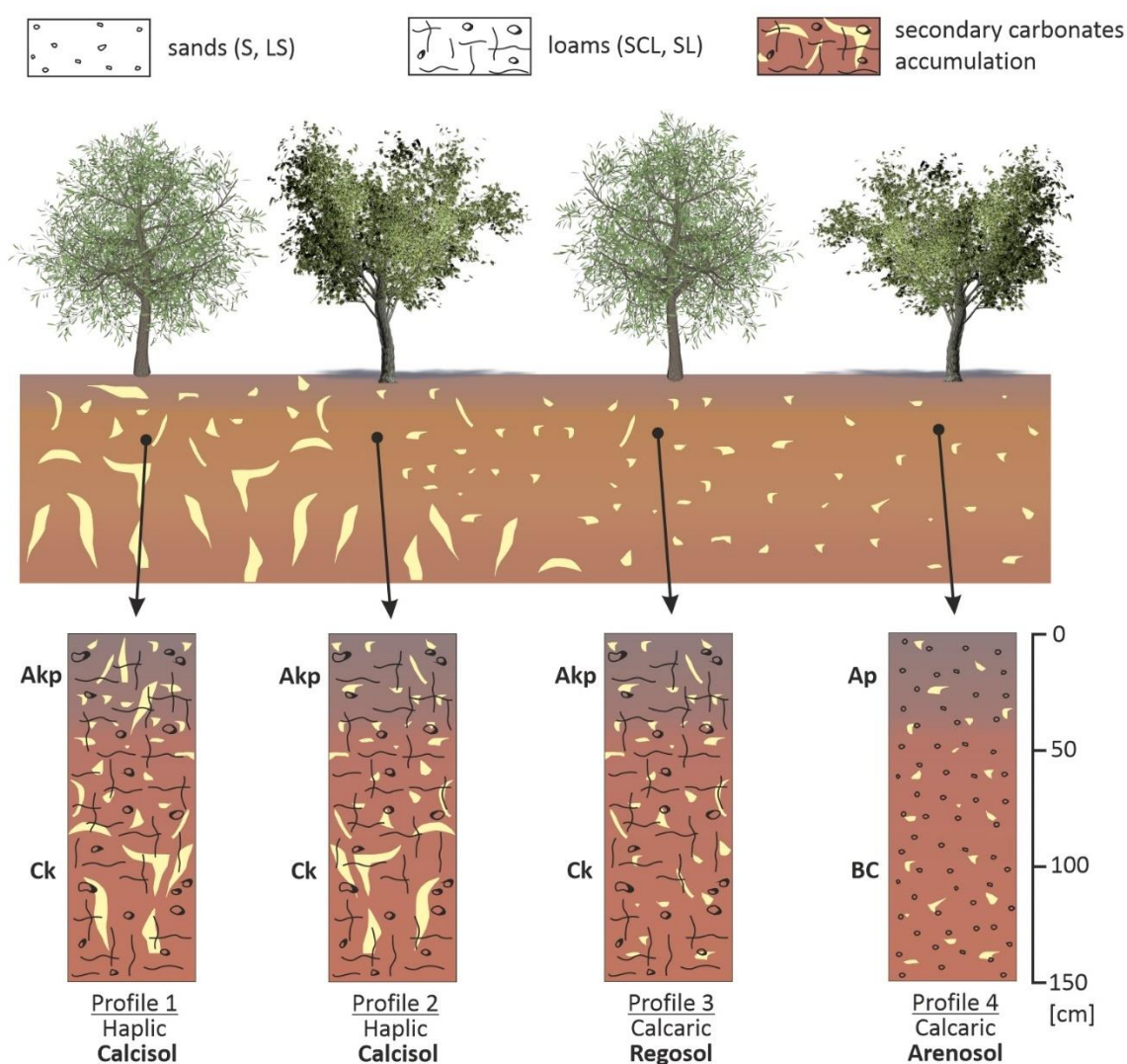


Fig. 2. Lithosequence

Soil genesis and systematic position

The presented soils are developed from loamy or sandy material – probably of aeolian origin. All profiles had simple morphology with only two genetic horizons – humus horizons (Akp or Ap) and underlying horizons with predominantly significant accumulation of calcium carbonates (Ck). Surface humus horizons were weakly developed with low amount of organic carbon (0,54–0,29%) and relatively light gray color. Agrotechnical treatments led to homogenization and the deepening (55–30 cm) of these horizons (*Aric* qualifier). Due to the low content of humus or light color, they are not diagnostic horizons and their presence was expressed only by *Ochric* qualifier (IUSS, 2015). According to the research of Belaid et al. (2012, 2019), the natural content of humus in investigated soils is very low. Previous studies show that in some cases in this region humus horizons are too weakly developed (less than 0.2% of OC) for *Ochric* qualifier (Baraket et al., 2021). Below the humus horizons, parent material with calcium carbonates occurred. The content of CaCO_3 in these horizons varied significantly. According to Mtimet (2001), the profiles developed from carbonate parent

materials are common and belong to the main soil groups in North Tunisia. In Profile 1 and 2, the CaCO_3 content was greater than 15%, which, with the presence of common forms of secondary carbonates (nodules, pseudomicelium), indicated the presence of *calcic* horizons and allowed to classify these soils as **Calcisols**. As in many other semi-arid countries with hot climates, this reference group is one of the most common in Tunisia according to Dewitte et al. (2013).

In Profile 3 and 4, the content of calcium carbonate was not high enough for *calcic* horizon. The presence of carbonates in these soils was expressed using the *Calcaric* qualifier. In both profiles there was the lack of diagnostic horizons and other (than *calcaric*) materials. Profile 3 had a loamy texture and was classified as Regosol. The last one was put in Arenosols due to sandy texture. The presence of similar weakly developed Arenosols derived from aeolian sediments has also been confirmed by Previtali et al., 2013. The colors of all surface horizons and some parent materials were brown-reddish (mostly 7.5YR) which is probably related to the alterations of iron compounds in subtropical climate. In the case of Arenosols, such color could be emphasized by adding the Rubic qualifier, but the thickness of reddish material was not sufficient. In Calcisols – this qualifier is not taken into account in the systematic position. On the surface of the third profile, *Aridic* properties connected with semi-desert environment were visible.

Soil sequence

The main pedogenic feature in described soils was the accumulation of secondary calcium carbonate – visible from shallow depths. Except that all the soils were poorly developed (lack of diagnostic horizons) due to the influence of a hot and dry climate (Driessen et al., 2001). Nevertheless, the variable content of calcium carbonate as well as the differentiated texture were inherited from the parent materials. These two features (CaCO_3 content and texture) determined the allocation of soils to Calcisols, Regosol and Arenosol, respectively. Therefore, the described sequence of soils is strongly connected with the lithological conditions. The spatial arrangement of soils resulting from such a set of soil-forming factors is called **lithosequence**.

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Anthrosequence of soils on Aeolian Sand Dunes in Westsik's experimental field, Nyíregyháza, Hungary

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The study area is a long-term crop rotation experimental field which is located at the city of Nyíregyháza (Hungary) in the Nyírség microregion. The Nyírség is one of the large sandy alluvial fans within the Great Hungarian Plain built up by the fluvial deposits of Tisza and its tributaries during the Quaternary. In late Pleistocene, streams left the landscape due to tectonic uplift and meandering, and aeolian processes became the most effective factors in shaping the landforms. The main landforms are inherited from alluvial processes and modified in surficial layers by winds during the late glacial periods and Holocene (Ádám et al., 2009; Józsa and Fábrián, 2016). Natural diversity of soils is connected to topographic position, but agricultural cultivation and intended reclamation left behind remarkable anthropogenic features in soil profiles.

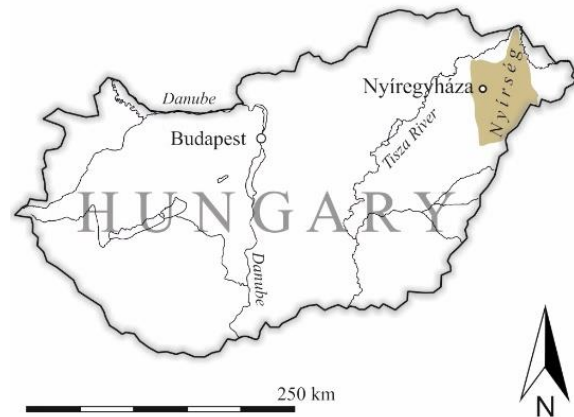


Fig. 1. Location

Lithology and topography

The presented catena is located in a slightly undulating sandy area built up from Quaternary fluvial deposits, mainly fine and very fine sand reshaped and remodelled by winds during the dry periods of Pleistocene and Holocene. Fluvial channels and windblown depressions, left behind by early Pleistocene fluvial landscape as partially wet environments, generally trapped more fine particles (silt) and organic matter coming also from larger distances, while the sand dunes are accumulation of locally translocated coarser sediments (medium sand) and are poor in organic material. The experimental station is at the edge of a wider old fluvial channel coming from the North to the South, located generally by about 10 meters lower than the surrounding highest sand dunes, next to the research station. The soil profiles are ordered in a W-E catena, from the lowest point up to the first elevated sand dune at the edge of the channel, within a 200-meter distance. The elevation ranges from 100 m in the western parts to 105 m in the direction of eastern parts. Also, slope degree gradually decreases from eastern parts about 4–5° heading to western parts around 0–2°, until it reaches flat parts. Lighter color pattern of the soil surface in higher parts of the study area indicates the wind-blown sand (dunes), while the lower parts of the study area become darker due to the aeolian accumulation of fine material and organic matter in the topsoil.

Land use

The main use of the area is arable land. Due to the combination of sandy plains and fertile silt rich materials, the Westsik's experimental field has a rather moderate agricultural value. This area is one of the most well-known examples of constant crop rotation which was established in 1929 to improve productivity of loose sandy soils applying deep rooting and nitrogen fixing crops as rye, potato, corn, white lupine, and green fallow in specified order (Westsik, 1951). The station is supposed to study the effect of different nutrient supplies and cropping systems for a variety of products and soil reclamation techniques under local conditions (Lazányi, 2000; Demeter et al., 2019; Szegi, 2009).

Profile 1 (WH) – Endocalcaric **Phaeozem** (Anthromollic, Pantoarenic, Aric)

Location: Sand dunes, Higher part (rise) - inclination 3°, arable land, elevation 105 m a.s.l.,
N 47°58'40.90" E 21°42'14.80"



Morphology:

- Ap** – 0–30 cm, *mollic* horizon, fine sand, dark brown (10YR 3/3 slightly moist), very weak structure, fine and medium sub angular blocky, very few and common roots, clear and smooth boundary;
- A** – 30–70 cm, humus horizon, fine sand, dark brown (10YR 3/3 slightly moist), very weak fine and medium subangular blocky, fine few roots; distinct and wavy bound material, loamy sand,
- C** – 70–100 cm, calcareous parent material, dark yellowish brown (10YR 4/4) loamy sand, single grain, few thin lamellae, (the color of lamellae: 7.5YR 3/3: dark brown), no secondary carbonates, very few roots, clear and smooth boundary;
- 2C** – 100–(120) cm, different parent material, calcareous sand, dark yellowish brown (10YR 4/4), no structure (single grain), no secondary carbonates.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		2.0-0.2	0.2-0.1	0.1-0.05	0.05-0.02	0.02-0.01	0.01-0.005	0.005-0.002	0.002-0.001	< 0.001	
Ap	0-30	0	72.3	20.1	1.6	1.3	1.5	2.5	0.4	0.3	FS
A	30-70	0	70.3	12.0	8.8	1.2	0.9	1.4	2.	3.4	LS
C	70-100	0	68.7	17.6	0.5	2.4	1.7	2.6	1.5	5.0	LS
2C	100-(120)	0	70.8	16.0	3.1	1.8	1.3	1.8	1.0	4.2	FS

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	pH		CaCO ₃ [g·kg ⁻¹]	EC [ms/cm ³]
			H ₂ O	KCl		
Ap	0-30	12.1	6.0	4.7	11.5	110
A	30-70	2.8	6.2	5.2	18.5	200
C	70-100	1.6	6.7	4.9	23.9	46
2C	100-(120)	1.4	6.7	5.2	23.2	43

Profile 2 (WT) – Calcaric **Phaeozem** (Anthromollic, Pantoarenic Areninovic)

Location: Sand dunes, slope, transitional section, slope inclination 2°, arable land, elevation 104 m a.s.l.,
N 47°58'40.44" E 21°42'9.81"



Morphology:

- Ap1** – 0–15 cm, *mollic* horizon, loamy sand, brown (10YR 3/2, moist), fine and very fine weak granular structure, fine and medium few and common roots, gradual and smooth boundary, artefacts and charcoals 2–5%;
- Ap2** – 15–35 cm, *mollic* horizon, loamy sand, brown (10YR 3/2 moist), medium and fine weak sub-angular and angular blocky structure, fine very few and few roots, clear and smooth boundary, artefacts and charcoal 2–5%;
- Ab** – 35–70 cm, buried topsoil horizon, loamy sand, very dark brown (10YR 2/2 moist), medium and fine weak angular and sub-angular blocky structure, abrupt and smooth boundary, fine very few roots, clear and smooth boundary;
- AC** – 70–(90) cm, transitional horizon, loamy sand, brown (10YR 3/2 moist), medium and fine weak sub-angular and angular blocky structure, no roots, no carbonate accumulation.

Table 3. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		2.0-0.2	0.02-0.01	0.1-0.05	0.05-0.02	0.02-0.01	0.1-0.05	0.05-0.02	0.02-0.001	<0.001	
Ap1	0–15	0	73.0	6.1	3.1	3.5	3.3	0.3	1.9	8.8	LS
Ap2	15–35	0	65.2	12.4	4.6	4.8	0.3	3.6	1.3	7.8	LS
Ab	35–70	0	68.7	8.0	4.8	4.1	2.7	2.6	0.1	9.0	LS
AC	70–(90)	0	70.3	8.2	3.5	4.3	0.7	2.4	0.1	10.5	LS

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	pH		CaCO ₃ [g·kg ⁻¹]	EC [ms/cm ³]
			H ₂ O	KCl		
Ap1	0–15	27.5	7.5	7.0	22.1	312
Ap2	15–35	18.2	7.3	7.0	27.3	215
Ab	35–70	5.5	7.0	6.4	32.1	124
AC	70–(90)	2.4	7.3	6.7	23.2	116

Profile 3 (WT2L) – Calcaric Phaeozem (Anthromollic, Anoarenic, Endoloamic, Aric, Areninovic)

Location: Sand dunes foot slope, lower slope position – slope inclination 0°, arable land.

101 m a.s.l., N 47°58'40.18" E 21°42'5.50



Morphology:

- Ap** – 0–10 cm, *mollic* horizon, loamy sand, dark grayish brown (10YR 4/2 dry), weak fine and medium granular – subangular blocky structure, moderately calcareous, fine and common roots, gradual and smooth boundary;
- Aup** – 10–30 (70) cm, *mollic* horizon, sand, dark grayish brown (10YR 3/2 moist), weak fine subangular blocky structure, moderately calcareous, artefacts: brick, plastic, glass 2–5%, abrupt and irregular boundary;
- Au/Ab** – 30–70 cm, loamy sand, very dark brown and very dark grayish brown (10YR 2/2 and 3/2 and 4/3 moist), weak fine and medium subangular and angular blocky structure, clear and smooth boundary, in deeper part incompletely mixed lumps of upper and lower soil horizons;
- Ab** – 70–(100) cm, sandy loam, black (10YR 2/1), weak medium subangular blocky structure, buried topsoil horizon.

Table 5. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		2.0-0.2	0.2-0.1	0.1-0.05	0.05-0.02	0.02-0.01	0.1-0.05	0.05-0.02	0.02-0.01	< 0.001	
Ap1	0–10	0	74.3	11.2	4.1	0.1	2.1	4.0	2.1	2.1	LS
Aup	10–30	0	82.5	7.2	2.8	1.5	1.3	2.0	1.2	1.5	S
Au/Ab	30–70	0	76.4	8.9	3.6	2.0	1.7	2.6	1.1	3.8	LS
Ab	70–(100)	0	62.4	10.0	6.0	1.6	3.1	5.1	2.6	9.1	SL

Table 6. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	pH		CaCO ₃ [g·kg ⁻¹]	EC [ms/cm ³]
			H ₂ O	KCl		
Ap1	0–10	12.5	7.9	7.4	65.2	247
Aup	10–30	6.1	7.9	7.5	76.7	187
Au/Ab	30–70	4.3	8.2	7.8	94.5	285
Ab	70–(100)	9.6	7.9	7.6	81.5	1322

Profile 4 (WL) – Pantocalcaric Katocalcic Chernic **Gleysol** (Aric, Pantoloamic)

Location: Local depression among sand dunes, lowest position – slope inclination 0°, arable land, 100 m a.s.l., N 47°58'40.18" E 21°42'5.50"



Morphology:

- Ap1** – 0–15 cm, *chernic* horizon, sandy loam, very dark brown (10YR 2/2), slightly moist, fine and medium strong granular – subangular blocky structure, moderately calcareous, soft concretions, fine and common roots, abrupt and smooth boundary;
- Ap2** – 15–35 cm, *chernic* horizon, sandy loam, very dark grayish brown (2,5Y 3/2), fine and medium strong granular – subangular blocky structure, moderately calcareous, fine and few roots, abrupt and smooth boundary;
- Ah** – 35–50 cm, *chernic* horizon, sandy clay loam, black (2,5Y 2,5/1), fine and medium strong subangular and angular blocky structure, strongly calcareous, pseudomycelia, fine and few roots, gradual and wavy boundary, few reductimorphic mottles;
- CI** – 50–75 cm, sandy clay loam, dark grayish brown and yellowish brown in oxidation (2,5Y 4/2 & 10YR 5/4), fine and medium weak subangular and angular blocky structure gleyic color pattern/reducing conditions, gradual and irregular boundary, few and common oximorphic mottles; in reductic colorized matrix;
- CI2** – 75–(100) cm, clay loam, light olive brown and yellowish brown (2,5Y 5/3 & 10YR 5/6), medium and fine weak angular and subangular blocky structure gleyic color pattern/reducing conditions, secondary carbonate nodules, and soft concentrations, common oximorphic mottles.

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		2.0-0.2	0.02-0.01	0.1-0.05	0.05-0.02	0.02-0.01	0.1-0.05	0.05-0.02	0.02-0.001	< 0.001	
Ap1	0–15	0	39.1	16.8	10.9	6	5.9	6.9	4.3	10.1	SL
Ap2	15–35	0	47.5	12.5	8.5	5.9	5.2	4.4	1.3	14.7	SL
Ah	35–50	0	33.1	18.1	9.1	5.2	5.7	6.7	3.5	18.6	SCL
Cl	50–75	0	41.9	12.1	4	6	4.1	9	3.7	19.2	SCL
Cl2	75–100	0	29.3	13.5	6.9	5.4	9.2	9.5	5.8	20.4	CL

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	pH		CaCO ₃ [g·kg ⁻¹]	EC [ms/cm3]
			H ₂ O	KCl		
Ap1	0–15	14.8	7.6	7.35	129.0	297
Ap2	15–35	11.4	7.75	7.36	130.7	275
Ah	35–50	15.3	7.84	7.48	185.3	248
Cl	50–75	8.9	8.05	7.52	227.9	265
Cl2	75–100	2.0	8.13	7.64	344.7	215

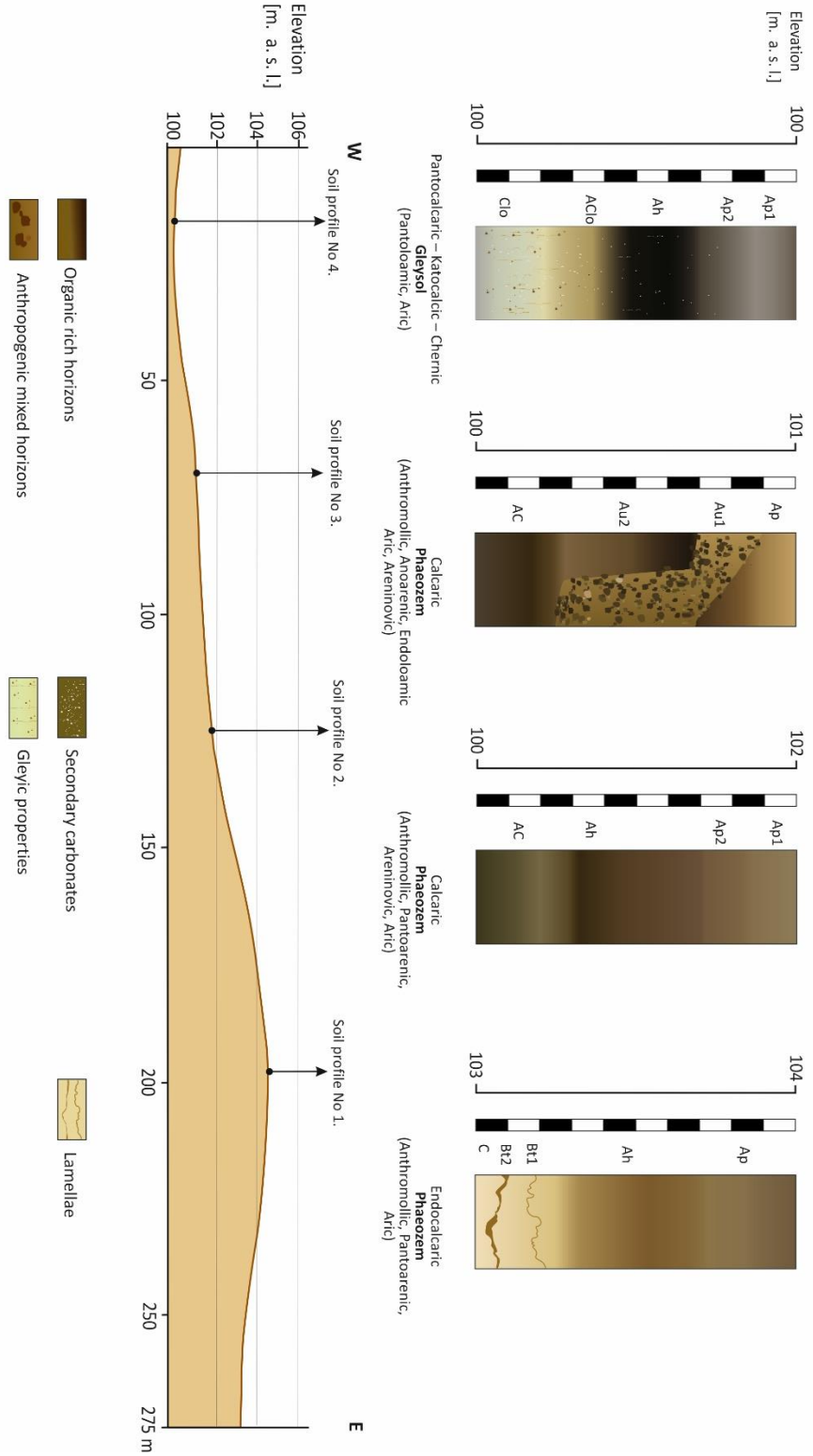


Fig. 2. Anthro-toposequence of soils on aeolian sand dunes of the experimental research station Nyíregyháza, Hungary

Soil conditions

The dominant soil reference group of the landscape are Arenosols. In depressions and old fluvial channels with higher stand of groundwater Gleysols occur. Also, the presence of Histosols before water regulation and artificial drainage cannot be excluded, however, there are no more recognizable after more than 100 years of cultivation and water regulation. Sandy and sandy loam textures cover most of the area. Only in the deeper locations the amounts of silt and clay content increase slightly. In terms of organic carbon the region is very poor; frequently, topsoils contain less than 0.2% organic carbon. Additionally to the lack of inorganic colloids, i.e. clays, this a strong limiting factor for the agricultural use of these soils. Exceptions are the local depression, as their wet habitats trapped the fine particles: silt, clay, and microaggregates of this size containing more organic and inorganic carbon in the topsoil layers. These conditions together with the better water supply due to generally higher stand of ground water level and capillary saturated zone are traditionally places for gardens and production of vegetables, since the highly depleted soil of the dune tops represents poor conditions for the agriculture. That was the reason for establishing an experimental research station here, to study how far the depleted sandy soils can be reclaimed with constant addition of organic matter, carbonates, and fertilizers combined with the crop rotation.

