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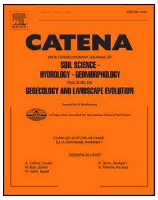

Influence of aeolian deposits on the pedogenesis process of the Costa da Morte soils (NW Spain)

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ABSTRACT

Aeolian deposition in coastal system can modify pedogenic processes or provide parent material for new pedogenesis cycles. In Galicia region (NW Spain), as in other regions of the world, the pedogenic processes associated with aeolian deposits under coastal conditions are little know. These processes are also conditioned by the development time from the formation of the sedimentary deposits, which in the case of the Galician coast is highly variable. The main objective was to identify the effect of aeolian deposits on coastal soils, through the characterization and classification of several soil profiles, and the identification of the main pedogenic process that contributed to their formation or modification. The studied soils presented one and two pedogenic cycles as well as in each one different level of pedogenic evolution. The soils with one pedogenic cycle were Endoleptic Umbrisol (Loamic, Hyperdystric, Hyperhumic, Pachic) from Xuxurantes and Haplic Umbrisol (Arenic, Humic, Pachic) from Cabo Vilano. The soils with two cycles were found in Muxia (Aeolic Calcaric Arenosol (Ochric-Novic) over Haplic Phaeozems (Endoloamic)) and Cementerio de los Ingleses (Albic Umbric Podzol (Pantoarenic)). This last type of soil constituted one more step in the evolution of aeolian deposits (first cycle of pedogenesis in the Muxia profile). Thus, changes in the pedogenesis processes and mechanisms were conditioned by the presence of a superficial aeolian deposition as well as the proximity to the coast and determine a chronosequence of the processes in the aeolian sediments.

1. Introduction

Aeolian deposition processes are mechanisms that occur in many areas of the Earth, from coastal, mountainous, or desert systems, among others, and that can modify the pedogenic processes or provide parent material for new pedogenesis cycles (Bäumler, 2001; D'Amico et al., 2023; Jahn, 2010; Monteiro et al., 2015; Mokma et al., 2004; Pelka-Gosciniak, 2013; Sauer et al., 2008; Singleton and Lavkulich, 1987; Thompson, 1981; Varga et al., 2016). In the Costa da Morte (NW of Spain, Galicia region) coexists polycyclic soils and paleosols, developed on igneous and metamorphic materials, with in situ parental rock alteration and a series of superficial sedimentary processes related to geomorphological processes of the coastal areas. These soils can contribute to the historical reconstruction of the sequence and scope of the different pedogenic processes, being processes that occur in other regions of the word and that there is a lack of information to understand their evolutionary sequence for the different regions and the influence of environmental conditions on the speed of edaphic process. In fact, some studies (Moares, 1997; Pérez Alberti et al, 2011) focused on paleosols have related the evolution of slopes of cliffs and beaches, where colluvial materials is accumulated, with periglacial processes. Recent works such as those by Arce-Chamorro et al. (2022) determine that the sedimentary deposits of the Galician coast present a high temporal variability in their formation, dating back between 166 and 5 ka. Similar studies also provided not only analogous dates for different sedimentary environments in Galician coast, but their relationship with the origin of the sands, their composition and dominant granulometry fractions (Arribas et al., 2010). Although it is important to know the pedogenic processes linked to cold conditions and from different periods of the last ice age, it is essential improve the knowledge about the most recent processes associated to alluvial, colluvial and aeolian materials deposited on soils and previous surfaces, in the Holocene.

The main objective of this study was to identify the effect of aeolian deposits on soils in coast environments. For this purpose, the following

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specific objectives were established: i) to characterize and classify the profiles of the different soils affected by aeolian deposition and, ii) to identify the main edaphic processes that contributed to their pedogenesis.

2. Materials and methods

2.1. Study area and sampling

The study area, called "Costa da Morte", is located on the NW coast of Spain, in Galicia region. Geomorphologically, the Galician coast is complex being constitute by beaches, rocky cliffs, and deep embayment's called Rias (Arce-Chamorro et al., 2022; Arribas et al., 2010; Otero and Macias, 2001). The coast is an abrupt mesotidal wave-dominated coast, where sedimentation shows a discontinuous distribution. The dominant geological materials are Hercynian magmatic and granitic rocks (granitic materials, two-mica granites, and biotitic granodiorites), whose main constituents are quartz, potassium feldspar, plagioclase and isolated biotite and muscovite (IGME, 1981).