Climate

The area is located in the moderately warm and dry to moderately cool and dry which has the average annual minimum and maximum air temperature of about 5 and 15°C respectively. The warmest month is August while the coldest one is January. The average annual precipitation is about 566.0 mm. February and June are considered the driest and wettest months (according to <https://weather-and-climate.com/>).

Soil genesis and systematic position

Profiles 1, 2 and 3, which are located in the higher places within the surveyed area, are classified as **Phaeozems**. Their topsoils have sandy texture and very weak structure but have >0.6 OC content, with slightly acidic to slightly basic pH, and color dark enough to classify them as *mollic* horizons. At this point of the experimental station, the soils are consciously and regularly fertilized with rotation of cover crops and green manure. Hence, these practices were going for more than a half century ago, and our expectation was to diagnose increased organic carbon content compared to the sand dunes around the station (Szegei, 2009). This is possible to measure only in the topsoil layer, where in fact, there were more than 10 g·kg⁻¹ in the surface horizon. Considering the soil organic carbon content it meets the requirements for *mollic* horizons. Compared to the surrounding sand dunes (Novák et al., 2014), the increased topsoil organic carbon content and darker color can be considered a result of the rotational crop cultivation, applying green manure, liming and fertilizers regularly for several decades. There are some obvious remarks of the anthropogenic origin of the *mollic* horizons, considering the incomplete mixing of materials in case of profile No. 3, the contradictory *Endocalcaric* character and low pH in case of profile 1, the recognizable plant remnants as result of green manuring; therefore, profiles 1–3 show *anthric* properties. The *mollic* horizon and the *anthric* properties allow the application of the *Anthromollic* supplementary qualifier, which points to the anthropogenic origin of the improved quality of topsoil horizons. Since the texture class of the soils are sand and loamy sand, in profile No. 1 and profile No. 2 the *Pantoarenic* supplementary qualifier can be added. In the case of the profile No. 3, the texture changes into loam below 70 cm depth; therefore, the texture can be classified with the application of *Anoarenic* and *Endoloamic* supplementary qualifiers.

In profile 1, few evidences of iron oxides mobilization appear in the form of few (2–4) thin lamellae within the third horizon and can be recognized at the depth of up to 100 cm, but the combined thickness of lamellae does not reach the required 5 cm for adding the Lamellic qualifier. The area is arable land, and the surface layer is ploughed to a depth of more than 20 cm (regularly top 30 cm); therefore, the *Aric* supplementary qualifier applies.

Profile 2 (WT) is located in the middle of catena on a smooth slope which is different from the other soils, since it contained artefacts and charcoals of about 2–5 % volume of the surface and subsurface horizons (0–35cm). In the middle of the profile, the color became darker and soil material showed more visible effervescence which indicated the higher amount of carbonates. Therefore, the topsoil horizon can be diagnosed as *mollic* horizon with anthric properties as well (*Anthromollic*). The profile has an effective base saturation of more than 50% in the major parts.

Profile 3 (WT 2) shows serious visible disturbances concerning the soil horization, which is recognizable in mixing of material from different horizons, and abrupt and irregular boundaries of materials with different color and origin. The topsoil classifies *Anthromollic* similarly to the first 2 profiles, but additionally, new sandy material at the surface is possible to point on; therefore, the supplementary qualifier *Areninovic* can also be applied.

Profile 4 (WL) represents soil located in lower topographic position. It has thicker, black colored upper horizon rich in humus – more developed than in other investigated soils. It shows a distinctive feature in subsurface layers which indicates the existence of oximorphic and reductimorphic mottles. It can also explain the *gleyic* properties throughout and *reducing conditions* in some parts of every sublayer. Thus, the profile belongs to *Gleysols* with high base saturation ≥ 50 % throughout the whole layers (but *Eutric* is not necessary due to another qualifier – *Pantocalcaric*) and organic carbon > 1 % major parts. The surface humus horizon is plowed and can fulfill the criteria for *chernic* horizon; therefore, the *Chernic* qualifier was applied. Moreover, *Pantocalcaric* was added because this soil contains calcaric material throughout between 20 and 100 cm from the soil surface. Since the profile has sandy loam texture in a layer ≥ 30 cm thick and is ploughed to a depth of ≥ 20 cm from the soil surface, the *Pantoloamic* and *Aric* were recognized as supplementary qualifiers.

Concerning the carbonate status of the soil profiles within the sequence, anthropogenic impacts can be detected too. Naturally, soils on the top of the dunes are highly depleted in their organic and inorganic carbonate status, showing up acidic or slightly acidic pH and no carbonates in the soil. In our sequence, profile 1. has acidic pH and 1.1–2.3% of calcium-carbonate. This strange situation is a result of the constant application of carbonates together with manure and fertilizers. In the classification it appears as *Endocalcaric* qualifier, since the requested 2% of carbonates for the qualifier is present in the soil only below 70 cm depth. The soil profiles in lower position of the surface (profiles 2–3) show $>2\%$ carbonates in the whole profile, which is partially the result of liming but also adding of calcaric material from direct vicinity, having more fine fraction and calcaric by its nature. The profile No. 4 represents a completely different carbonate status, being a natural trap for finest fraction of wind blown dust, including inorganic carbonates. Therefore, its carbonate content is quite high right at the surface (12%), and it is increasing with the depth up to 34%. In deeper horizons also secondary carbonates appear; therefore, the profile is not only *Pantocalcaric*, but also gets the *Endocalcic* qualifier.

Soil sequence

This sequence can be considered an **anthropogenic transformed soil sequence**, where the cultivation and management practices represent important soil forming factor, a situation which is usually common in settlements, suburbs and intense agricultural landscapes (Novák et al., 2018).

Land use of the area is ploughland, and the effects of ploughing and mixing of the topsoil horizon is recognizable in all profiles; therefore, *Aric* qualifier applies for all of them. The ploughing in case of the organic rich, very dark topsoil of the profile 4 resulted in decrease of the organic content and the darkness of plough layer (horizon became brighter), due to the increased aeration and oxidation. Anyway, out of the *Aric*, no other qualifier expressing human soil formation processes can be applied in this case.

In the case of higher three profiles (No. 1–3) at higher elevation, and therefore in natural conditions, poor in organic matter, the constant addition of lime, green manure and fertilizers leads to the development of better aggregation of soil, darker color and higher organic carbon content. Therefore, the original *Ochric* topsoil (frequently underlain by subsoil with *Brunic* qualifier, showing initial iron mobilization) of the natural soil profiles, which can be identified outside of the experimental station, developed to a *mollic* horizon. As indication of the anthropogenic origin, these horizons qualify as *Anthromollic* in the classification, and we do not consider them as very stable. Most probably they can maintain in these conditions only with constant supply of organic matter, lime and careful management. Additionally, the improvement of the soils in case of profiles 2–3 is not only the result of management, but also deposition on the surface of rich in organic matter material, containing particular artefacts and worked into the soil due to ploughing. This material is sandy textured, and transported from the surroundings; therefore, the *Areninovic* qualifier can be applied. The strongest anthropogenic influence, even disturbances, can be identified in case of profile 3, where the incomplete mixing of the material of different horizons is recognizable even in deeper soil horizons. Anyway, there is no qualifier in WRB expressing these conditions in the profile, so at the level of classification and soil name, the heavier human impact cannot be distinguished from that in profile 2.

Acknowledgement

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From Arenosols to Luvisols – lithosequence of soils in North Poland

Marcin Świtoniak

The study was carried out in young morainic areas of North Poland within two mesoregions – Brodnica Lake District and Świecie Plateau (Kondracki, 2009; Solon et al., 2018) within the range of Pomeranian phase (16–17 kyr BP) of the Weichselian glaciation (Niewiarowski, 1986; Niewiarowski and Wysota, 1986; Marks, 2012), which left deposits of morainic glacial tills or fluvioglacial sands and gravels in the analyzed area.

Lithology and topography

First profile was located on flat Pleistocene terrace built of non-calcareous fluvial sands (Niewiarowski, 1968) in bottom part of tunnel valley (these valleys in Polish literature are also known as subglacial channels). Second and third soils were developed from sandy deposits of outwash plains (also called sandurs) formed by meltwaters flowed out from the ice sheet to the south. Last profile represents pedon developed from glacial tills covered by ablation or fluvioglacial sands within hummocky moraine plateau.

Land use

The most of investigated soils are overgrown with managed forests dominated by Scots pine (*Pinus sylvestris*) in the upper floor. Species typical of hornbeam forest (*Carpinus betulus*, *Tilia cordata*, and *Quercus sp*) dominate in the understory, the herb layer and the forest floor. Deciduous forests with a dense forest floor regenerate at the bottoms of erosional valleys. Only Profile 3 was located in agricultural area – vineyard, near to the border of managed forest.

Climate

The area is located in the zone of moist and cool temperate climate (IPCC, 2006). According to Köppen–Geiger Climate Classification, the region is located in the fully humid zone with temperate and warm summer (Kottek et al., 2006). Average annual air temperature (based on data from period 1951–1970) in the central part of studied area is 7.5°C (Wójcik and Marciniak, 1987a). The warmest month is July with average air temperature of 17.5°C, and the coldest month is February with average air temperature of -3.3°C. The average annual precipitation is 519 mm with the majority of precipitation occurring in summer and the maximum in July – 101 mm (Wójcik and Marciniak, 1987b). The humid period lasts for a whole year conditioning the leaching soil-water regime in pedons with good natural drainage.

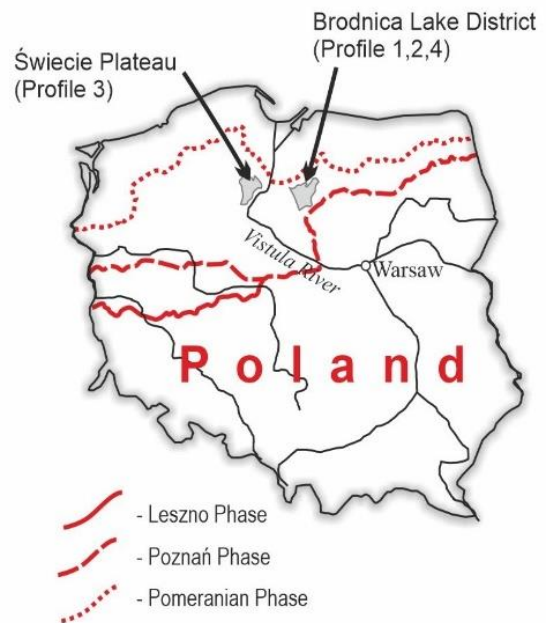


Fig. 1. Location

Profile 1 – Dystric Brunic Arenosol (Aric, Nechic, Ochric)

Location: Pleistocene terrace in bottom part of tunnel valley, flat, inclination 1°, pine plantation with deciduous forest undergrowth, 81 m a.s.l., N 53°19'13.2" E 19°26'54.7"



Morphology:

- Oi** – 2–1 cm, slightly decomposed organic material;
- Oe** – 1–0 cm, moderately decomposed organic material;
- A** – 0–10 cm, humus horizon, fine sand, dark grayish brown (10YR 5/3; 10YR 3/3), slightly moist, weak granular fine structure, few uncoated white sand grains, fine and medium common roots, clear and smooth boundary;
- A(p)** – 10–30 cm, humus horizon with plough features, fine sand, dark yellowish brown (10YR 5/4; 10YR 3/4), slightly moist, weak granular fine structure, fine and medium few roots, abrupt and smooth boundary;
- Bw** – 30–70 cm, *brunic* material, *in-situ* concentration of sesquioxides, fine sand, dark yellowish brown (10YR 6/5; 10YR 4/6), slightly moist, weak granular very fine/single grain structure, very few roots, diffuse boundary;
- C** – 70–(130) cm, parent material, fine sand, pale brown (10YR 7/4; 10YR 5/4), slightly moist, single grain structure, very few roots.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
A	0-10	1	1	2	18	53	17	7	1	0	1	FS
A(p)	10-30	0	1	1	18	55	14	6	2	1	2	FS
Bw	30-70	1	1	2	16	56	14	9	2	0	0	FS
C	70-(130)	1	1	3	22	60	9	4	1	0	1	FS

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH	
					H ₂ O	KCl
Oi	2-1	493	11.8	42	4.8	4.2
Oe	1-0	345	15.2	23	4.3	3.8
A	0-10	17.1	0.74	23	4.1	3.4
A(p)	10-30	6.7	0.43	16	5.3	4.2
Bw	30-70	2.1	0.10	21	5.4	4.1
C	70-(130)	-	-	-	5.5	4.2

Profile 2 – Anodystric Endoeutric Brunic Arenosol (Lamellic, Nechic, Ochric)

Location: Outwash plain, upper slope, inclination 4°, mixed forest with dominant pines in overstory, 91 m a.s.l., N 53°22'08.8" E. 19°23'08.2"



Morphology:

- Oi** – 3–1 cm, slightly decomposed organic material;
- Oe** – 1–0 cm, moderately decomposed organic material;
- A** – 0–20 cm, humus horizon, fine sand, dark grayish brown (10YR 6/4; 10YR 4/3), slightly moist, weak granular fine structure, few uncoated white sand grains, fine and medium common roots, clear and smooth boundary;
- Bw** – 20–60 cm, *brunic* material, in-situ concentration of sesquioxides, fine sand, dark yellowish brown (10YR 6/5; 10YR 4/5), slightly moist, weak granular very fine/single grain structure, very few roots, diffuse boundary;
- C** – 60–(130) cm, parent material, fine sand, pale brown (10YR 7/4; 10YR 5/4), slightly moist, single grain structure, very few roots, common sandy loam and strong brown (7.5 YR 6/6; 7.5 YR 4/6) clay-sesquioxides lamellae;

Table 3. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
A	0-20	2	1	4	6	62	22	4	0	1	0	FS
Bw	20-60	1	5	1	7	52	28	4	0	2	1	FS
C	60-(130)	5	11	3	4	48	25	2	3	1	3	FS
lamellae	-----	0	1	3	5	36	30	6	2	2	15	SL

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH	
					H ₂ O	KCl
Oi	2-1	462	10.7	43	4.6	4.1
Oe	1-0	388	17.1	23	4.1	3.6
A	0-20	21.2	0.77	27	4.3	3.9
Bw	20-60	2.6	0.16	16	5.0	4.2
C	60-(130)	-	-	-	5.6	4.9
lamellae	-----	3.0	0.43	7	6.2	5.1

Profile 3 – Lamellic Stagnic **Luvisol** (Arenic, Aric, Cutanic, Nechic, Ochric)

Location: Outwash plain on boundary with morainic plateau, upper slope, inclination 2°, vineyard, 85 m a.s.l., N 53°19'31.5" E 8°04'15.0"



Morphology:

- Ap** – 0–30 cm, ploughed humus horizon, sand, very dark gray (10YR 5/4; 10YR 3/3), slightly moist, weak granular fine structure, fine and medium few roots, abrupt and smooth boundary;
- Bw** – 30–40 cm, material with in-situ concentration of sesquioxides, sand, dark yellowish brown (10YR 6/6; 10YR 4/6), slightly moist, weak granular very fine/single grain structure, very few roots, diffuse boundary;
- E** – 40–50/60 cm, eluvial horizon, sand, pale brown brown (10YR 7/4; 10YR 5/4), slightly moist, weak granular very fine/single grain structure, very few roots, clear boundary;
- Btg** – 50/60–80 cm, *argic* horizon composed of lamellae with *stagnic properties*, many clay infillings and clay films on ped surfaces, loamy sand, strong brown (7.5 YR 6/6; 7.5 YR 4/6), slightly moist, weak and moderate granular fine structure, very few roots, diffuse boundary;
- C** – 80–(140) cm, parent material, sand, pale brown (10YR 7/4; 10YR 6/4), slightly moist, single grain structure, very few roots.

Table 5. Texture

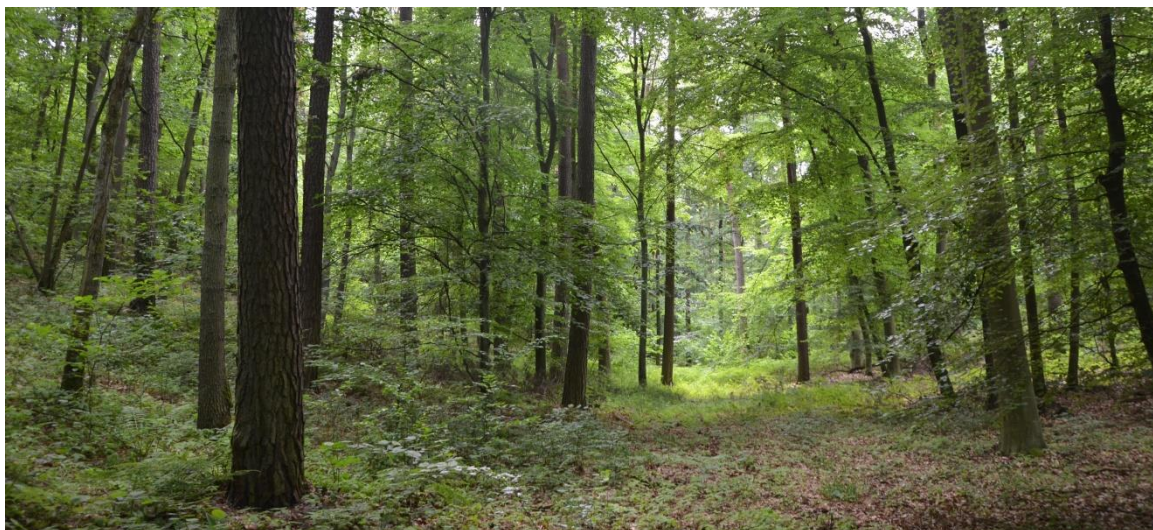
Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ap	0-30	1	2	11	38	37	7	1	1	1	2	S
Bw	30-40	2	2	7	35	45	9	1	0	0	1	S
E	40-50/60	4	2	4	29	49	12	1	1	0	2	S
Btg	50/60-80	9	6	5	18	42	16	2	1	0	10	LS
C	80-(140)	7	10	11	15	32	26	2	0	0	4	S

Table 6. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH		CaCO ₃ [g·kg ⁻¹]
					H ₂ O	KCl	
Ap	0-30	6.6	0.72	9	4.5	4.1	1
Bw	30-40	-	-	-	5.1	4.5	0
E	40-50/60	-	-	-	5.1	4.6	1
Btg	50/60-80	-	-	-	5.5	4.5	1
C	80-(140)	-	-	-	6.0	4.9	1

Profile 4 – Albic Abruptic Luvisol (Arenic, Cutanic, Ochric, Endoraptic, Brunic)

Location: hummocky morainic plateau, upper slope (shoulder), inclination 13°, mixed forest, 115 m a.s.l., N 53°20'9" E 19°27'10"



Morphology:

- Oi** – 2–1 cm, slightly decomposed organic material;
- Oe** – 1–0 cm, moderately decomposed organic material;
- A** – 0–20 cm, humus horizon, sand, dark grayish brown (10YR 5/4; 10YR 3/3), slightly moist, weak granular fine structure, few uncoated white sand grains, fine and medium common roots, clear and smooth boundary;
- Bw** – 20–55 cm, sand, dark yellowish brown (10YR 6/4; 10YR 4/4), dry, weak subangular very fine structure, very fine and very few roots, gradual and smooth boundary;
- BE** – 55–80 cm, transitional horizon, sand, light yellowish brown (10YR 7/3; 10YR 4/4), dry, weak subangular very fine structure, gradual and smooth boundary;
- E** – 80–100 cm, eluvial horizon, sand, pale yellow (10YR 7/3; 10YR 5/3), slightly moist, weak granular very fine/single grain structure, very few roots, clear and irregular boundary;
- 2Bt** – 100–(150) cm, *argic* horizon, sandy loam, dark brown (7.5YR 5.5/6; 7.5YR 4/5), dry, strong angular coarse structure, common faint clay coatings.

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
A	0–20	10	6	8	19	35	19	5	5	1	2	S
Bw	20–55	8	3	9	22	36	18	4	4	3	1	S
BE	55–80	10	6	8	18	37	19	5	4	2	1	S
E	80–100	10	4	12	24	34	15	4	4	2	1	S
2Bt	100–(150)	12	4	10	23	28	12	3	2	3	15	SL

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH	
					H ₂ O	KCl
Oi	2–1	534	14.4	37	5.3	4.8
Oe	2–0	462	16.2	29	4.6	4.1
A	0–20	6.9	0.41	17	4.7	3.9
Bw	20–55	2.7	0.19	14	4.8	4.2
BE	55–80	1.6	0.11	15	4.9	4.3
E	80–100	-	-	-	5.4	4.3
2Bt	100–(150)	-	-	-	5.6	4.2

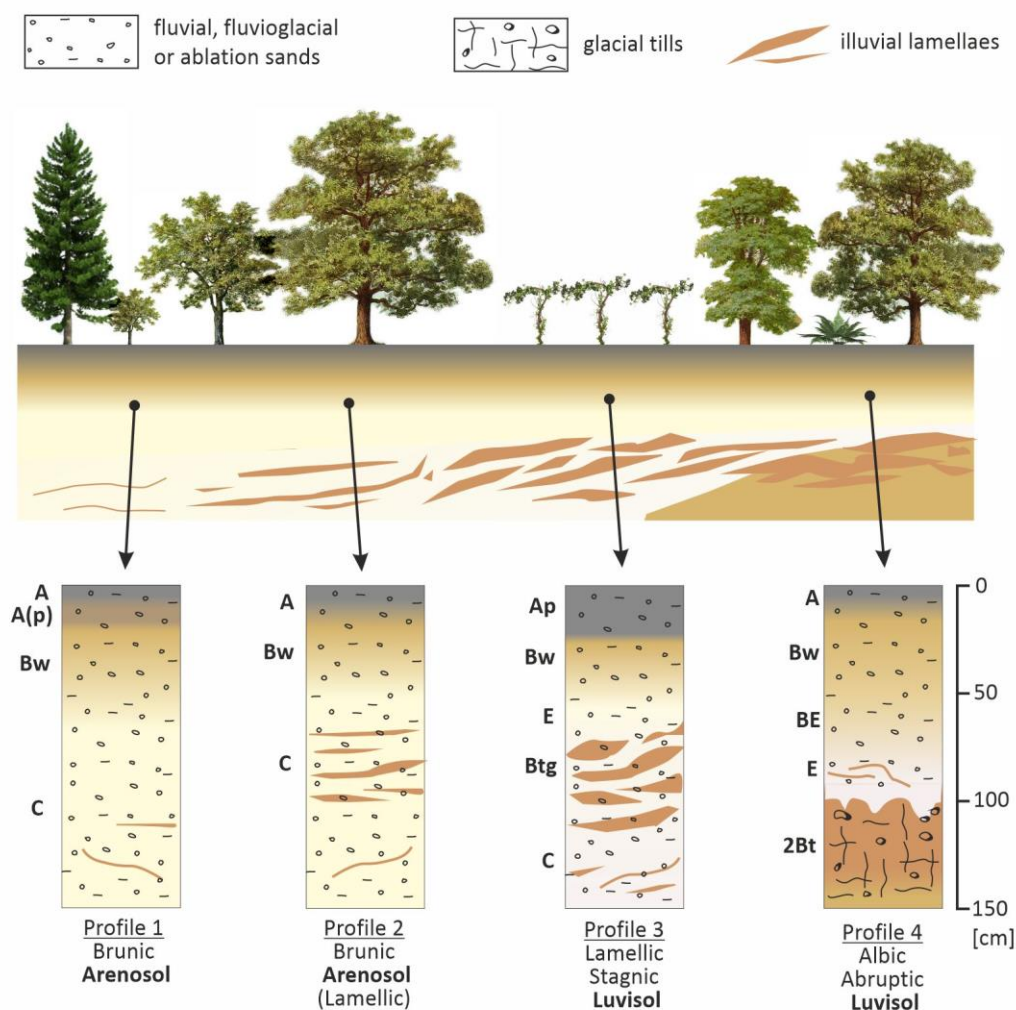


Fig. 2. Lithosequence from Arenosols to Luvisols

Soil genesis and systematic position

Soil cover of thick sandy deposits – fluvioglacial outwash plains, Pleistocene terraces – is dominated by **Arenosols** (profile 1 and 2) according to IUSS Working Group WRB (2015). These soils are sandy-textured and do not have (up to a depth of 100 cm) diagnostic horizons. Within and in immediate surroundings of the moraine plateaus **Luvisols** with well-developed illuvial horizons *argic* appears. Illuvial clay coatings and infillings were easily visible already at the stage of field work. This was also verified by micromorphological examination (Świtoniak, 2014; Świtoniak et al., 2016). Illuvial genesis of *argic* Bt was expressed by the *Cutanic* supplementary qualifier. The clay accumulation process is also accompanied by periodic stagnation of rainwater (*Stagnic* qualifier in profile 3). The prevalence of the lessivage process in young morainic deposits has already been described by several researchers (Dąbkowska-Naskręt and Jaworska, 1997a, b; Frielinghaus and Vahrson, 1998; Kühn, 2003; Marcinek and Komisarek, 2004; Kobierski, 2013; Podlasiński, 2013). Humid climate and mild average air temperatures of the investigated region favor the downward transport of clay particles (Quénard et al., 2011). Also the development of eluvial horizons (E) is the result of the lessivage process. In profile 4, the leaching of iron was so strong that it led to a whitening of sandy material above Bt. The *Albic*

qualifier emphasizes this feature. Moreover, *lithic discontinuity* occurred at 100 cm of profile 4 allowing the use of the *Endoraptic* supplementary qualifier. It was identified by (i) an abrupt change in the particle-size distribution which may not only be caused by lessivage, (ii) a clear or abrupt boundary between ablation materials and lodgement tills, (iii) the occurrence of rounded pebbles in sandy ablation/fluvioglacial material, while the underlying till has angular rock fragments. Because *abrupt textural difference* (a twofold increase in the clay content within 5 cm) in this case was caused by litho- and pedogenesis, the *Abruptic* qualifier was also used.

A common feature of all analyzed soils is a relatively weak development of humus horizons. In general, the OC content was sufficient ($> 6 \text{ g}\cdot\text{kg}^{-1}$) for diagnostic horizons, but the color did not meet the criteria for *mollic* or *umbric*. It is probably due to the relatively high share of fulvic acids which is a typical feature of A horizons developed in sandy and acidic deposits (Plichta, 1981; Licznar et al., 1993). Only the upper part of A horizon (0–10 cm) in the first profile met the criteria of *umbric* but it was not thick enough. The only possibility to express the presence of mentioned humus horizons in the name of soil in all described profiles was to apply *Ochric* supplementary qualifier. In profiles 1–3, the A horizons had common uncoated quartz grains of sand in upper parts, which was expressed in the name of soil by using the *Nechic* qualifier. In profiles 1 and 2, these uncoated grains that were whitish in color are probably the result of the initial podzolization process. The downward movement of Al, Fe and organic compounds was stimulated by acidification of the upper part of soil as a consequence of planting of pine monocultures (Jankowski, 2014; Sewerniak and Jankowski, 2021). The homogeneous nature of A horizon from 0 to 20 cm in profile 1 and its clear lower boundary could be inherited from past agricultural use of pedon (Bednarek and Michalska 1998; Sewerniak et al., 2014a) or are remnants of alterations resulting from tree planting (Sewerniak et al., 2014b). Despite the presence of the above-mentioned “tillage” features, the studied profile 1 has not been ploughed for many years and the “p” designation was used in brackets. Modern tillage was expressed in profile 3 by qualifier *Aric*.

In all investigated profiles directly below the humus horizons occur Bw horizons with significant in-situ concentration of aluminium and iron sesquioxides. This is clearly visible in the form of brown and orange coloring of the mineral material. The accumulation of iron and aluminium in these horizons is mainly the result of biochemical weathering of sandy materials (Bednarek, 1991). In described cases the Bw material meets diagnostic criteria 2–4 of the *cambic* horizon but fails to meet textural criterion 1 (IUSS Working Group WRB, 2015). Therefore, the presence of this pedogenic material could only be emphasized by the use of *Brunic* principal qualifier. It cannot be used only in profile 3 due to the lack of sufficient thickness (less than 15 cm) of Bw.

In all presented profiles also some lamellae with higher (than in the surrounding sands) clay content were noticed. Only in profiles 2 and 3, they met the total volume criterion ($> 5 \text{ cm}$) specified for the *Lamellic* qualifier.

Soil sequence

The clay-illuviation with development of *argic* horizon is the most common soil-forming process in loamy and silty textured soils of Poland. The horizons of illuvial accumulation of the clay fraction are observed in approx. 50% of Polish soils. The *in-situ* biochemical weathering and accumulation of iron in Bw horizons (in Polish this process is called “rustification”, horizon – “sideric”; Polish Soil Classification, 2019) concerns almost half of all sandy soils in the country – 14% of the total soil cover (Świtoniak, 2021). Due to the different lithological conditions of both processes, they lead to the formation of two different types of soils – *Luvisols* (or *Retisols*) and *Brunic Arenosols*. The

presented conceptual sequence of soils shows, that both processes can occur simultaneously. It means that some of the soils constitute a kind of poligenetic intermediate stages.

The first profile shows the most typical unit among **Brunic Arenosols** for northern Poland. Due to the lack of clay fraction and sandy texture, it represents soil where rustification is definitely the main soil-forming process. The illuvial displacement of iron and aluminum is only visible in the form of very thin lamellae in the parent material. These lamellae, in addition to their low thickness, also have a low clay content, which makes the use of the **Lamellic** qualifier impossible here.

In the second **Brunic Arenosol**, in addition to the well-developed Bw level, the parent material shows very distinct lamellae with a higher clay content and a dark brown color. These lamellae may be partially lithogenic in nature, but they are certainly emphasized by the post-sedimentation illuvial process (Gus-Stolarczyk et al., 2021). The occurrence of interlayers and loamy lenses in sandy materials is common, especially in outwash sediments. Described soil is already on the border between **Arenosol** and **Luvisol** – almost reaching the thickness criterion (minimum 7.5 cm) for distinguishing the *argic* Bt horizon composed of illuvial bands.

Profile 3 is similar to the previous soil, however, the illuvial lamellae combined thickness is much greater here. Thanks to this, it could be classified as **Luvisol**. Most of the lamellae are lithologically conditioned. In this type of ecotone zones on the border with the moraine plateau, sandy materials are often less sorted and contain increased amounts of fine fractions (Świtoniak and Wojtczak, 2018). Due to the erosive shallowing of the soil (Świtoniak, 2014), the Bw horizon in the described soil is too thin for the **Brunic** qualifier.

The last investigated soil – **Abruptic Luvisol** – was developed from texturally contrasted deposits – fluvioglacial or ablation cover sands overlying glacial tills. The sandy top of the profile met the criterion of distinguishing **Brunic** but at the same time contained sufficient clay fraction for possible development of Bt under *lithic discontinuity* in the upper part of glacial till. This profile represents typical, fully developed soil of the morainic plateaus of northern Poland (Świtoniak 2014, 2021). Some authors already describe soils with sandy deposits covering loamy materials where brunification or rustification and clay-illuviation processes overlapping in one profile were also noticed in other countries (e.g., Kühn, 2003; Kuhn et al., 2006; Yost et al., 2019).

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Short-time evolutionary sequence of the typical arable Chernozems as related to forest shelterbelt (Central Russian Upland)

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The experience of shelterbelts construction has a long history in Russia; the first belts were arranged in 1890s, and severe droughts with their consequences, such as people starvation, enhanced this activity (Yerusalimskiy and Rozhkov, 2017). Well-known is the system of shelterbelts initiated by Dokuchaev in Kamennaya Step in early 1890s; it was so efficient and multifunctional that soon it received the name of “Dokuchaev’s oasis”. In the post-war years (after 1945), a huge plan of “Nature transformation” was developed by the Government, and State shelterbelts were among its results; they were constructed during 1950–1960s in the Central Chernozemic region, Middle and Lower Volga regions; their total area reaches 2.1 mln ha (Chendev et al., 2015 b; Yerusalimskiy and Rozhkov, 2017).

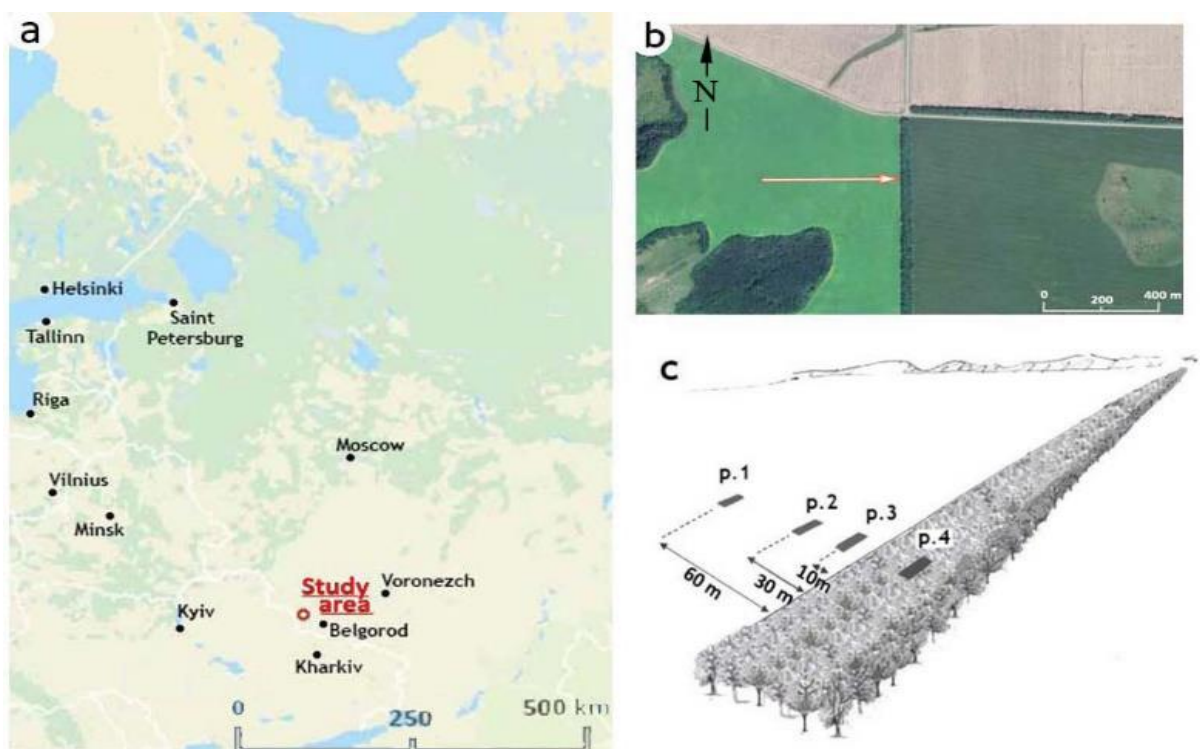


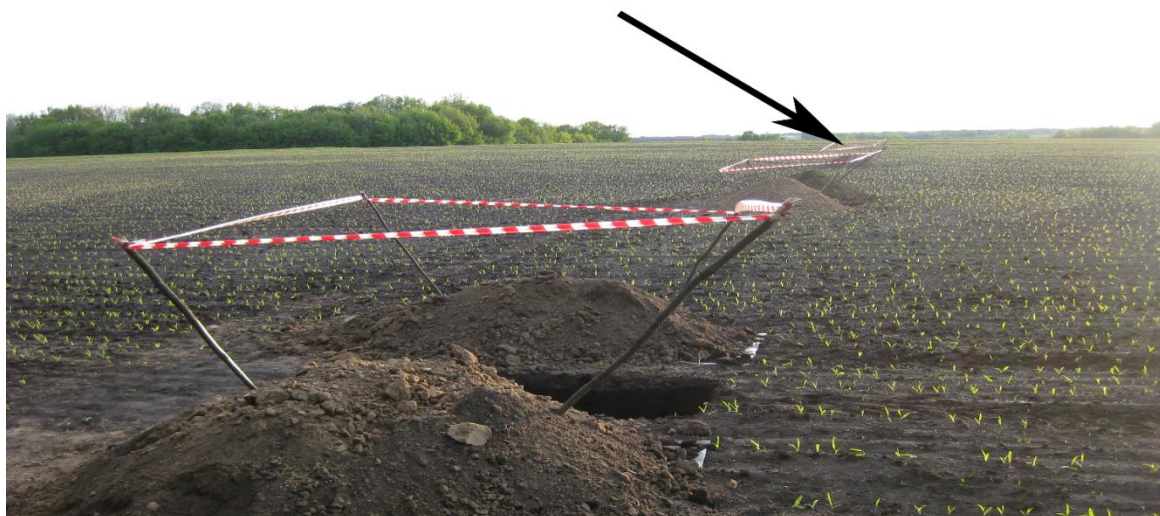
Fig. 1. Location (a) satellite image (b) and scheme (c) of the study area

In accordance with the interest concerning the problems of soil evolution and humans’ impacts on soils, publications appeared, where soils under shelterbelts were compared with those under neighboring cropland (Mil’kov et al., 1992; Hernandez-Ramirez et al., 2011; Sauer et al., 2012; Prikhod’ko et. al., 2013; Novykh and Chendev, 2014; Chendev et al., 2015 a).

Profile 1 – Haplic Chernozem (Aric, Clayic, Vermic)

Location: even surface, 60 m to the west from the edge of the shelterbelt, arable field, 214 m a.s.l.,

N 50°52'52.4" E 35°31'23.5"



Morphology:

- Ap** – 0–32 cm, ploughed layer in *chernic* horizon, silty clay, very dark gray (10YR 3/1), slightly moist to dry, friable, granular and crumb structure with clods, many fine roots, fragments of inplowed stubble, clear and smooth boundary;
- Ah** – 32–44 cm, *chernic* horizon, silty clay, very dark gray (10YR 3/1), slightly moist, weakly compact, fine granular structure, many fine roots, some earthworm channels and gray brown krotovinas, gradual and wavy boundary;
- AhBk** – 44–64 cm, transitional horizon with *protocalcic* properties, silty clay loam, heterogeneous in color: very dark grayish brown (10YR 3/2) and dark yellowish brown (10YR 4/4) mottles: krotovinas, dry to slightly moist, weakly compact, granular, crumb and fine to medium subangular blocky structure, weak effervescence; secondary carbonates as mottles of pseudomycelium 1–1.5 cm in diameter and dispersed fine veins (tubes), many fine roots, few earthworm pathways partly (~ 50%) filled with coprolites, gradual and wavy boundary;
- AhBk2** – 64–99 cm, transitional horizon with *protocalcic* properties, silty clay, dark grayish brown (10YR 4/2), slightly moist, weakly compact, medium crumb and subangular blocky structure, secondary carbonates as few mottles of soft powdery lime and pseudomycelium, fine roots, about 80% of horizon is zooturbated – krotovinas, gradual and wavy boundary;



The term “krotovina” is not completely adequate in our case, since burrowing mammals are not moles (krot in Russian) but another blind animal – European mole rat (slepysh in Russian) – *Spalax microphthalmus*

- Bck** – 99–150 cm, transitional horizon with *protocalcic properties*, silty clay loam, brown (10YR 5/3), slightly moist, weakly compact, coarse angular and subangular blocky structure, secondary carbonates as veins up to 1 mm in diameter (5–6 to 12–15 per 1 dm²), few fine roots, approximately 70% are occupied by krotovinas, gradual and wavy boundary;
- Ck** – 150–(160) cm, loess parent material with *protocalcic properties*, silty clay, light yellowish brown (10 YR 6/4), slightly moist, compact, carbonate pseudomycelium as fine filaments, 0.2–0.7 mm in diameter (10–20 per 1 dm²), very few fine roots; 10–15% are occupied by krotovinas.