The climate is oceanic with mild temperatures throughout the year (annual average of 15 °C, and a range of values from 12 to 14 °C in winter and to more than 20 °C in the summer), and the accumulated annual precipitation is 1200–1400 mm, determining a hot-humid ombrothermal regime (Martínez Cortizas et al, 1999). The distribution of precipitation in the different months of the year was grouped into three ranges: 35–70 mm from May to September; 135–160 mm from October to January and ~ 100 mm from February to April.

The soil sampling points were selected in an attempt to capture the different environments present in the study area, with and without the apparent influence of aeolian sediments. For this purpose, four soil profiles were selected and described along the coast: 1. Xuxarantes (UTM Coordinates, 29T 482612 4769844); 2. Cabo Vilano (29T 484711 4778168), 3. Muxía (29T 482539 4771792) and 4. Cementerio de los Ingleses (29T 486230 4781188) (Fig. 1). The soil profile description was done in accordance with the soil description guide, from its location to the description of the identified horizons (FAO, 2009). After the description of the profile, soil samples were collected from the several differentiated horizons for posterior physicochemical analysis.

2.2. Analytical methods

For the classification of the sampled soils, a set of analytical determinations were made in the solid fraction and equilibrium soil solution. The soil samples were air dried, sieved to < 2 mm and the following parameters were determined: particle size distribution by pipette method (Gee and Bauder, 1986) and previous oxidation of soil organic matter (OM), pH in water (1:2.5 $m:V$) (Guitián and Carballas, 1976), pH in KCl (Urrutia et al., 1989), electrical conductivity in the saturation extract (EC), total C and N using the LECO TruSpec CHN autoanalyzer, total S using LECO SC-144DR, effective cation exchange capacity (CEC) extracted with NH_4Cl (modified method of Peech et al., 1947), selective forms of Fe and Al in aqueous solutions of sodium pyrophosphate (p) (Bascomb, 1968), ammonium oxalate (o) (Blakemore, 1983) and dithionite-sodium citrate (d) (Holmgren, 1967), as well as concentration of oxidizable carbon (Co) and OM (Sauerlandt method), labile carbon (Cp), available P (Olsen et al., 1954) and carbonates by calcimetry