Table 1. Texture

Horizon	Depth [cm]	Percentage of fractions [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ap	0–32	0.0	0.0	0.5	0.2	0.5	0.2	29.6	18.2	10.0	40.9	SiC
Ah	32–44	0.0	0.0	0.3	0.1	1.9	0.6	29.6	18.0	9.2	40.2	SiC
AhBk	44–64	0.0	0.0	0.1	0.0	0.3	0.1	30.1	19.1	11.4	38.8	SiCL
AhBk2	64–99	0.0	0.0	0.1	0.1	0.4	0.1	31.9	20.0	6.5	40.9	SiC
Bck	99–150	0.0	0.0	0.1	0.1	0.3	0.1	32.0	19.3	9.9	38.2	SiCL
Ck	150–(160)	0.0	0.0	0.1	0.0	1.8	0.6	29.8	16.3	11.0	40.3	SiC

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH H ₂ O	CaCO ₃ [g·kg ⁻¹]
Ap	0–32	47.3	2.6	18.2	7.6	0.0
Ah	32–44	46.8	2.3	20.3	8.0	2.2
AhBk	44–64	32.3	1.5	21.5	8.3	22.0
AhBk2	64–99	25.5	1.4	18.2	8.3	46.2
Bck	99–150	18.2	0.8	22.8	8.3	61.6
Ck	150–(160)	9.4	0.5	18.8	8.3	70.4

Profile 2 – Haplic Chernozem (Aric, Loamic, Vermic)

Location: top position on the interfluvium, slightly convex surface, 30 m from the edge of the shelterbelt, arable field, 214 m a.s.l., N 50°52'52.4" E 35°31'25.1"



Morphology:

- Ap** – 0–30 cm, ploughed part of *chernic* horizon, silty clay loam, very dark gray (10YR 3/1), slightly moist, friable, angular blocky and crumb structure, a plowpan is identified in the lower part by angular acute-edge aggregates, many fine roots, fragments of stubble, abrupt and smooth boundary;
- Ah** – 30–45 cm, *chernic* horizon, silty clay loam, very dark grayish brown (10YR 3/2), slightly moist, weakly compact, fine crumb, granular and blocky angular structure, many fine roots, some empty earthworm channels, krotovinas, gradual and wavy boundary;
- AhB** – 45–67 cm, transitional horizon, silty clay loam, dark grayish brown (10YR 4/2), slightly moist, weakly compact, fine crumb and subangular blocky structure with some granular aggregates, many fine roots, few krotovinas, gradual and wavy boundary;
- Bk** – 67–97 cm, *protocalcic* properties from the depth of 72 cm, silty clay loam, heterogeneous in color: grayish brown (10YR 5/2) background and very dark grayish brown (10YR 3/2) and yellowish brown (10YR 5/4) mottles owing to strong burrowing by mammals: 80–90% of the area are occupied by krotovinas, slightly moist, weakly compact, crumb to coarse angular and blocky structure. Weak effervescence at the depth of 72 cm, and strong one at 90 cm; secondary carbonates occur as mottles of powder mixed with pseudomycelium 3–4 cm in size, mostly confined to krotovinas, also few veins; fine roots, gradual and wavy boundary;

Bck – 97–130/145 cm, transitional horizon with *protocalcic* properties, silty clay loam, brown (10YR 5/3), slightly moist, weakly compact, coarse angular and subangular blocky structure with prismatic elements. Secondary carbonates occur on pedfaces as fine pseudomycelium, locally – thin crusts, veins 0.5–1 mm in diameter are dispersed in the soil mass (10–20 per 1 dm²), few fine roots. Krtovinas occupy ~ 50% of the vertical section, gradual and wavy boundary;

Ck – 130/145–(160) cm, loess parent material with *protocalcic* properties, silty clay, light yellowish brown (10YR 6/4), slightly moist, compact; secondary carbonates as mycelium mottles and dispersed fine pseudomycelium, few fine roots, krtovinas compose ~ 10–15% of the wall.

Table 3. Texture

Horizon	Depth [cm]	Percentage of fractions [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ap	0–30	0.0	0.0	0.2	0.1	0.1	0.0	32.9	15.7	11.1	39.8	SiCL
Ah	30–45	0.0	0.0	0.1	0.1	0.1	0.0	33.5	17.5	10.4	38.3	SiCL
AhB	45–67	0.0	0.0	0.1	0.0	0.1	0.0	35.6	17.4	8.3	38.6	SiCL
Bk	67–97	0.0	0.0	0.1	0.0	0.1	0.0	34.9	16.8	9.3	38.8	SiCL
Bck	97–130/145	0.0	0.0	0.1	0.0	0.1	0.0	33.4	18.8	10.7	37.0	SiCL
Ck	130/145–(160)	0.0	0.0	0.1	0.1	2.2	0.7	24.3	15.8	13.0	43.9	SiC

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH H ₂ O	CaCO ₃ [g·kg ⁻¹]
Ap	0–30	52.0	2.4	21.7	7.7	0.0
Ah	30–45	43.2	2.0	21.6	7.7	0.0
AhB	45–67	26.5	1.6	16.6	7.7	0.0
Bk	67–97	23.9	1.3	18.4	7.9	13.2
Bck	97–130/145	14.6	0.7	20.9	8.4	66.0
Ck	130/145–(160)	5.7	0.4	14.3	8.4	61.6

Profile 3 – Haplic Chernozem (Aric, Clayic, Densic, Vermic)

Location: flat interfluve, 10 m from the edge of the shelterbelt, arable field, 214 m a.s.l.,

N 50°52'52.4" **E** 35°31'26.2"



Morphology:

- Ap** – 0–25 cm, ploughed part of *chernic* horizon, silty clay, very dark gray (10YR 3/1), slightly moist, friable in 0–4 cm and firm in 4–24 cm, fine subangular blocky to crumb and cloddy structure, many fine roots, fragments of stubble, abrupt transition and smooth boundary;
- Ap2** – 25–30(31) cm, ploughed part of *chernic* horizon, silty clay, dark gray (10YR 4/1), slightly moist, very firm, medium blocky angular to cloddy structure, few fine roots, abrupt and wavy boundary;
- Ah** – 30(31)–35 cm, lower part of *chernic* horizon, silty clay, dark grayish brown (10YR 4/2), moist, firm, fine granular and blocky angular structure, many fine roots, clear transition and wavy boundary;
- AhB** – 35–55 cm, transitional horizon, silty clay, brown (10 YR 4/3), moist, weakly compact, fine granular, angular and subangular blocky, weak effervescence at the depth of 44 cm, many fine roots, few empty earthworm channels, with krotovinas at ~ 30% of the section, gradual transition and wavy boundary;
- AhBk** – 55–67 cm, transitional horizon, silty clay, heterogeneous in color: grayish brown (10YR 5/2) background and very dark grayish brown (10YR 3/2), yellowish brown (10YR 5/4) mottles, slightly moist, weakly compact, medium to coarse angular blocky structure, locally granular, pseudomycelium as clusters (5 per 1 cm²) and mottles with pseudomycelium and powdery lime 1–1.5 cm in size, tree roots*; krotovinas occupy ~ 50–60% of the area, gradual transition and wavy boundary;



Secondary carbonates as soft powdery lime with pseudomycelium in BCK horizon

Bk – 67–102 cm, *protocalcic* properties from the depth of 72 cm, silty clay loam, heterogeneous in color: brown (10YR 5/3) background and very dark grayish brown (10YR 3/2), yellowish brown (10YR 5/4) mottles, slightly moist, weakly compact, crumb and coarse angular blocky structure, fragmentary pseudomycelium and small mottles of soft powdery carbonates, tree roots both alive and rotten, krotovinas make up ~ 80 % of the section, gradual transition and wavy boundary;

BCK – 102–130 cm, transitional horizon with *protocalcic* properties, silty clay loam, heterogeneous in color: yellowish brown (10YR 5/4) background and brown (10YR 4/3) mottles, slightly moist, weakly compact, coarse angular blocky to prismatic structure, pseudomycelium, most abundant on pedfaces, few roots with tree roots among them, krotovinas compose 70–80% of the area, gradual transition and wavy boundary;

BCK2 – 130–(160) cm, transitional horizon with *protocalcic* properties, silty clay loam, heterogeneous in color: light yellowish brown (10YR 6/4) background and brown (10YR 4/3) mottles, slightly moist, weakly compact to compact, coarse cloddy-prismatic structure, porous, pseudomycelium as fine veins (2–3 per 1 cm²), few tree roots, ~ 30% of the area is occupied by krotovinas.

*Tree roots are most abundant in 50–100 cm.

Table 5. Texture

Horizon	Depth [cm]	Percentage of fractions [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ap	0–25	0.0	0.0	0.3	0.1	2.2	0.7	29.4	16.8	8.8	41.7	SiC
Ah	25–35	0.0	0.0	0.2	0.1	0.3	0.1	32.1	17.6	8.9	40.7	SiC
AhB	35–67	0.0	0.0	0.1	0.0	0.1	0.0	30.7	19.3	8.2	41.5	SiC
Bk	67–102	0.0	0.0	0.1	0.1	0.1	0.0	34.1	18.6	10.1	36.9	SiCL
BCK	102–130	0.0	0.0	0.1	0.1	0.1	0.0	33.3	18.6	10.9	36.9	SiCL
BCK2	130–(160)	0.0	0.0	0.1	0.0	0.1	0.0	32.6	19.5	9.4	38.2	SiCL

Table 6. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH H ₂ O	CaCO ₃ [g·kg ⁻¹]
Ap	0–25	49.9	2.4	20.8	7.8	0.0
Ah	25–35	46.8	2.4	19.5	7.8	8.8
AhB	35–67	34.3	1.9	18.1	8.3	28.6
Bk	67–102	21.8	1.2	18.2	8.3	48.4
BCK	102–130	20.3	0.9	22.6	8.3	59.4
BCK	130–(160)	18.7	0.9	20.8	8.3	50.6

Profile 4 – Greyzemic Chernozem (Anoclayic, Endoloamic, Pachic, Vermic)

Location: flat interfluvial, central part of the shelterbelt (60 years old) with *Fraxinus excelsior*, *Ulmus minor* and *Acer negundo*, 214 m a.s.l., N 50°52'52.4" E 35°31'27.8"



Morphology:

- O** – 3–0 cm, slightly decomposed organic material;
- Ah** – 0–26 cm, *chernic* horizon, silty clay, very dark gray (10 YR 3/1), slightly moist, very friable to friable, fine granular and crumb structure, many earthworm channels and coprolites, many fine roots, gradual transition and wavy boundary;
- Ah2** – 26–53 cm, *chernic* horizon, silty clay, very dark grayish brown (10 YR 3/2), slightly moist, friable, crumb-granular and subangular blocky structure; when drying, bleached silty mottles, 1–1.5 cm in size (siltans), some earthworm channels and krotovinas, many fine roots, gradual and wavy boundary;
- AhB** – 53–67 cm, transitional horizon, silty clay loam, dark brown (10 YR 3/3), slightly moist, weakly compact, crumb and subangular blocky structure, few granular aggregates, Some subangular aggregates have thin discontinuous coatings on pedfaces, many fine roots, few earthworm channels, krotovinas make up ~ 20% of the section, gradual transition and wavy boundary;
- AhB2** – 67–82 cm, transitional horizon, silty clay loam, organic material brown (10 YR 4/3), slightly moist, weakly compact, medium to coarse subangular blocky structure, few granular aggregates, many roots, few earthworm channels, ~ 30–35 % of krotovinas, gradual transition and wavy boundary; few fine discontinuous shiny coatings on part of ped faces;
- B** – 82–108 cm, silty clay loam, heterogeneous in color: dark yellowish brown (10 YR 4/4) background and very dark grayish brown (10 YR 3/2), dark yellowish brown (10 YR 4/4) mottles,



Organo-mineral impregnations of some subangular blocky peds in B horizon



Secondary carbonates in BCK(g) horizon – pseudomycelium, veins

slightly moist, weakly compact, medium to coarse subangular blocky few crumb aggregates, grayish brown discontinuous organo-mineral impregnations of some pedfaces along with very few brown fine coatings, few iron-manganic soft concretions, some roots, krotovinas make up ~ 60–70% of the area, clear transition and wavy boundary;

BCK(g) – 108–144 cm, transitional horizon with *protocalcic* properties, silty clay loam, brown (10YR 5/3), slightly moist, weakly compact, coarse and very coarse angular and subangular blocky to prismatic structure, pseudomycelium: abundant (2–4 per 1 cm²) carbonate veins, 1–1.5 mm thick, soft carbonates mottles (up to 1 cm) on faces of prismatic and blocky peds, iron-manganic soft concretions 0.2–0.5 mm in diameter and abundance of 5–7/cm², few fine roots, krotovinas make up ~ 50% of the area, clear transition and wavy boundary;

Ck – 144–(160) cm, loess parent material with *protocalcic* properties, silty clay loam, pale brown (10 YR 7/4), slightly moist, compact, overall pseudomycelium as yellowish whitish veins (1–3/cm²), common whitish mottles of soft carbonates on pedfaces, few fine roots.

Table 7. Texture

Horizon	Depth [cm]	Percentage of fractions [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ah	0–26	0.0	0.0	0.2	0.1	0.0	0.0	33.7	17.2	6.2	42.5	SiC
Ah	26–53	0.0	0.0	0.1	0.0	0.0	0.0	34.1	16.5	5.0	44.3	SiC
AhB	53–82	0.0	0.0	0.1	0.0	0.1	0.0	35.3	19.5	5.5	39.4	SiCL
B	82–108	0.0	0.0	0.1	0.0	0.0	0.0	37.1	18.6	5.7	38.5	SiCL
BCKg	108–144	0.0	0.0	0.1	0.0	0.1	0.0	36.5	17.8	8.5	36.9	SiCL
Ck	144–(160)	0.0	0.0	0.1	0.1	1.4	0.5	33.4	19.5	9.0	36.0	SiCL

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH H ₂ O	CaCO ₃ [g·kg ⁻¹]
Ah	0–26	53.6	2.7	19.9	6.8	0.0
Ah	26–53	49.4	2.0	24.7	6.8	0.0
AhB	53–82	39.0	1.7	22.9	6.9	0.0
B	82–108	31.7	1.5	21.1	7.0	2.2
BCKg	108–144	19.8	1.1	18.0	7.1	4.4
Ck	144–(160)	15.0	0.8	18.8	8.2	57.2

They mostly concerned Chernozems and Mollisols, since the majority of shelterbelts were constructed on soils with dark-humus horizons. In monographs and papers on Russian Chernozems, their authors showed the importance of shelterbelts for crop yields, changes in water and nutrition regimes, soil biota, as well as in humus content and composition. Secondary carbonates in the profiles of chernozem subtypes (leached, typical, ordinary, southern) traditionally identified in Russia, were among important phenomena indicating the effect of shelterbelts (Chendev et al., 2015a; Prikhod'ko et al., 2013; Novykh and Chendev, 2014; Chendev et al., 2015b).

In this case study, modifications in soil properties were revealed in a sequence of chernozem profiles on a cropland adjacent to the 60-year-old shelterbelt at different distances from the latter. All the parameters of this key site and of its soils, in particular, are very homogeneous, which permits to reveal the effect of the forest shelterbelt and its intensity on soils. Soils were classified as typical plowed chernozems according to the traditional system of 1977 (Classification..., 1977), or migrational-mycellary agrochernozems in the new system of 2004 (Classification..., 2004), or Haplic Chernozems (Aric) in WRB (IUSS Working Group WRB, 2015). Revealing and interpreting the minor changes in soil properties were among the objectives of this study.

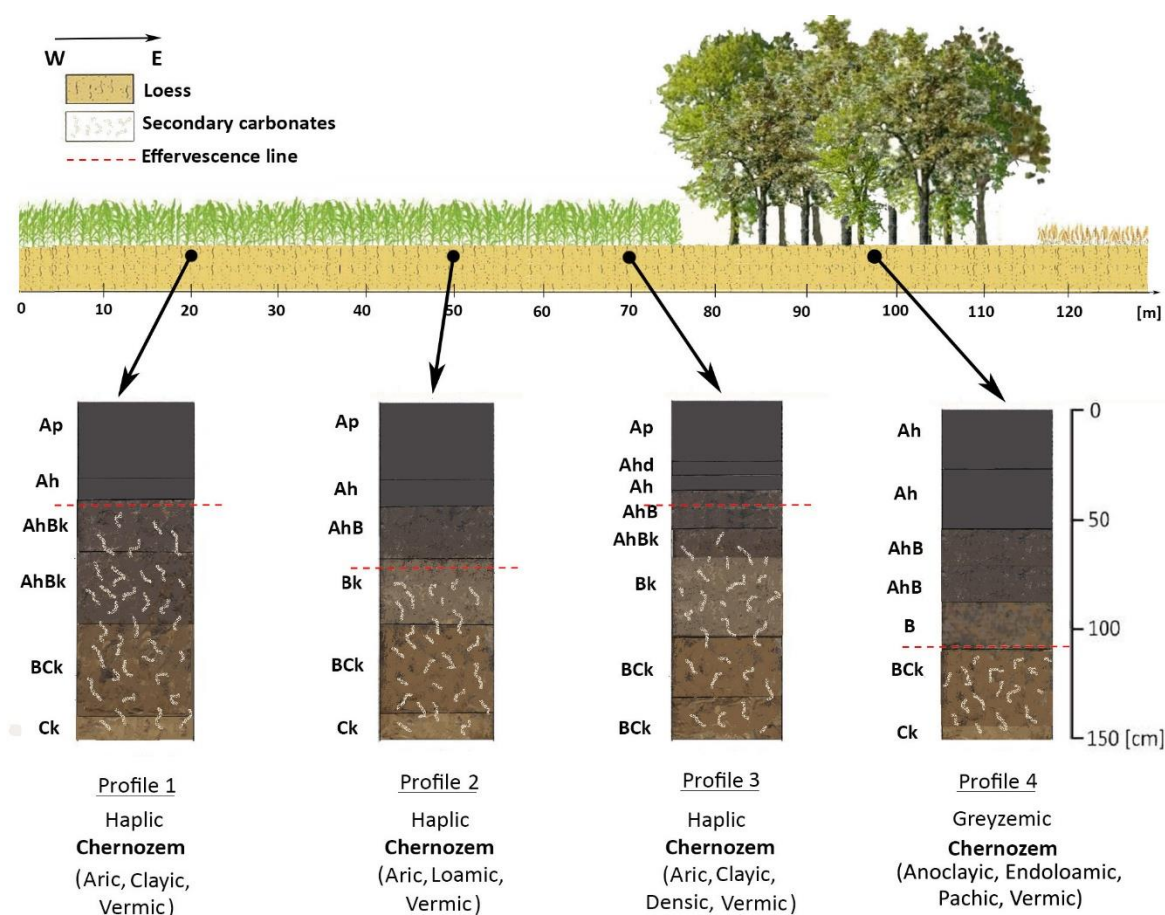


Fig. 2. Soil sequence

Lithology and topography

The key site “Bondarev” was chosen on the absolutely flat horizontal surface weakly inclined to the south ($<1^\circ$). Parent material – carbonate-containing loess-like loams; ground water table is deeper than 8 m.

Land use

The area has been used for cropping not less than 170 years (Belevantsev and Chendev, 2015). Moldboard plowing and disking were the main tillage operations, technical and grain crops are grown, and the 5-fields rotations were recently used.

Shelterbelt construction

The forest belt is 30 m wide; it is composed of 6 double rows of trees dominated by *Fraxinus excelsior*; *Ulmus minor* and *Acer negundo* are admixtures. Trees are about 60 years old, the ground cover is composed of semi-decomposed tree falloff; there are single plants of *Poa nemoralis* and *Urtica dioica*.

Climate

Bondarev key site is located in the most humid part of the forest-steppe, mean annual precipitation is 600 mm, mean annual air temperature is +6.5°C, with + 19.0°C in July and -6°C in January. The snow cover is preserved from December until March; soil freezing extends to 0.5 m and more in extremely cold years.

Soil genesis and systematic position

Three profiles of soils under cropland are similar in their properties and are definitely qualified for **Chernozems** as they have a *chernic* horizon and *protocalcic* properties appearing within 0.5 m below the boundary of *chernic* horizon (IUSS Working Group WRB, 2014, page 95).

Chernic horizon in these profiles is undoubtedly identified as it meets 3 major requirements: although ploughed, it is rich in organic carbon (4.7–5.0% versus >2.5% required); its structure is strong granular with participation of fine subangular blocky peds, and earthworm coprolites make up its prominent part; color requirements are met as well. It is worth noting that structure is of very high quality (it is strong, of high pedality, diverse in shape and size of dominant peds); a small admixture of blocky peds may be due to tillage, which contributes to aggregate destruction and transfer of blocky peds from underlying layer.

Protocalcic properties appear in due place and are manifested as labile secondary carbonates – veins (tubes), pseudomycelium, weak impregnations as mottles on pedfaces. No concretionary pedofeatures were recorded.

Among principal qualifiers for *Chernozems*, only *Haplic* was found suitable. We looked for the possibility to apply *Greyzemic* and/or *Luvic*, but failed to find arguments. The supplementary qualifiers for all profiles were *Clayic* (*Loamic* for pit №2 and №4), *Aric* and *Vermic*.

The soil under the forest shelterbelt was also referred to as *Chernozems*, although secondary carbonates appear rather deeply, at “their ultimate limit”. Nevertheless, the upper horizon has properties of *chernic* (not *mollic* as required for **Phaeozems**), and secondary carbonates appear at the depth of 108 cm, while the lower boundary of Ah horizon *sensu stricto* lies at the depth of 53 cm, whereas the AhB horizon ends at the depth of 82 cm. Thus, in terms of formal criteria, we have an interval of 55 cm instead of 50 cm required if we accept the first assumption, and 26 cm, or slightly more, if we accept the second one. In the first case, the soil cannot be referred to **Chernozems**, and its *chernic* horizon hinders referring it to **Phaeozems**. This controversial situation was resolved in favor of *Chernozems*, and the name of the soil under the forest belt is: **Greyzemic Chernozem** (*Clayic*, *Pachic*, *Vermic*). Principal qualifier *Greyzemic* is argued by the presence of whitish siltans in Ah

horizon, *Pachic* is introduced since Ah horizon (*sensu stricto*) is 53 cm thick versus 50 required, earthworm coprolites are abundant as in all soils of the site.

A final remark: all 4 profiles are strongly mixed by burrowing mammals (zooturbated), most intensely in the depth interval of 50–100 cm, which is crucial for soil diagnostics, and the burrowing animals distort the horizons' boundaries, thus making the tasks of soil diagnostic more hard.

Particularities of **Chernozems** of the key site are worth noting. High activity of pedobiota, both mammals and earthworms, may be attributed to favorable environment in this key site – forest-steppe in its humidic part. Therefore, chernozems have excellent humus horizons¹, on one hand, and a broad spectrum of labile secondary carbonates, on the other hand. Their name in the Russian Soil classification system is migrational-mycellary indicating the behaviour of carbonates and shape of resulting pedofeatures (Classification..., 2004).

Soil sequence

The sequence studied is anthropogenic by nature and concerns soil modifications both in time and space.

Time sequence. The age of cropland is not less than 170 years (Belevantsev and Chendev, 2015), and that of the shelterbelt – approximately 60 years. Thus, it is possible to assess changes that have happened during 60 years, and they are in good agreement with published data on chernozems (Mil'kov et al., 1992; Hernandez-Ramirez et al., 2011; Sauer et al., 2012; Prikhod'ko et. al., 2013; Novykh and Chendev, 2014; Chendev et al., 2015 a). It is stated by all authors that in soils under shelterbelts, the effervescence line descends by 20–50 cm (in our case about 0.5 m), pH shifts to the acid area by 1–2 units, mull humus acquires some features of moder, and beloglazka starts to dissolve. In soils under the oldest shelterbelts, the taxonomic position of soil changed at the subtype level for chernozems.

In terms of WRB, the shift from Chernozems to Phaeozems was expectable, and we recorded it with Rienk Miedema 30 years ago in Kamennaya Step under the famous 100-year-old shelterbelt. This trend is manifested in the key site by weak traces of eluviation (siltans), and hardly visible clay illuviation (thin discontinuous coatings on some pedfaces). Presumably, the half-century period seems too short for profile textural differentiation even against a favorable climatic background. Additionally, a very conventional comparison of zooturbation intensity in soils under forest belt and cropland showed a higher one in the latter case.

Spatial sequence. As mentioned above, the difference in properties among soils of the cropland at different distances of the shelterbelt is not very obvious and is manifested in some details concerning secondary carbonates and moisture regime.

The upper boundary of secondary carbonates appearance is higher in the remote profile and is the lowest in the profile in the belt. The profile near the belt (№3) has a plow pan, which may be explained either by higher air humidity during the growing period, or by snow accumulation in winter, or both; hence, higher soil moisture. However, tree roots spreading from the shelterbelt and concentrated in the 50–100 cm layer consume this additional moisture, thus restricting the development of stagnic regime. Very weak and, probably, short-time water stagnation cannot be excluded in the upper part of the profile due to the plow pan, the origin of which is also related to direct and current human impact: more frequent passages of agricultural vehicles there as compared

¹ Ivan V. Tiurin, who is world-wide known as specialist in humus, once said that maximum of chernozemic process falls on forest-steppe.

to other arable soils in this catena. It is also clear that tree roots from the shelterbelt do not reach other soils.

The soil under the shelterbelt may be regarded as a final member of this short human-created catena, its properties are in good agreement with those described in publications on young or middle-age shelterbelts on chernozems.

Acknowledgements

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Soils Sequences of the Southern slope in Chelgerd Region, Central Zagros of Iran

Mohammad Hassan Salehi, Sepideh Etedali, Marcin Świtoniak

Iran is located in central Eurasia and southwest of Asia between 44° 02' and 63° 20' eastern longitudes and 25° 03' and 39° 46' northern latitudes. The studied area is located in the Chelgerd region of Chaharmahal-Va-Bakhtiari province, Central Zagros of Iran (Fig. 1) with an average height of 2480 meters above the sea level. The Zagros Mountains are a long mountain range in Iran, Iraq and southeastern Turkey. This mountain range has a total length of 1,600 km which begins in northwestern Iran and roughly follows Iran's western border while covering much of southeastern Turkey and northeastern Iraq and its highest point is Mount Dena, at 4,409 meters.

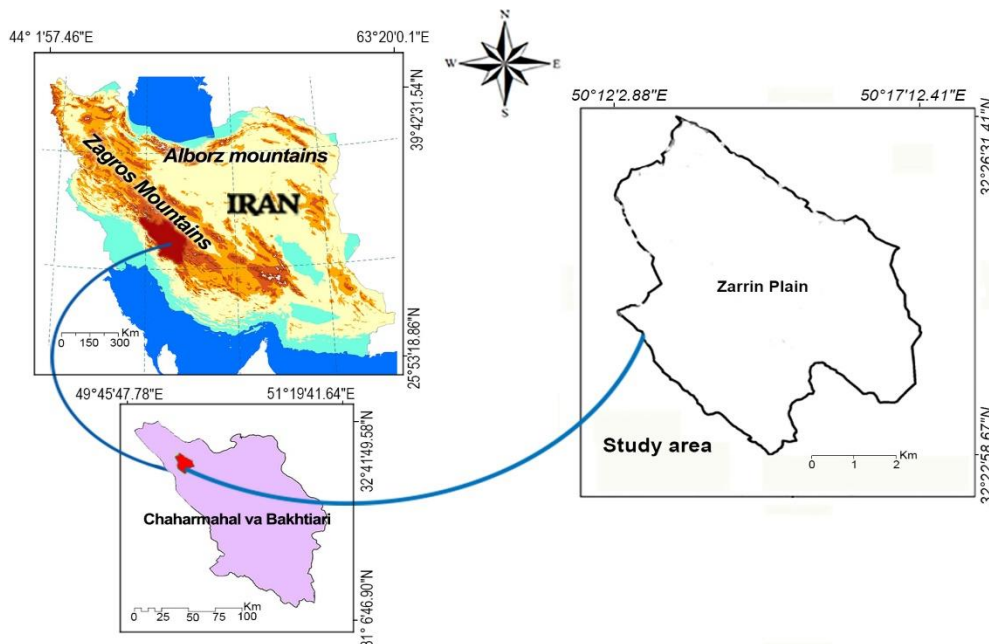


Fig. 1. Location

Lithology and topography

Five pedons with approximately 300 meters intervals were excavated along the southern slope with a length of 2 km and ranging from 5 to 45 percent of inclination and a height difference of 200 meters (Fig. 2). Quaternary limestones are the main parent materials in the area. Physiographic units in the area included mountains, hills, and plains. In the study area, no evidence of lithologic discontinuity was observed. The study area is a semi-arid region and there is no evidence of the strong aeolian process.

Land use

The majority of areas within the Chelgerd region are covered with grassland and rain-fed agriculture.

Climate

Mean annual rainfall of 1389.6 mm and soil temperature of 9.5°C. Soil temperature and moisture regimes of this region are mesic and xeric, respectively.

Profile 1 – Haplic Calcisol (Ochric, Pantoloamic)

Location: back slope, semi-desert vegetation, inclination 45°, N 32°25'57" , E 50°15'27"



Morphology:

- A** – 0–20 cm, humus horizon, sandy clay loam, brown (7.5YR 4.5/4), dry, weak granular fine and weak wedge medium structure, medium and few carbonate masses, violently effervescent with HCl;
- Bk1** – 20–100 cm, *calcic* horizon, clay loam, brown (7.5YR 5.5/4), moist, massive, medium and many carbonate masses, violently effervescent with HCl;
- Bk2** – 100–(130) cm, *calcic* horizon, clay loam, brown (7.5YR 6/4), moist, massive, medium and many carbonate masses, violently effervescent with HCl.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm					Textural class
		> 2.0	2.0-0.05	0.05-0.002	<0.002	<0.0002	
A	0–20	4	54.0	21.0	25	10.2	SCL
Bk1	20–100	8	39.5	22.5	38	15.9	CL
Bk2	100–(130)	10	38.0	23.0	39	16.0	CL

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	pH	ECe [dS·m ⁻¹]	CEC [meq/100g soil]	COLE	Carbonate calcium equivalent, CCE [g·kg ⁻¹]
A	0–20	6	7.8	0.6	24.4	0.01	70
Bk1	20–100	5	7.9	0.4	16.3	0.02	470
Bk2	100–(130)	4	7.9	0.3	15.8	0.03	475

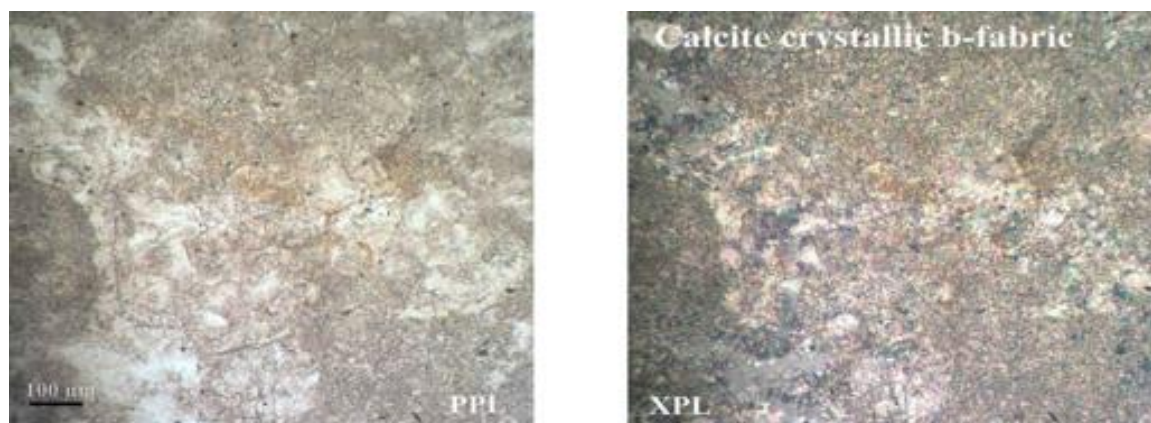


Fig. 2. Calcite crystalline b-fabric in the Bk horizon of pedon 1 (No evidence of clay illuviation and stress coating were observed).

Profile 2 – Haplic Calcisol (Chromic, Katoclayic, Ochric)

Location: back slope, semi-desert vegetation, inclination 35°, N 32°25'48" , E 50°15'21"



Morphology:

- A** – 0–20 cm, humus horizon, loam, brown (5YR 4.5/5), dry, moderate granular fine structure, medium and few carbonate masses, strongly effervescent with HCl;
- Bk1** – 20–70 cm, *calcic* horizon, clay, brown (5YR 6/5), moist, massive, medium and many carbonate masses, medium and many carbonate nodules, violently effervescent with HCl;
- Bk2** – 70–(130) cm, *calcic* horizon, clay, brown (5YR 6.5/4), moist, massive, medium and many carbonate masses, violently effervescent with HCl.

Table 3. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm					Textural class
		> 2.0	2.0-0.05	0.05-0.002	<0.002	<0.0002	
A	0–20	20	37.0	37.5	25.5	11.7	L
Bk1	20–70	27	39.5	17.5	43.0	21.8	C
Bk2	70–(130)	29	40.0	17.0	43.0	22.0	C

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	pH	ECe [dS·m ⁻¹]	CEC [meq/100g soil]	COLE	Carbonate calcium equivalent, CCE [g·kg ⁻¹]
A	0–20	6	7.9	0.6	23.9	0.01	110
Bk1	20–70	5	8.0	0.4	18.3	0.03	470
Bk2	70–(130)	4	8.0	0.3	17.9	0.03	470

Profile 3 – Katocalcic **Vertisol** (Aric, Hypereutric, Ochric, Cutanic, Katoluvic)

Location: foot slope, inclination 25°, N 32°25'43" , E 50°15'18"



Morphology:

Aip – 0–25 cm, humus horizon, clay loam, brown (7.5YR 4.5/4), dry, moderate granular fine and moderate wedge medium structure, many distinct slickensides on top faces of peds and on the surface along root channels;

Btik1 – 25–65 cm, *vertic*, *argic* and *calcic* horizon, clay, brown (7.5YR 5/4), moist, massive, many distinct slickensides on top faces of peds and on the surface along root channels, few faint clay films on top faces of peds, strongly effervescent with HCl;

Btik2 – 65–(130) cm, *vertic*, *argic* and *calcic* horizon, clay, brown (7.5YR 5.5/4), moist, massive, many distinct slickensides on top faces of peds and on the surface along root channels, few faint clay films on top faces of peds, strongly effervescent with HCl.

Table 5. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm					Textural class
		> 2.0	2.0-0.05	0.05-0.002	<0.002	<0.0002	
Aip	0–25	10	40	25	35	13	CL
Btik1	25–65	27	29	22	49	20	C
Btik2	65–(130)	28	30	20	50	22	C

Table 6. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	pH	ECe [dS·m ⁻¹]	CEC [meq/100g soil]	COLE	Carbonate calcium equivalent, CCE [g·kg ⁻¹]
Aip	0–25	6	7.8	0.5	25.6	0.05	15
Btik1	25–65	5	7.9	0.4	18.4	0.06	390
Btik2	65–(130)	4	7.9	0.3	17.6	0.07	400

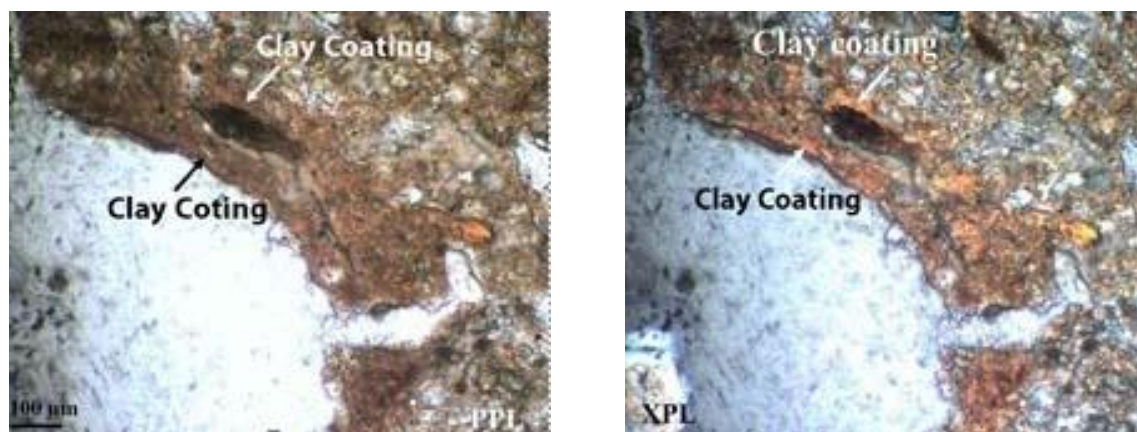


Fig. 3. Clay coating in the Btik1 horizon of pedon 3 in the footslope

Profile 4 – Katocalcic Vertisol (Aric, Gilgaic, Ochric, Hypereutric)

Location: foot slope, inclination 10°. N 32°25'14" , E 50°14'55"



Morphology:

- Aip** – 0–25 cm, humus horizon, clay, brown (10YR 5/4), dry, moderate granular fine and moderate wedge medium structure, many distinct slickensides on top faces of peds and on the surface along root channels, very slightly effervescent with HCl;
- Bik1** – 25–95 cm, *vertic* and *calcic* horizon, clay, brown (7.5YR 4.5/4), moist, massive, many distinct slickensides on top faces of peds and on the surface along root channels, medium and few carbonate masses, strongly effervescent with HCl;
- Bik2** – 95–(120) cm, *vertic* and *calcic* horizon, clay, brown (7.5YR 5/4), moist, massive, many distinct slickensides on top faces of peds and on the surface along root channels, medium and few carbonate masses, strongly effervescent with HCl.

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm					Textural class
		> 2.0	2.0-0.05	0.05-0.002	<0.002	<0.0002	
Aip	0–25	4	27.0	32.5	40.5	16.8	C
Bik1	25–95	4	29.5	22.5	48.0	23.0	C
Bik2	95–(120)	5	30.0	21.0	49.0	23.5	C

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	pH	ECe [dS·m ⁻¹]	CEC [meq/100g soil]	COLE	Carbanate calcium equivalent, CCE [g·kg ⁻¹]
Aip	0–25	12	7.7	0.8	30.8	0.08	65
Btik1	25–95	5	7.7	0.4	27.0	0.09	220
Btik2	95–(120)	4	7.7	0.4	26.5	0.09	230



Fig. 4. Microrelief (gilgai) and cracks in the surface of pedon 4 in the footslope

Profile 5 – Haplic Vertisol (Gilgaic, Hypereutric, Ochric, Bathycalcic, Bathycutanic)

Location: toe Slope, inclination 5°, N 32°25'11", E 50°14'45"



Morphology:

- Aip** – 0–15 cm, humus horizon, clay loam, brown (7.5YR 3.5/4), dry, moderate granular fine structure;
- Bi1** – 15–60 cm, *vertic* horizon, clay, brown (7.5YR 4/4), dry, moderate wedge coarse structure, many distinct slickensides on top faces of peds and on the surface along root channels;
- Bi2** – 60–105 cm, *vertic* horizon, clay, brown (7.5YR 3/4), moist, weak wedge medium structure, many distinct slickensides on top faces of peds and on the surface along root channels;
- Btik** – 105–(140), *vertic* and *calcic* horizon, clay, brown (7.5YR 4/4), moist, massive, many distinct slickensides on top faces of peds and on the surface along root channels, few faint clay films on top faces of peds, medium and few carbonate massive, medium and common carbonated nodules, violently effervescent with HCl.

Table 9. Texture

Horizon	Depth [cm]	Percentage share of fractions, size of fractions in mm					Textural class
		> 2.0	2.0-0.05	0.05-0.002	<0.002	<0.0002	
Aip	0–15	2.0	31.0	34.0	35.0	14.0	CL
Bi1	15–60	2.0	25.5	31.5	43.0	18.0	C
Bi2	60–105	4.0	29.0	29.0	42.0	18.2	C
Btik	105–(140)	12.0	19.0	22.0	59.0	25.0	C

Table 10. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	pH	ECe [dS.m ⁻¹]	CEC [meq/100g soil]	COLE	Carbonate calcium equivalent, CCE [g·kg ⁻¹]
Aip	0–15	7	7.3	1.1	26.7	0.08	15
Bi1	15–60	7	7.4	0.6	31.6	0.10	33
Bi2	60–105	24	7.5	0.5	32.8	0.14	5
Btik	105–(140)	0	7.6	0.4	20.1	0.15	365

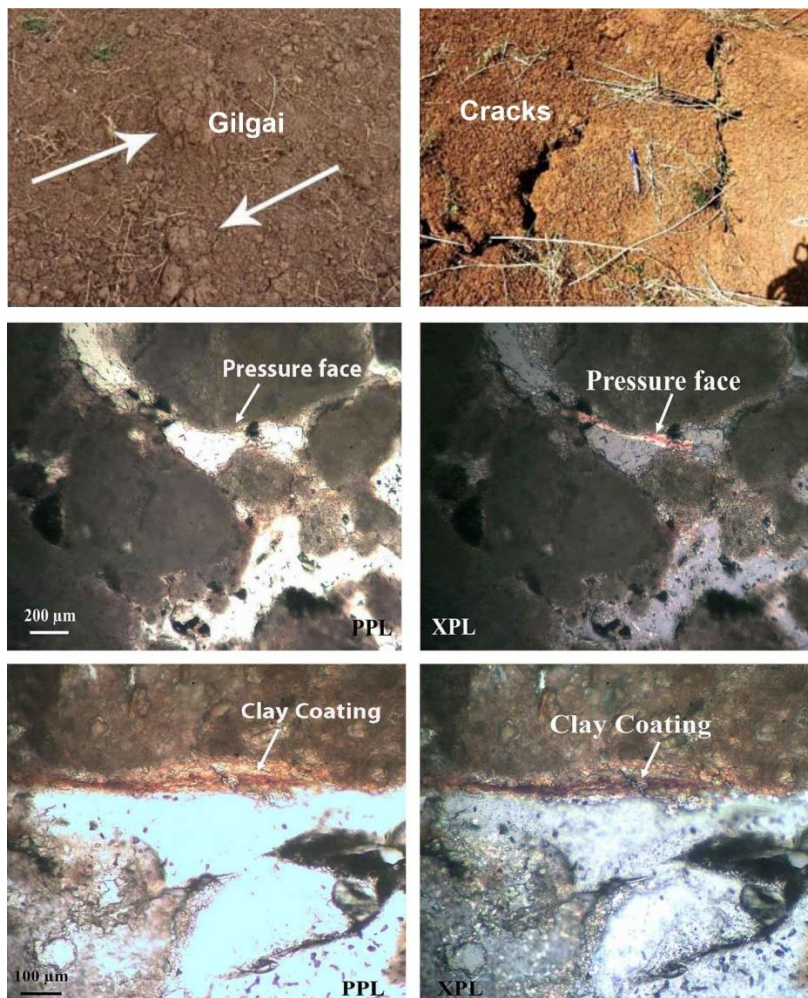


Fig. 5. Microrelief gilgai and cracks on the surface and pressure face and clay coating in horizon Btik in profile 5