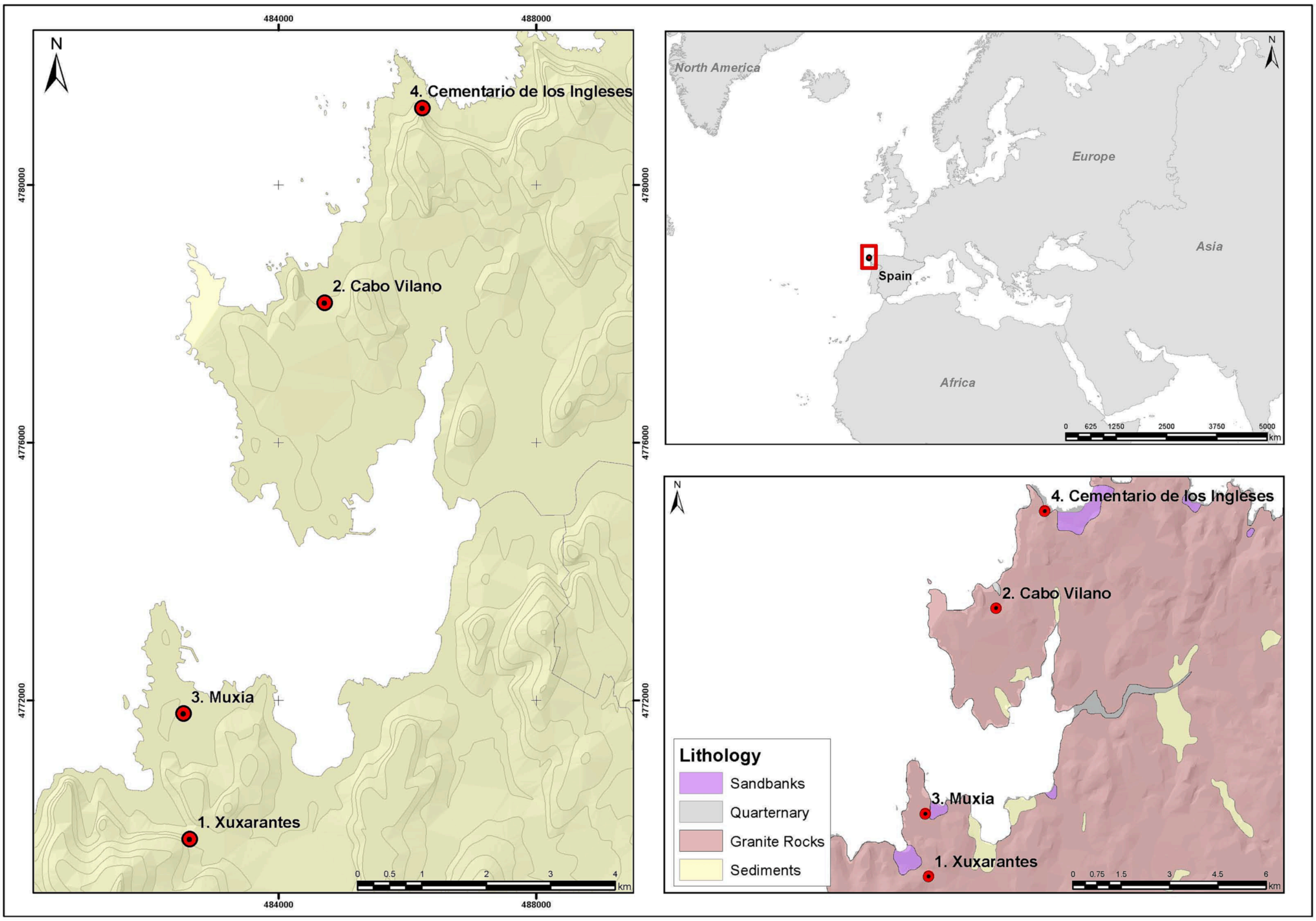

Fig. 1. Location of soil profiles and lithology in the study area.

(Guitián and Carballas, 1976). The pseudo-total contents of the elements were obtained by *aqua regia* extraction (3:1 HNO_3:HCl) in ETHOS PLUS microwave attack. Total P was determined by spectrophotometry UV–VIS (Jasco V-630 equipment), while the other elements were analyzed by flame atomic absorption spectroscopy (Perkin Elmer 1100B). The concentration of chlorides, nitrates and sulfates was measured by ion chromatography (Dionex 4500i series) and fluorides were determined with a METROHM 692 pH/ION METER selective electrode. Ammonium was analyzed by method n° FLW-NH3-04 in a continuous flow analyzer (third generation continuous flows analyzer 2000, Systea).

The contents of elements in the available fraction, extracted in water (1:20 m:*V*) were obtained from an equilibrium soil solution (Buján et al., 2010), and then the cations and anions were determined by the same methodologies previously indicated. These concentrations were used for the thermodynamic evaluation, namely speciation of existing species and their activity, in PHREEQC program (Parkhurst and Appelo, 2013).

The characteristics and properties of the soil samples allowed an adequate identification of the horizons and classification of the soils according to the World Reference Base of Soil system (IUSS Working Group WRB, 2022).

3. Results

The field information on the general conditions and description of the horizons from four profiles are presented in Supplementary Material (Table S1). The results are shown for each soil profile evaluated.

3.1. Soil profile 1. Xuxarantes

In soil profile from Xuxurantes, a single cycle of pedogenesis was identified with a superficial horizon A, up to a depth of 80–105 cm, and a clear and abrupt limit on the parent material (Fig. 2). The soil is located a foot slope, with a straight form and class 6 of slope gradient. There showed a surface without rock outcrops and coarse fragments. The main vegetation is a plantation of *Eucalyptus globulus* combined with a natural understory of *Ulex europaeus* L. and *Pteridium aquilinum* (L.) Kuhn (Table S1).