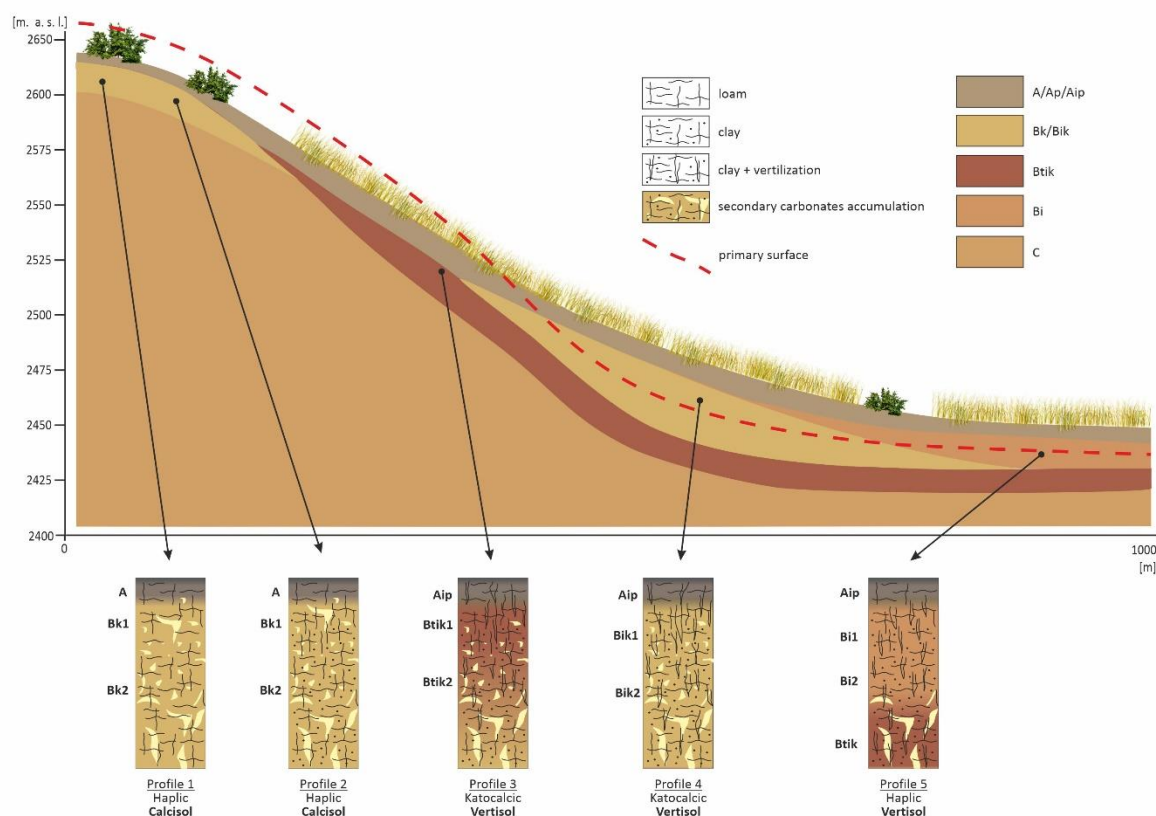


Fig. 6. Location of pedons along the toposequence

Soil genesis and systematic position

Profiles 1 and 2 represent relatively shallow and weakly developed soils. The main result of pedogenesis in these soils is a significant amount of secondary carbonates. Studies of thin sections of the Bk horizon of pedon 1 located in the shoulder slope confirm the secondary nature of carbonates and caused calcitic crystallitic b-fabric. Calcite needle crystals were observed at the surface of minerals in this position of the slope. According to the results of Khormali et al. (2006), accumulation of this form of calcium carbonate can be attributed to highland area, enough moisture in the soil, low salinity of soil and presence of biodegradable organic matter. Due to the presence of *calcic* horizon within 100 cm from the soil surface and no presence of other diagnostic horizons or properties above the *calcic* horizon, these pedons were classified as *Haplic Calcisols*. The content of calcium carbonate (with many secondary forms) in both soils is very high and reaches nearly 50% of the mineral material. Both soils have a light-colored, with a low organic carbon content poorly developed humus horizons. Their presence can only be marked by using the *Ochric* qualifier. In both cases, the texture of the surface horizons is loamy. The content of the clay fraction clearly increases in the Bk. In the first profile, it is still a little below 40%; therefore, the entire profile has a loamy texture and it was possible to use the *Pantoloamic* qualifier. In the second case, clay textural class begins at a depth of 20 cm (*Katoloamic*).

The *Chromic* supplementary qualifier in the WRB name of pedon 2 shows the presence of subsurface layer within 30 cm or thicker within 150 cm of the soil surface that has a munsell color hue redder than 7.5YR, moist (IUSS Working Group WRB, 2015).

In the next profiles (3–5), the clay content does not fall below 35%, even in the humus horizons, while in the deeper horizons this fraction exceeds 40%. Clay texture and significant changes in soil moisture during the year led to the development of features characteristic for vertilization process –

shrink-swell cracks and slickensides. The *vertic* horizon is therefore one of the major characteristics of pedons 3, 4 and 5. Based on the recent WRB soil classification system (IUSS Working Group WRB, 2015), Vertisols must have 30% of clay throughout and have either slickensides or wedge-shaped structural aggregates and shrink-swell cracks – all at least 25 cm thick. In the older versions of WRB, the presence of both slickensides and wedge-shaped structural aggregates was essential. Esfandiarpour et al. (2013) suggested replacing the word ‘or’ instead of conjunctions ‘and’ to solve this problem. Nevertheless, all three profiles meet the **Vertisols** criteria.

All investigated **Vertisols** have also *calcic* horizons – accumulation of secondary calcium carbonates. In pedons 3 and 4, calcic starts very shallow – under lower boundary of humus horizons (*Katocalcic*) while in the last profile 5, the upper boundary of *calcic* is at the depth 105 cm (*Bathycalcic*). In profiles 3 and 5, the features of illuvial clay accumulation (*argic* horizons) are visible simultaneously with the secondary carbonates. The presence of Bt was expressed by Kato- and Bathyluvic qualifier respectively.

Thin sections of the Btk horizon of pedon 3 located in the back slope confirm clay coatings (cutans) and are evidence of translocation of clay (*Cutanic*). The formation clay on the walls of the pores shows that there is high rainfall and enough water available for transfer of clay from the upper horizons in the lower horizons in this region. It seems several processes happened in this area including: 1) Decalcification, 2) Illuviation and 3) Calcification.

In the thin sections of the Btk horizon of the pedon 5 located in the footslope, clay coating and pressure face as well as some excrements were observed. Less clay crust in this horizon compared with the pedons located on the higher slope can be attributed to the expansion and contraction of clays due to higher value of smectite (Kemp and Zerate, 2000; Verhey and Stoops, 1973). Cole values (Tables 2, 4, 6, 8 and 10) also indicate that clay content increased with decreasing elevation and depth.

In all thin sections studied, various forms of calcium carbonate including calcite infilling, calcite cover, calcite nodule and calcite bridge were observed. The presence of these pedofeatures in the lower soil horizons indicates the presence of a large amount of calcium carbonate in parent material and fluctuating in wet and dry periods in summer and winter.

All investigated Vertisols, despite weakly developed humus horizons (*Ochric* qualifier), were used as arable land. Plowing to the depth deeper than 20 cm was expressed by *Aric* qualifier in profiles 3 and 4. In the last profile, the thickness (15 cm) of plowing horizon was not sufficient for this suffix.

Soil structure was granular in surface horizon and wedge shape and prismatic in the subsurface horizons of pedons. Granular structure was formed due to accumulation of organic matter that is produced from plant residues and presence of high clay in these soils (Tarasawa, 1975; Hassannezhad et al., 2008).

Pedons 4 and 5 have special morphological features. In these pedons, *Gilgaic* qualifier in the WRB name shows the presence of microhighs and microlows with a difference in level of at least 10 cm.

Soil sequence

Considering the presented catena, it can be clearly seen that the highest located soils (Profile 1 and 2 – **Calcisols**) have the least pronounced features of pedogenesis. Despite the large amount of clay and significant precipitations throughout the year, there is lack of features related to the lessivage process, as it is in profiles 3 and 5. The *calcic* horizons in these soils begin at a depth of 20 cm, just below the humus horizons. In dry and semi-arid climates, the presence of large amounts of secondary calcium

carbonates close to the surface is a natural feature due to high evaporation (e.g. Driessen et al., 2001; Koca, 2019; Fatma et al., 2021). Nevertheless, the occurrence of this type of soils can also be a result of slope processes, truncation and excavation of Bk (Ck) horizons. This was previously noted in many countries of the temperate zone (Hristov, 2014; Novak, 2018; Žižala, 2019; Drewnik and Żyła, 2019; Matecka and Świtoniak, 2020) but also in subtropical regions (Martinez-Casasnovas and Ramos, 2009). In the presented sequence, it is very possible that Calcisols are the result of erosive shallowing of soils. This is confirmed by the results of studies on the intensity of erosion in the Zagros Mountains (e.g., Bruthans, 2008; Mohammadi et al., 2021)

All soils of the study area had some amount of gravels in their layers. Gravel content decreased by decreasing the elevation which can be an indicator for increasing degree of weathering (Tables 1, 3, 5, 7 and 9). These findings are in agreement with the results reported by other researchers (Dahlgern et al., 1997; Yuanjun and Mangan, 2008; Balayneh et al., 2021). However, higher content of skeletal fraction can be caused by erosive washing down of finer fractions from the upper part of the slopes. Atofarati et al. (2012), in a study in Ile-Oluji, Ondo state, Nigeria concluded that clay content increased with depth and the highest concentration of OC occurred at the down slope and decreased with depth. Similarly, in the studied area, with decreasing elevation, sand content decreased (Tables 1, 3, 5, 7 and 9) and clay content increased (Tables 2, 4, 6, 8 and 10). Clay content was high in alluvial plain and lowland but clay film was not observed in all pedons in this situation probably because of dry-wet alternation (Nettleton et al., 1969; Prakongkep et al., 2007). The increasing clay content can be used as an indicator or for increasing degree of weathering. These findings accord well with the results reported by Takoutsing et al. (2017) and Ehabu et al. (2020). Van wambeke (1962) used silt and clay ratio to estimate the degree of weathering of soil pedon and postulated that the lower the ratio, the higher the degree of weathering.

Soil reaction was neutral to slightly basic. pH ranged from 7.3-8.0. The highest accumulation of soil organic carbon was observed in soil surface of all pedons and decreased with depth. The lowest concentration of OC occurred at the topsoil of upper slope and increased with decreasing elevation (Tables 2, 4, 6, 8 and 10). Our results accord well with those reported by Idoga and Azogaku (2005), Atofarati et al. (2012) and Awooner and Dogbey (2021). Such a distribution of the OC content in humus horizons in particular parts of the slope is characteristic for erosion-accumulation catenas (Świtoniak, 2014; Deumlich et al., 2018). Cation exchange capacity (CEC) seems to be related to elevation, and thus also related to the degree of soil weathering. As discussed earlier, soil weathering tends to increase with decreasing elevation. As soil weathering increased in pedons with medium elevation, more exchangeable cations could be released (Tables 2, 4, 6, 8 and 10). CEC was also high in lowland because of high presence of organic matter in surface horizons and high clay content in subsurface horizons (Hikmatullah et al., 2003; Seyedmohammadi Meresht., 2013). Electrical conductivity showed higher values in soils of lowland due to the draining water from uplands (Tables 2, 4, 6, 8 and 10). The *calcic* and *argic* horizons "buried" at the depth of 105 cm in profile 5 and lack of clay translocation and calcium carbonate accumulation in the upper part (from 0 to 105 cm) of this profile confirm high probability of relatively young slope deposits or alluvium accumulation. The *argic* horizons with upper boundary at a depth of 1 m may of course be a natural feature – especially in soils where the surface materials have sandy texture and the clay can easily migrate to these depths (Świtoniak, 2014). However, this does not seem to be possible in the case of profile 5, where the material is very rich in the clay fraction from the mineral surface of soil.

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Example of toposequence in a degraded landscape in the watershed of Huay Ma Nai, Nam Mae Than River, Phrae Province, Northeast of Thailand

Pascal Podwojewski, Jean-Louis Janeau

To monitor the effects of rapid land use change and land degradation in cultivated steep slopes of Southeast Asia, a regional network called 'the Management of Soil Erosion Consortium' (Magliano and Leslie, 2001) was established towards the end of the 1990s.

This long-term research program aimed at monitoring changes in farming practices and the resulting runoff and sediment yields at the catchment scale in five representative small watersheds in Indonesia, Laos, the Philippines, Thailand, and Vietnam (Valentin et al., 2008). The monitoring process was implemented by the International Water Management Institute (IWMI) and the French Institut de Recherche pour le Developpement (IRD).

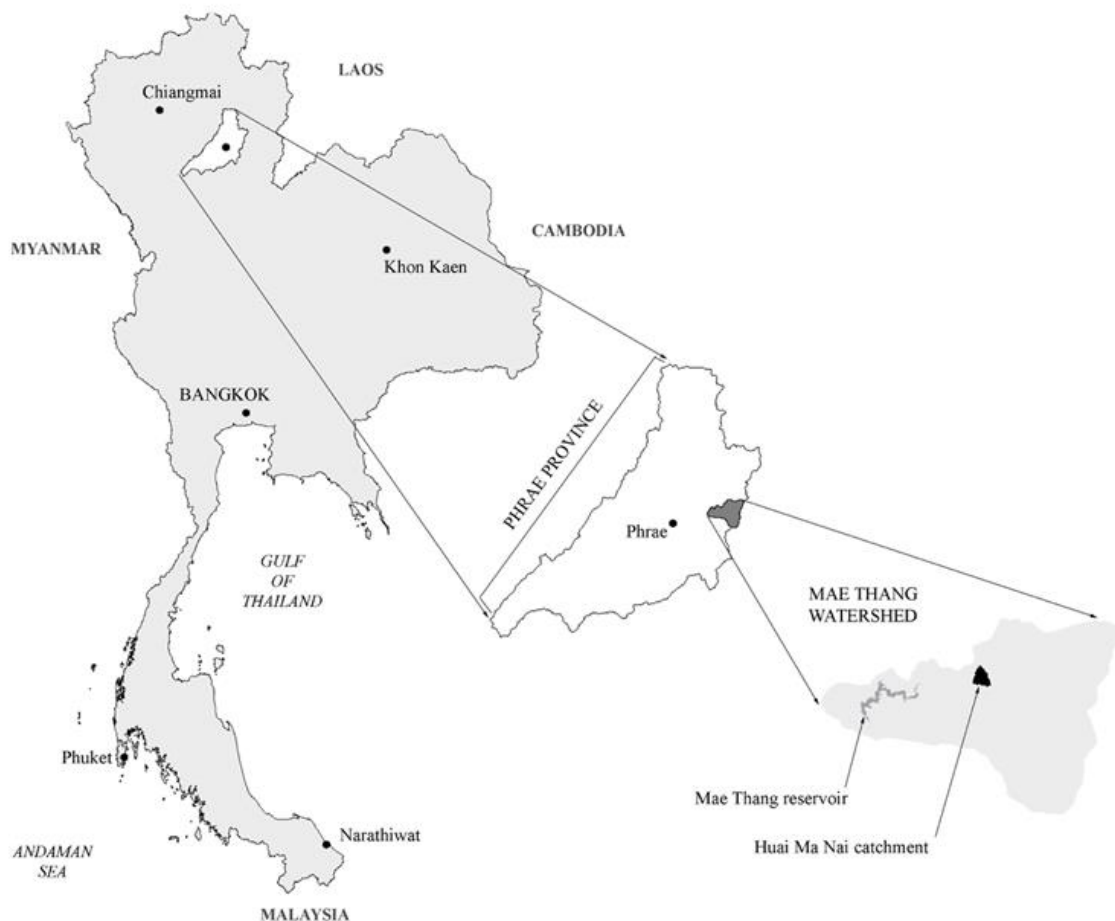


Fig. 1. Location of the Huay Ma Nai catchment upstream of the Mae Thang reservoir

The Huay Ma Nai catchment

In Thailand, the experimental site of MSEC programme (Fig. 2) is in the Mae Tang River catchment, in northern Thailand, 30 km northeast of the city of Phrae, in the de Rong Kwang district, in the same province of Phrae. This catchment is in the piedmont plain of Doi Khun Sathan relief between $18^{\circ}10'$ and $18^{\circ}16'$ of latitude North and $100^{\circ}22'$ and $100^{\circ}28'$ of longitude East. The sub catchment of Huay Ma Nai covers 95 ha and was equipped with a meteorological station and 5 weirs to monitor the water runoff and the sediment losses. A rainfall simulation to measure detachment process, soil loss and infiltration rate was conducted in 2002 in a part of a steep slope of one MAE YOM toposequence (Janeau et al., 2003). At largest scale, we studied the exportation of the trace metal elements (TME) from the catchment to the reservoir located downstream showing off-site effects. We observed that despite large use of pesticides for agriculture, the average concentrations of TME in the reservoir were in the limit of the international and Thai standard, except for two minerals in the bottom of the reservoir (Grellier et al., 2013).

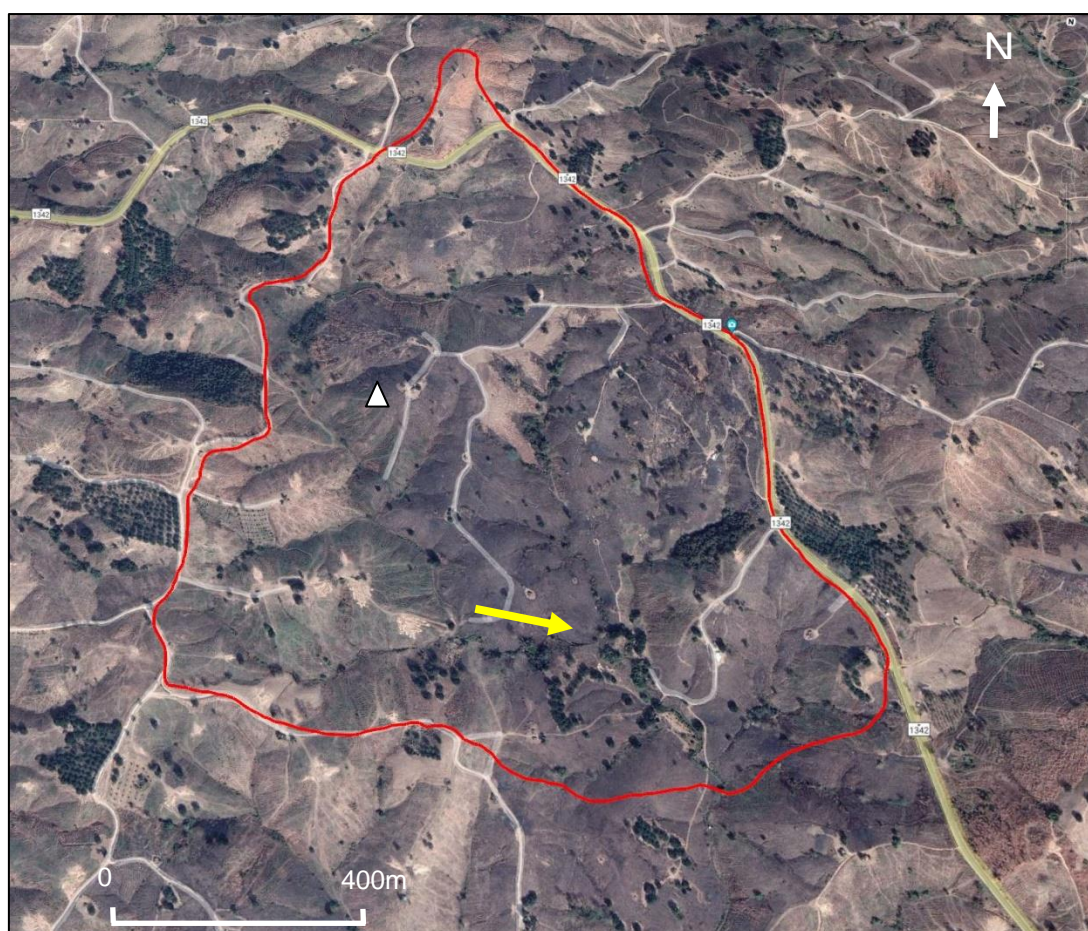


Fig. 2. Limit of the studied MSEC catchment.
The Δ reference point is located $18^{\circ} 14' 12''$ N and $100^{\circ}, 23'$ and $07''$ E, altitude 455 m.
The yellow arrow indicates the orientation of the toposequence.

Geomorphology and Geology

The geomorphology consists of a series of half orange hills of less than 500 m in diameter with steep convex sides and steep slope (up to 60 %). The geology is mainly composed of folded Permo Triassic volcano-sedimentary shales with some locally observed micro-layers of calcite and dolomite. Further to the East, a N/S fault reveals the Doi Khun Sathan relief covered by a forest.

Climate

The average annual rainfall over the last 26 years is 1072 mm. The climate is typically a monsoon tropical climate with two main seasons, the rainy season from May to October and a cooler and dryer season from November to February, March (Table.1).

Table 1. Meteorological data for Huay Ma Nai catchment, Mae Yom province

	J	F	M	A	M	J	J	A	S	O	N	D	Year*
Rainfall [mm]	7.1	4.0	39.9	38.8	226.2	158.1	139.8	248.7	288.9	72.0	34.5	37.7	1296
T [°C]	22.9	25.5	27.4	29.7	27.5	26.7	26.4	26.1	25.7	25.5	23.6	22.1	25.8

*Year: total yearly rainfall, mean average temperature – period from 2001 to 2005

Land use

The hills have been cleared illegally and intensively cultivated since 1982. In Thailand, maize has replaced soya bean and mung bean (*Vigna radiata*) since 2003 due to a fungus infecting mung bean, the shorter rainy season, and higher prices for maize (*Zea mais*). Abandoned land, forest patches and even orchards of sweet tamarind (*Tamarindus indica*) trees were slashed and cultivated with maize. The soils are intensively tilled and ploughed with heavy machineries acting from the top of the hills to downstream generating some tillage erosion (Figures 3, 4, 5, 6).



Fig. 3. 2000 – succession of convex hills and with tree cover in the valleys and scattered tree cover on top of the hills



Fig. 4. 2002 – Land clearing by fire



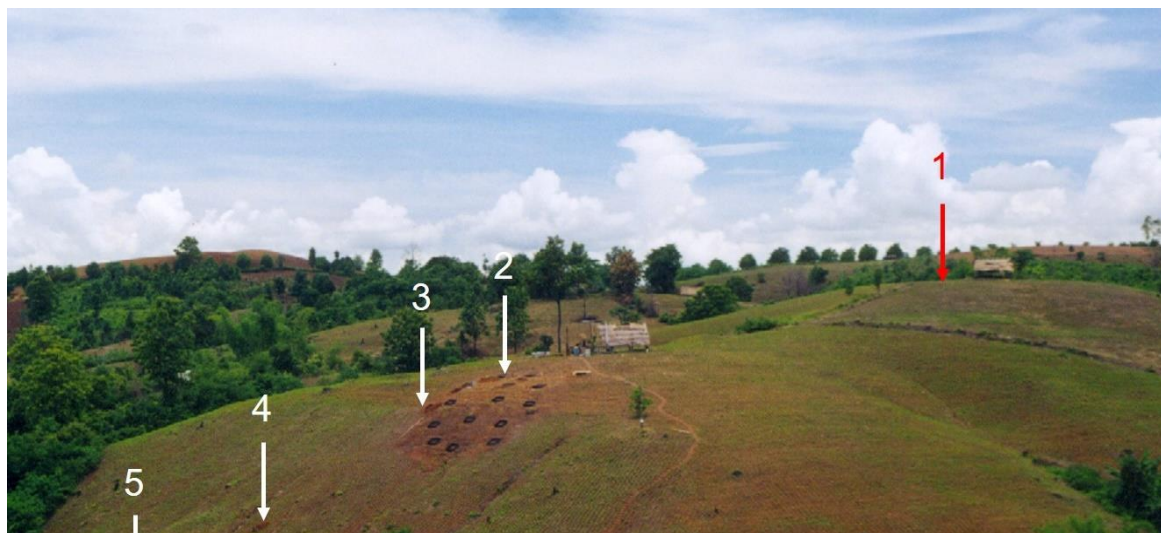
Fig. 5. Complete land clearing after fire. Signs of rill erosion



Fig. 6. Complete Land clearing with annual maize crop cycle during the rainy season

Profile 1 – Hypereutric Hyperskeletal **Leptosol** (Ochric)

Location: Cleared bare surface, plantation of mungbean, top of the hill, soil surface: 95% of gravels and stones, 20% of straw and vegetal debris, parent-rock: volcano-sedimentary schists, 440 m a.s.l., N 20°16'32" E 64°69'54"



Morphology:

- A** – 0–10 cm, humiferous horizon, loam, dark brown (7.5YR 3/3), soft, friable, structure very fine granular and subangular blocky, many very fine pores between aggregates, 50% of gravels and stones of weathered schists, many very fine roots, boundary regular and clear;
- BC** – 10–(30) cm, weathered rock and structural horizon BC, Layers of clayey material between layers of weathered schists; brown (7.5 YR 5/4), clay loam, many very fine pores.

Table 2. Texture

Horizon	Depth [cm]	Percentage of fractions (mm)						Textural class
		> 2.0	2.0-0.2	0.2-0.05	0.05-0.02	0.02-0.002	< 0.002	
A	0-10	48	36	7	5	27	25	L
BC	10-(30)	nm	34	5	5	28	27	CL

nm: non measured

Table 3. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH		P [g kg ⁻¹]	BD [g cm ⁻³]
					H ₂ O	KCl		
A	0-10	17.6	1.2	14.3	5.6	4.8	1.93	0.98
BC	10-(30)	nm	nm	nm	5.5	4.4	nm	nm

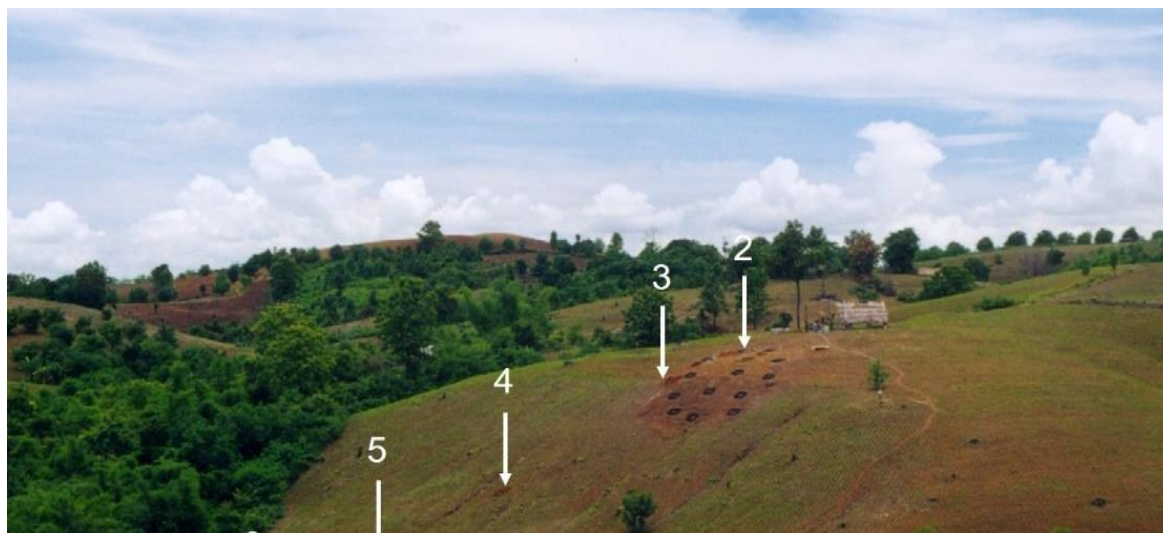
BD: bulk density

Table 4. Sorption properties

Horizon	Depth [cm]	Exchangeable cations (cmol ⁽⁺⁾ kg ⁻¹)						BS [%]
		Ca ⁺⁺	Mg ⁺⁺	K ⁺	Na ⁺	S (Sum of cations)	T [CEC]	
A	0-10	7.3	3.7	0.5	0.0	11.6	14.9	78
BC	10-30+	5.4	4.7	0.4	0.0	10.6	12.1	87

Profile 2 – Skeletic Rhodic Luvisol (Amphiloamic, Epieutric, Ochric)

Location: Cleared bare surface – plantation of mungbean, slope 25%, upper part of the hill, soil surface: 80% gravels and 10% stones, 10% of straw and vegetal debris, parent-rock: volcano-sedimentary schists, 427 m a.s.l., N 20°16'26"0 E 64°70'28"



Morphology:

- A** – 0–10 cm, humus horizon, loam, dark brown (7.5YR 3/2), soft, friable, structure very fine fine granular, many very fine pores between aggregates, 30% of gravels and stones of weathered schists, many very fine roots; boundary clear and smooth;
- Bt** – 10–27 cm, *argic* horizon, clay, yellowish red (5YR 4/6), firm, slightly plastic; structure fine subangular blocky, very fine pores between aggregates, 50% of gravels and stones of weathered schists, many very fine roots, boundary gradual and smooth;
- Bw** – 27–40 cm, structural horizon, silty clay loam, red (2.5YR 4/6), firm, plastic, structure fine subangular blocky, few fine pores between aggregates, 50% of gravels and stones of weathered schists, boundary gradual and wavy;
- BC** – 40–(60) cm, weathered rock and structural horizon – layers of clayey material between layers of weathered schists, texture of the clayey layers: clay loam, few very fine pores, Mn oxides on planar voids, surface of weathered schists.

Table 5. Texture

Horizon	Depth [cm]	Percentage of fractions (mm)						Textural class
		> 2.0	2.0-0.2	0.2-0.05	0.05-0.02	0.02-0.002	< 0.002	
A	0–10	55	28	8	5	28	32	L
Bt	10–27	nm	18	4	7	27	45	C
Bw	27–40	nm	12	8	8	34	38	SICL
BC	40–(60)	nm	12	7	8	43	30	CL

Table 6. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH		P [g kg ⁻¹]	BD [g cm ⁻³]
					H ₂ O	KCl		
A	0–10	20.4	1.2	16.5	6.3	5.6	2.01	0.77
Bt	10–27	9.7	0.7	14.3	6.2	5.2	0.71	nm
Bw	27–40	nm	nm	nm	6.1	4.5	nm	nm
BC	40–(60)	nm	nm	nm	6.1	3.8	nm	nm

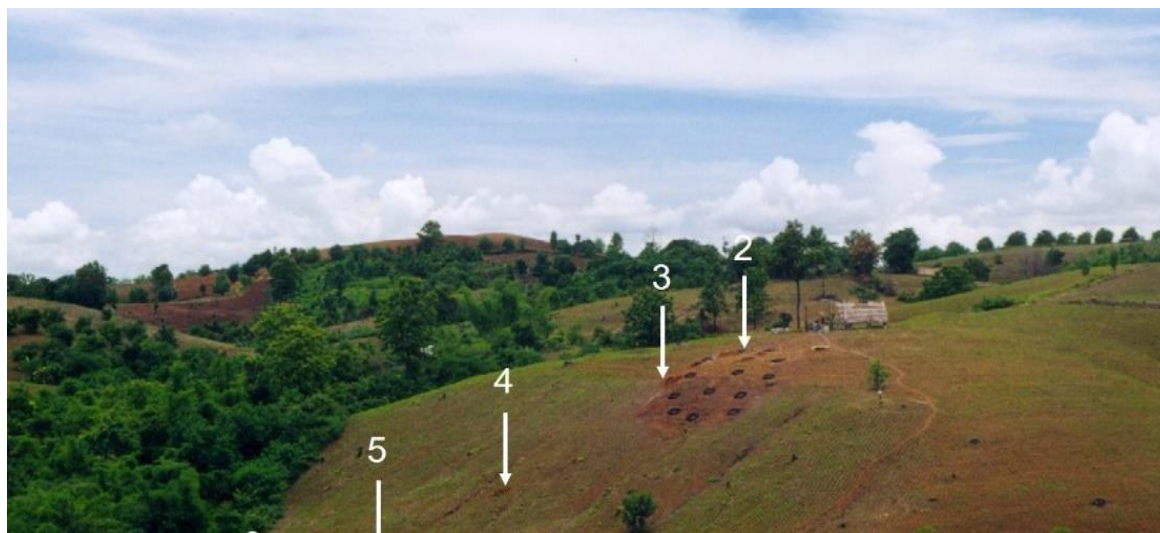
Table 7. Sorption properties

Horizon	Depth [cm]	Exchangeable cations (cmol ⁽⁺⁾ kg ⁻¹)						BS [%]
		Ca ⁺⁺	Mg ⁺⁺	K ⁺	Na ⁺	S (Sum of cations)	T [CEC]	
A	0–10	15.7	4.1	0.4	0.1	20.3	17.7	SAT
Bt	10–27	9.3	5.4	0.3	0.1	15.1	17.2	88
Bw	27–40	11.8	11.2	0.1	0.1	23.3	16.7	SAT
BC	40–(60)	17.8	15.6	0.1	0.3	33.7	11.9	SAT

SAT: saturated

Profile 3 – Skeletic Rhodic Luvisol (Amphiclayic, Epieutric, Ochric)

Location: Cleared bare surface – plantation of mungbean, slope 35%, upperpart of the slope, soil surface: 80% gravels and 10% stones, 10% of straw and vegetal debris, parent-rock: volcano-sedimentary schists, 425 m a.s.l., N 20°16'25"7 E 64°70'34"



Morphology:

- A** – 0–20 cm, humiferous horizon, loam, dark brown (7.5YR 3/2), soft, friable, structure very fine granular, many very fine pores between aggregates, 30% of gravels and stones of weathered schists, many very fine roots, boundary clear and smooth;
- Bt** – 20–35 cm, *argic* horizon, clay, yellowish red (5YR 4/6), firm, slightly plastic, structure fine subangular blocky, very fine pores between aggregates; 30% of gravels and stones of weathered schists, many very fine roots, boundary gradual and smooth;
- Bt2** – 35–70 cm, *argic* horizon, clay, yellowish red (5YR 4/6), firm, slightly plastic, structure fine subangular blocky, very fine pores between aggregates, 30% of gravels and stones of weathered schists, many very fine roots, boundary gradual and smooth;
- BC** – 70–(90) cm, weathered rock and structural horizon – layers of clayey material between layers of weathered schists, texture of the clayey layers: silty clay loam, few very fine pores, Mn oxides on planar voids, surface of weathered schists.

Table 8. Texture

Horizon	Depth [cm]	Percentage of fractions (mm)						Textural class
		> 2.0	2.0-0.2	0.2-0.05	0.05-0.02	0.02-0.002	< 0.002	
A	0–20	50	27	6	5	28	34	L
Bt	20–35	nm	18	4	8	27	43	C
Bw	35–70	nm	15	4	7	30	44	C
BC	70–(90)	nm	8	2	9	43	38	SiCL

Table 9. Chemical and physicochemical properties

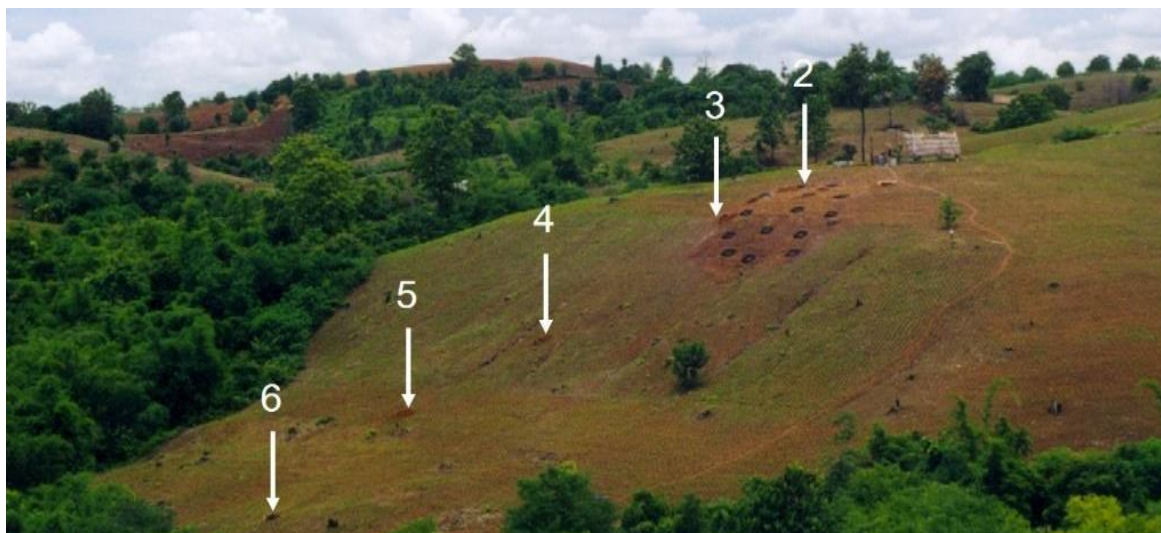
Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH		P [g kg ⁻¹]	BD [g cm ⁻³]
					H ₂ O	KCl		
A	0–20	21.9	1.6	13.5	7	6.2	1.61	0.74
Bt	20–35	13.1	0.8	16.8	6	5	0.78	nm
Bw	35–70	nm	nm	nm	6	4.7	nm	nm
BC	70–(90)	nm	nm	nm	5.9	4.4	nm	nm

Table 10. Sorption properties

Horizon	Depth [cm]	Exchangeable cations (cmol ⁽⁺⁾ kg ⁻¹)						BS [%]
		Ca ⁺⁺	Mg ⁺⁺	K ⁺	Na ⁺	S (Sum of cations)	T [CEC]	
A	0–20	17.2	4.0	0.3	0.2	21.7	20.2	SAT
Bt	20–35	11.5	4.9	0.2	0.1	16.7	19.2	87
Bw	35–70	8.7	6.6	0.2	0.1	15.6	18.2	86
BC	70–(90)	13.1	10.0	0.1	0.1	23.4	20.2	SAT

Profile 4 – Skeletic Rhodic Luvisol (Clayic, Epieutric, Ochric)

Location: Cleared bare surface – plantation of mungbean, steeper part of the slope – 45%, soil surface: 80% gravels and 10% stones, 10% of straw and vegetal debris; parent-rock: volcano-sedimentary schists, 421 m a.s.l., N 20°16'25"4 E 64°70'42"



Morphology:

- A** – 0–10 cm, humiferous horizon; clay, dark brown (7.5YR 3/3), soft, friable, structure very fine fine granular; many very fine pores between aggregates, strong biologic activity, 20% of gravels and stones of weathered schists, many very fine roots, boundary clear and smooth;
- Bw** – 10–30 cm, *cambic* horizon, clay, dark red (2.5YR 3/6) firm, slightly plastic, structure fine subangular blocky, many very fine pores between aggregates, many fine tubular pores, 20% of gravels and stones of weathered schists, many very fine roots, boundary gradual and smooth;
- Bt** – 30–45 cm, *argic* horizon, clay, red (2.5YR 4/6), firm, plastic, structure fine subangular blocky, few fine pores between aggregates, 30–35% of gravels and stones of weathered schists; boundary gradual and smooth;
- Bt2** – 45–60 cm, 30–45 cm, *argic* horizon, clay, red (2.5YR 4/6), firm, plastic, structure fine subangular blocky, few fine pores between aggregates, few vesicular pores; 40–50% of gravels and many stones of weathered schists; boundary clear and smooth;
- BC** – 60–(90) cm, transitional horizon; clay, brown (7.5YR 5/4), firm, plastic, structure medium subangular blocky, few fine pores between aggregates, common medium vesicular pores, coarse elements: 5–10% of gravels and stones of weathered schists, Mn oxides on planar voids, surface of weathered schists.

Table 11. Texture

Horizon	Depth [cm]	Percentage of fractions (mm)						Textural class
		> 2.0	2.0-0.2	0.2-0.05	0.05-0.02	0.02-0.002	< 0.002	
A	0–10	47	19	5	3	23	51	C
Bw	10–35	nm	9	1	7	24	58	C
Bt	35–45	nm	8	2	6	19	66	C
Bt2	45–60	nm	9	2	4	23	63	C
BC	60–(90)	nm	7	2	6	28	57	C

Table 12. Chemical and physicochemical properties

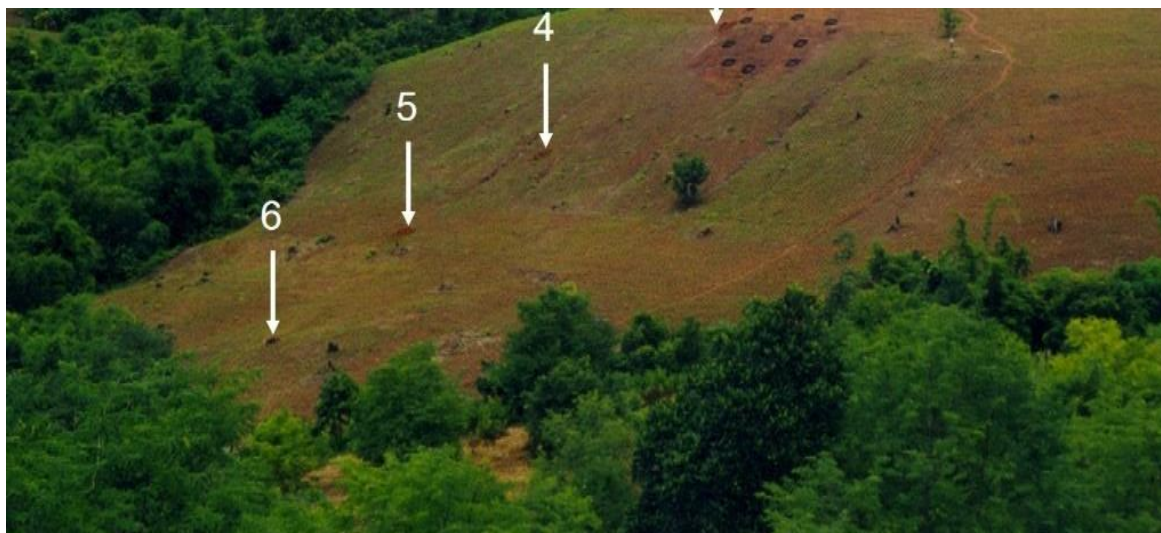
Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH		P [g kg ⁻¹]	BD [g cm ⁻³]
					H ₂ O	KCl		
A	0–10	26.6	1.8	14.7	6.2	5.5	0.87	0.75
Bw	10–35	11.2	0.8	13.5	5.8	5.1	0.55	nm
Bt	35–45	nm	nm	nm	5.4	4.6	nm	nm
Bt2	45–60	nm	nm	nm	5.3	4.5	nm	nm
BC	60–(90)	nm	nm	nm	5.4	4.4	nm	nm

Table 13. Sorption properties

Horizon	Depth [cm]	Exchangeable cations (cmol ⁽⁺⁾ kg ⁻¹)						BS [%]
		Ca ⁺⁺	Mg ⁺⁺	K ⁺	Na ⁺	S (Sum of cations)	T [CEC]	
A	0–10	18.2	5.0	0.3	0.1	23.7	24.2	98
Bw	10–35	7.2	4.7	0.2	0.1	12.1	17.2	71
Bt1	35–45	8.7	4.5	0.2	0.1	13.5	15.2	89
Bt2	45–60	7.7	5.5	0.3	0.1	13.6	17.9	76
BC	60–(90)	18.2	5.0	0.3	0.1	23.7	24.2	98

Profile 5 – Hypereutric Skeletic Rhodic **Cambisol** (Clayic, Ochric)

Location: Cleared bare surface – plantation of mungbean, slope 25% decreasing, soil surface: little stairs 5 cm high, 40 cm wide, 70% gravels and 10% stones, 10% of straw and vegetal debris, parent-rock: volcano-sedimentary schists, 418 m a.s.l., N 20°16'25''O E 64°70'51''



Morphology:

- A** – 0–10 cm, humiferous horizon, clay, dark brown (7.5YR 3/3), soft, friable, structure very fine granular, many very fine pores between aggregates, big vesicular pores, 20% of gravels and stones of weathered schists, many very fine roots, boundary clear and irregular;
- Bw** – 10–40 cm, *cambic* horizon; clay, reddish brown (5YR 4/4), firm, slightly plastic, structure fine subangular blocky, many very fine pores between aggregates, big vesicular pores, 20% of gravels and stones of weathered schists, many very fine roots, boundary gradual and smooth;
- Bw2** – 40–60 cm, *cambic* horizon; clay, reddish brown (5YR 4/4), firm, slightly plastic, structure medium subangular blocky, few fine pores between aggregates, 20% of gravels and stones of weathered schists, boundary diffuse and smooth;
- Bw3** – 60–(80) cm, *cambic* horizon; clay, red (2.5YR 4/6), distinct fine light yellowish brown mottles (10YR 6/4), black dendrites of Mn; firm, plastic, structure medium subangular blocky, few fine pores between aggregates, 20% of gravels and stones of weathered schists.