The superficial mineral horizon presented a color very dark brown (10YR2/2) and dark brown (10YR3/3) under wet and dry conditions, respectively (Table S1). This soil presented acid reaction with a predominance of negative change and low EC (Table 1). The OM content was high (131.5 g/kg) with 79 % of the total C as labile forms (C_p: 60.6 g/kg) and 20 % as more stable carbon (C_o = 15.40 g/kg). The presence of inorganic or recalcitrant forms of C was low (<1 g/kg), representing < 1% of total C (Table 1).

The CEC was low, being the exchange complex dominated by Al (80 % of the total CEC; Table 2). In the selective extractions of Fe and Al, a predominance of non-crystalline forms was observed, with a high oxalate/dithionite ratio (0.8 and 1, respectively), mainly associated with organometallic complexes (Table 2). The texture was sandy loam (Table 2) and crumbly structure. The highest pseudo-total contents were obtained for Al and Fe (Table 3).

Fig. 2. Soil profile from Xuxarantes.

3.2. Soil profile 2. Cabo Vilano

The soil profile from Cabo Vilano is a soil development on granitic materials with a single cycle of pedogenesis (Fig. 3). The soil profile is characterized by four horizons and a greater edaphic development compared to soil from Xuxurantes. The soil is located on a foot slope, with a straight form and class 4 of slope gradient. It showed a surface without rock outcrops and coarse fragments. The main vegetation is a plantation of *Pinus radiata* D. Don combined with the same natural understory of Xuxurantes, *U. europaeus* and *P. aquilinum*.

This soil presented a slightly acidic reaction (Table 1). The OM content varies between 61.4 and 54.5 g/kg in the superficial horizon (A1 and A2) and decreases progressively with the depth up to 4.5 g/kg in the last horizon, saprolite (C) (Table 1). This OM showed a tendency to humification in the superficial horizons, because was obtained a Co/N ratio between 16.95 and 21 derived from the low N contents. In the cambic horizon of subsurface alteration (B_w), this Co/N ratio decreases to values of 10.5. Another characteristic common to all the horizons of this profile was the predominance, in more than 70 %, of active or humified forms of carbon, obtained from the relationship between the C in pyrophosphate (C_p) and total C. For the other forms of carbon, the content of non-oxidizable carbon (C_{no}) of the A2 horizon stood out (2.8 g/kg, corresponding to 8.5 % of the total C) due to the highest value in

Table 1

Main physicochemical characteristics of the studied soils. pHw: Soil reaction in water; EC: Electrical Conductivity in the saturation extract; total contents of N, S and C; Co: oxidable C; Cp: labile C; C-CO3: C in carbonates; P Olsen: available P; LD: Detection limit.

Profile	Hor.	Depth (cm)	pHw –	pH KCl –	EC dS/m	Total N g/kg	Total S g/kg	Total C g/kg	Co g/kg	Cp g/kg	C-CO3 g/kg	P Olsen mg/kg
Xuxarantes	A	0–80 (105)	4.63	3.75	0.101	5.3	0.3	76.3	76.0	60.6	<1	5.05
Cabo Vilano	A1	0–30	5.06	3.85	0.073	2.12	<LD	35.6	35.2	28.5	<1	1.31
	A2	30–60	5.27	4.4	0.050	1.54	<LD	31.5	28.8	27.3	<1	<0.33
	Bw	60–70	5.52	4.21	0.039	0.48	<LD	5.20	5.00	4.80	<1	<0.33
	C	> 70	5.88	4.24	0.030	0.08	<LD	2.60	2.20	1.80	<1	<0.33
Muxia	A	0–40	8.77	8.38	0.082	0.90	<LD	55.1	5.50	1.20	50.7	0.54
	C	> 40	8.82	8.63	0.067	0.35	<LD	53.6	4.30	0.00	51.4	<0.33
	2Ab1	25–52	8.27	7.54	0.080	1.72	<LD	23.9	21.1	9.70	<1	13.18
	2Ab2	52–97	8.34	7.70	0.061	0.60	<LD	7.20	7.00	5.50	<1	3.74
	2Bwb1	97–124	8.23	7.61	0.077	0.85	<LD	13.6	12.9	9.40	<1	4.71
	2Bwb2	124–184	8.12	7.52	0.087	0.55	<LD	8.00	7.60	0.00	<1	6.50
	2C	> 184	8.2	7.54	0.061	0.38	<LD	4.20	4.10	3.50	<1	4.86
Cementerio de los Ingleses	A1	0–20	5.47	4.08	0.090	1.50	<LD	28.4	26.8	12.1	1.50	1.92
	A2	20–60	4.95	3.39	0.045	0.51	<LD	15.4	14.9	9.70	<1	<0.33
	E	60–90	5.06	3.77	0.026	0.15	<LD	3.40	3.30	0.30	<1	<0.33
	Bhs	>90 - >200	5.92	4.40	0.045	0.48	<LD	8.10	8.00	5.10	<1	0.92
	Bhs2	> 200	5.34	4.33	0.056	0.71	<LD	17.0	15.3	14.9	<1	1.25