Table 14. Texture

Horizon	Depth [cm]	Percentage of fractions (mm)						Textural class
		> 2.0	2.0-0.2	0.2-0.05	0.05-0.02	0.02-0.002	< 0.002	
A	0-10	39	15	7	8	24	47	C
Bw	10-40	nm	8	5	6	20	61	C
Bw2	40-60	nm	8	4	4	20	63	C
Bw3	60-(80)	nm	6	4	5	18	67	C

Table 15. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH		P [g kg ⁻¹]	BD [g cm ⁻³]
					H ₂ O	KCl		
A	0-10	28.5	1.8	15.5	6.2	5.5	0.71	0.8
Bw	10-40	12.2	0.9	13.9	5.5	4.5	0.41	nm
Bw2	40-60	nm	nm	nm	5.6	4.5	nm	nm
Bw3	60-(80)	0.77	0.07	11	5.5	4.3	nm	nm

Table 16. Sorption properties

Horizon	Depth [cm]	Exchangeable cations (cmol ⁽⁺⁾ kg ⁻¹)						BS [%]
		Ca ⁺⁺	Mg ⁺⁺	K ⁺	Na ⁺	S (Sum of cations)	T [CEC]	
A	0-10	18.2	5.0	0.3	0.1	23.7	24.2	98
Bw	10-40	7.2	4.7	0.2	0.1	12.1	17.2	71
Bw2	40-60	8.7	4.5	0.2	0.1	13.5	15.2	89
Bw3	60-(80)	7.7	5.5	0.3	0.1	13.6	17.9	76

Profile 6 – Hypereutric Skeletic Rhodic **Cambisol** (Clayic, Colluvic, Ochric)

Location: Cleared bare surface – plantation of mungbean; slope 10% decreasing, footslope; soil surface: little stairs 5 cm high, 40 cm wide; 5% gravels and stones; in some colluvial places, gravel and stones are concentrated and cover 80–90% of soil surface in depleted zones, in small 5 cm high and 20 cm circumference, gravel and stones cover less than 30%; in other places, gravel and stones cover less than 10%; parent-rock: volcano-sedimentary schists, 412 m a.s.l., N - 20°16'23"9 E 64°70'76"



Morphology:

- A** – 0–15 cm, humiferous horizon, clay, dark brown (7.5YR 3/2), soft, friable, structure very fine granular, many very fine pores between aggregates, big vesicular pores, <5% of gravels and stones of weathered schists, many very fine roots, boundary clear and smooth;
- Bw** – 15–30 cm, *cambic* horizon; clay, dark brown (7YR 3/3), firm, slightly plastic, structure fine subangular blocky, many very fine pores between aggregates, big vesicular pores, <5% of gravels and stones of weathered schists, many very fine roots, boundary gradual and smooth;
- Bw2** – 30–(75) cm, *cambic* horizon; clay, dark reddish brown (5YR 3/3), firm, slightly plastic, structure medium subangular blocky, few fine pores between aggregates, 20% of gravels and stones of weathered schists, many very fine roots.

Table 17. Texture

Horizon	Depth [cm]	Percentage of fractions (mm)						Textural class
		> 2.0	2.0-0.2	0.2-0.05	0.05-0.02	0.02-0.002	< 0.002	
A	0–15	37	18	8	6	22	47	C
Bw	15–30	nm	16	7	8	23	46	C
Bw2	30–(75)	nm	17	9	7	22	45	C

Table 18. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg ⁻¹]	Nt [g·kg ⁻¹]	C/N	pH		p [g kg ⁻¹]	BD [g cm ⁻³]
					H ₂ O	KCl		
A	0–15	25.5	1.5	16.8	6.2	5.3	0.42	0.7
Bw	15–30	18.6	1.1	17	5.3	4.3	0.41	nm
Bw2	30–(75)	nm	nm	nm	5.4	4.3	nm	nm

Table 19. Sorption properties

Horizon	Depth [cm]	Exchangeable cations (cmol ⁽⁺⁾ kg ⁻¹)						BS [%]
		Ca ⁺⁺	Mg ⁺⁺	K ⁺	Na ⁺	S (Sum of cations)	T [CEC]	
A	0–15	17.0	5.2	0.3	0.1	22.6	23.5	96
Bw	15–30	6.9	4.3	0.3	0.1	11.6	18.9	61
Bw2	30–(75)	7.0	4.9	0.3	0.2	12.4	17.7	70

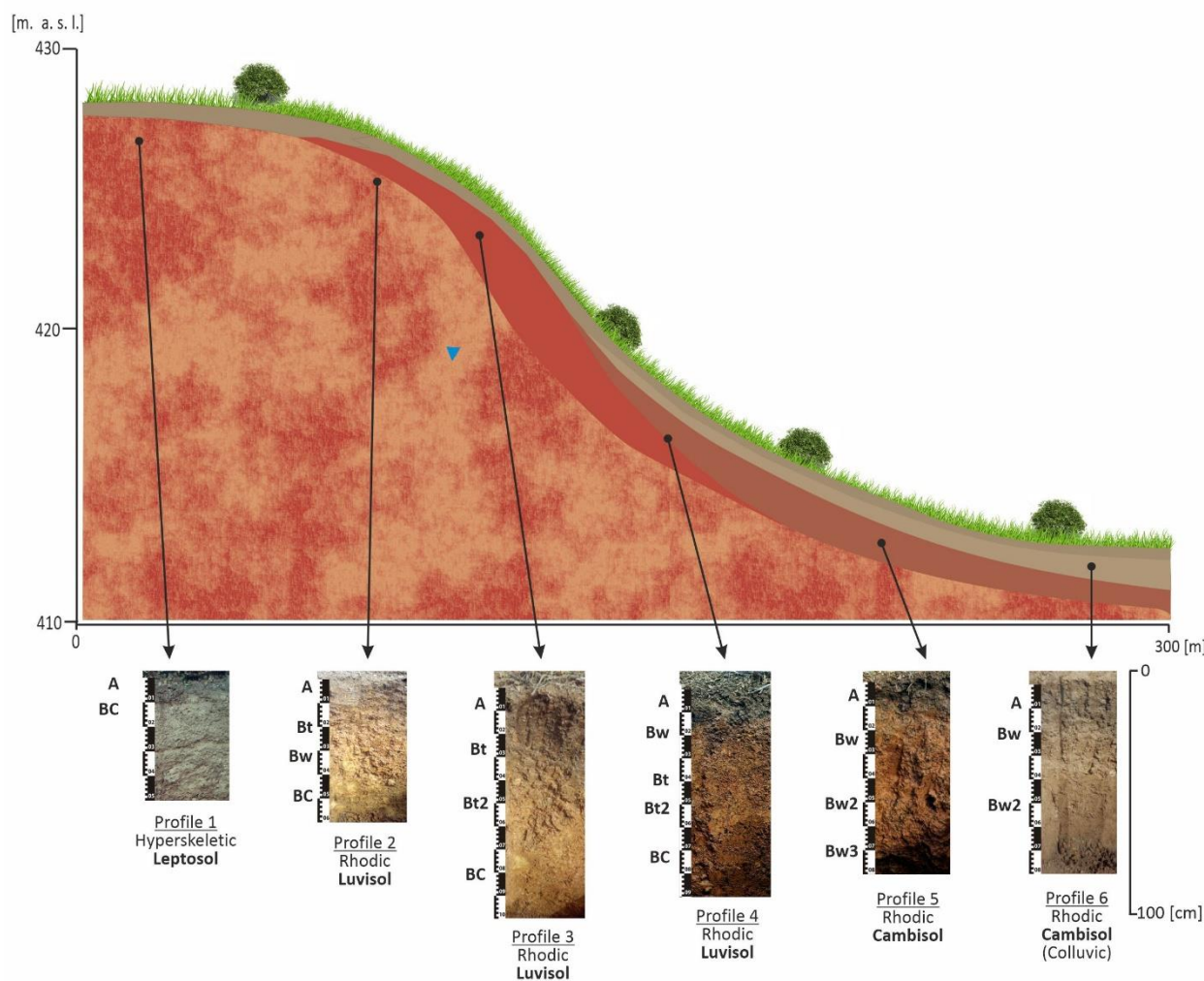


Fig. 7. Representative toposequence on Huay Ma Nai catchment, position of the profiles

Soil genesis and systematic position

Soils are shallow (**Leptosols**) at the top of the hills and below the sub-horizontal flat surfaces. They are derived from schists and shales and are very gravelly (0.2–2cm size of lithorelics of schists), with hyper-skeletal features (**Hyperskeletal**) at the top to skeletal features downstream. From upstream (Profiles 1, 2, 3), the gravel content (by weight) in the topsoil is $\approx 50\%$ and it decreases to 39 and 37% in Profiles 5 and 6 respectively. The bulk density of the fine earth of the surface horizon is therefore very low: 0.98 in Profile 1 and it fluctuates from 0.80 to 0.70 in the lower part of the sequence.

Soils are loamy on the surface in the upper part of the sequence (Profile 1, 2 and 3) in which they are very porous with a fine granular structure and are 0.5–0.7m deep and become deeper and much more clayey ($> 45\%$ clay – **Clayic**) in the steep slope (Profile 4 and 5). They get enriched in clay in depth and they develop an *argic* horizon with higher clay content in the convex part of the slope (**Luvisols** – Profile 2, 3 4). The humus horizon is very shallow, between 10 and 20 cm and the C content is never $>3\%$ (30g kg^{-1}) with a slight increase of soil organic carbon from upstream to downstream. The color of A in dry state is not dark enough for diagnostic horizons – only qualifier **Ochric** can express accumulation of humus. They all have a granular structure. All the soils of the toposequence became reddish in color in the Bt or Bw horizon (**Rhodic**), with enrichment in free iron

for Profile 2 and Profile 4. With the increase of clay content, the structure becomes more subangular blocky.

The soil pH is always >5.0 and >6.0 in all top-horizons except for the eroded Profile 1. All horizons have a rate of exchangeable cations $>50\%$ (*Eutric* and *Hypereutric* qualifiers), some of them are saturated indicating the likely presence of dolomite. In these levels, the soil pH is >6.5 . The CEC related to 100% clay content is $>24\text{cmol (+) kg}^{-1}$ indicating the presence of high activity clays.

Soil sequence

The soil toposequence is representative of the half orange geomorphology. The slope is facing East and is 200 m long with difference of altitude of 20 m. A set of 6 profiles has been implemented in the toposequence. Two of them – Profile 2 and 3 – are in the convex section of the slope on both extremities of the rainfall simulation plots instrumented by Janeau et al. (2003) (Figure 7). The top of the hill has a relatively long sub-horizontal surface. These flat surfaces are generally connected with other hills, used for road network and occupied by some wood constructions.

All soils from the upper part of the toposequence show evidence of strong erosion features with a strong decrease of clay content in the surface horizon. At the base of the toposequence, the profile YOM 6 is typically colluvial with constant loamy texture, more homogenous and with more brownish color and lower free iron content (40 g kg^{-1}) when its rate is >60 in all other profiles.

Total sediment yield was already high with soya bean/mung bean ($4.9\text{ Mg ha}^{-1} \cdot \text{year}^{-1}$), and even under tamarind ($3.0\text{ Mg ha}^{-1} \cdot \text{year}^{-1}$); however, it more than doubled following land use changes with complete land clearing and maize plantations ($11.7\text{ Mg ha}^{-1} \cdot \text{year}^{-1}$) (Janeau et al., 2003). The coarse sediments in the Mae Tang reservoir increased from $8.2\text{ Mg ha}^{-1} \cdot \text{year}^{-1}$ between the period 1995–2004 to $37.7\text{ Mg ha}^{-1} \cdot \text{year}^{-1}$ for the period 2004–2006 (Thothong et al., 2006). The erosion is maximal at the beginning of the rainy season when after tillage the soil has no vegetal soil cover.

A set of 15 erosion plots of 1 m^2 were established between profiles 2 and 3. The slope gradient range was divided into four equal intervals, so that five levels of slope gradients 20, 30, 40, 50 and 60% were tested. Three replications were implemented so that 15 plots were prepared. These plots were located at the same place that the rainfall simulation plots by Janeau et al. (2003) described. These plots were tilled such as the tilled fields of mung bean and maintained bare during the experiment. After a complete rainy season of 790 mm between 30/06 to 23/09/2001, the results were following (Figure 8):

- the infiltration rate increased with the slope value from 35 (20% slope value) to 60% (65% slope value).
- The soil loss by detachment increased rapidly from 4.5 kg to a maximal value of 7.0 kg for a slope of 40% and decreased to less than 3 kg for a slope value of 60%.

These results confirm the result of the rainfall simulation with an increase of infiltration (regular decrease of runoff) with slope value. They also validate the measurements of soil detachment for the two successive simulated rains of 60 and 120 mm h^{-1} intensities. These results were confirmed by Ribolzi et al. (2011), by comparing through rainfall simulation in Laos, the runoff and detachment rate of 2 plots with 2 gradients of slope of 35 and 70%, showing much higher infiltration rate and less detachment for the latter.

The results are a combination of different factors:

- With an increase of slope value, the kinetic energy of raindrops referred to 1 m^2 horizontal plot is lower with increasing slope value according to the increase of the surface of contact.

- With the increase of slope value, the degree of soil crusting (embedded gravel crust) is decreasing, and therefore favors soil infiltration rate.

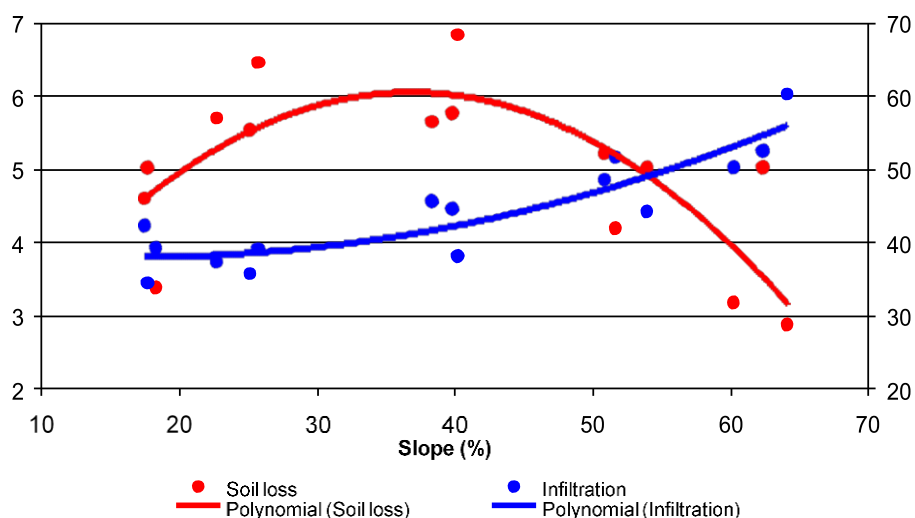


Fig. 8. Runoff and soil detachment below natural rain (790mm) between 30/06 to 23/09/2001 in 15 erosion 1m² plot.

- If the kinetic energy of runoff is increasing with slope value, with the increase of soil infiltration rate, the global kinetic energy reaches a maximum detachment rate for a slope of 40 %; then, with steeper slopes value, the strong decrease of runoff rate leads to a decrease of detachment rate.
- With higher detachment rate on areas with low slope values located upstream, the mineralogical composition of the fine earth is changing. The occurrence of vermiculite and illite associated with kaolinite is important in the weathered parent rock, while the exclusive soil clay type in the not eroded topsoil of Profile 4 Luvisol is kaolinite (Figure 9). This occurrence of illite and vermiculite decreases from the topsoil of Profile 1 located upstream with 5% slope to Profile 4 with 45% slope. However, the soil aggregates stability is lower with high contents of illite and vermiculite compared to those with only kaolinite because of higher swelling properties of illite and vermiculite (Denef et al., 2002). Therefore, in the plots located upstream, the complete erosion of kaolinite rich horizons generates positive feedback on soil erodibility: the more the soil is eroded, the more the topsoil is enriched in illite and vermiculite, and the more it is erodible.

The Mae Thang toposequence Leptosol-Luvisol-Cambisol is representative of a landscape of small hills in northern Thailand. This landscape is submitted to severe deforestation and intensive annual cultivation. Surprisingly, the steep slopes are less exposed to soil erosion according to a higher structure stability, lower crusting, and higher infiltration rate. Therefore, soils in the upper part of the toposequence are very shallow and they become deeper with clay leaching in the steep slope and colluvial accumulation in the lower part of the sequence. The synthetic results of Valentin et al. (2008) pointed out that the development of land clearing with annual crop was the key factor for the increase of erosion rate in 27 watersheds in Southeast Asia, while the slope value was not a significant factor controlling the erosion rate.

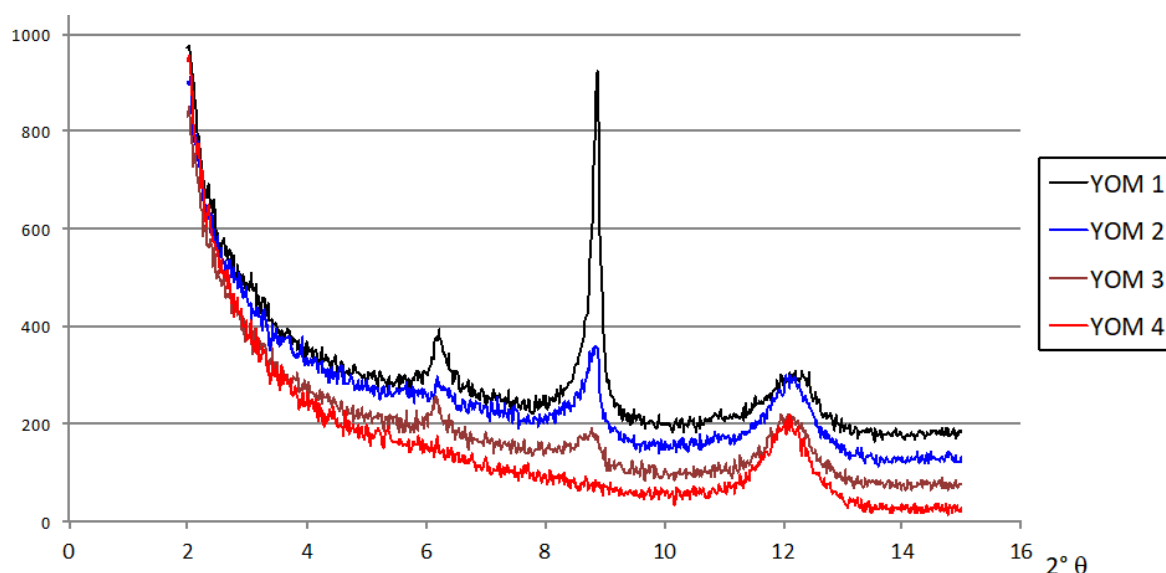


Figure 19. XRD determination of the surface horizon of the convex part of the toposequence related to the rainfall simulation (Janeau et al., 2003).

The relatively high content in nutrients and the high degree of saturation in cations give these soils a relatively high potential of fertility encouraging intensive cultivation. However, the very high erosion rate will rapidly generate limitations in the soil depth and potential limits in the soil water reserve emphasized with climate change.

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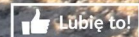
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