Table 2

Values of effective cation exchange capacity (CEC); selective forms of Fe and Al extracted with: (p): sodium pyrophosphate; (o): ammonium oxalate; (d): dithionite-sodium citrate, and granulometry in the studied soils.

Profile	Hor.	H	Al	Ca	Mg	Na	K	CEC	Fep	Feo	Fed	Alp	Alo	Ald	Sand	Slit	Clay
		Cmolc/kg							g/kg						%		
Xuxarantes	A	0.75	6.80	0.15	0.46	0.32	0.02	8.51	3.7	3.8	4.5	8.1	7.2	6.60	68.53	22.40	9.07
Cabo Vilano	A1	0.35	1.95	2.18	0.99	0.19	0.01	5.67	2.0	1.1	2.5	1.5	0.7	1.36	85.42	11.11	3.47
	A2	–	2.07	0.47	0.20	0.14	0.01	2.87	5.5	5.1	6.9	8.1	7.8	7.28	83.40	9.85	6.75
	Bw	–	1.27	0.41	0.53	0.13	0.01	2.35	3.0	1.6	8.1	4.7	1.9	2.60	82.08	9.00	8.92
	C	–	0.58	0.43	0.69	0.13	0.01	1.84	0.3	0.3	1.0	0.6	0.6	0.33	87.27	10.12	2.61
Muxia	A	–	<0.11	23.02	0.82	0.18	0.01	24.03	0.02	0.16	0.37	0.08	0.2	0.17	97.46	0.85	1.69
	C	–	<0.11	31.71	1.28	0.24	0.01	33.25	0.01	0.15	0.40	0.06	0.2	0.14	98.00	21.18	9.71
	2Ab1	–	<0.11	22.63	1.15	0.22	0.01	24.01	3.8	4.8	10.3	3.2	4.9	3.02	69.10	13.38	7.59
	2Ab2	–	<0.11	10.93	0.53	0.11	0.01	11.57	1.2	2.7	5.5	1.2	3.9	2.16	79.02	16.97	11.47
	2Bwb1	–	<0.11	17.12	0.82	0.14	0.01	18.09	1.9	4.4	6.7	1.6	6.1	2.78	71.55	18.89	10.69
	2Bwb2	–	<0.11	12.21	0.66	0.44	0.02	13.33	1.6	4.0	6.6	1.7	5.0	2.86	70.43	27.37	0.42
	2C	–	<0.11	8.95	0.53	0.15	0.01	9.64	0.7	1.9	5.6	1.9	4.3	1.96	72.21	21.18	9.71
Cementerio de los Ingleses	A1	0.22	0.21	2.76	1.12	0.32	0.02	4.64	0.19	0.22	0.44	0.27	0.26	0.33	95.43	2.66	1.91
	A2	0.56	1.08	0.44	0.26	0.15	0.01	2.50	0.11	0.13	0.24	0.38	0.31	0.38	96.93	1.97	1.10
	E	0.08	0.42	0.06	0.03	0.06	0.00	0.66	0.055	0.052	0.18	0.20	0.16	0.23	99.28	0.36	0.36
	Bhs	–	0.87	0.23	0.13	0.14	0.01	1.37	0.75	0.76	0.85	1.4	1.5	1.77	99.35	0.21	0.44
	Bhs2	–	1.51	0.26	0.20	0.13	0.01	2.11	0.11	0.94	1.04	4.3	3.8	3.80	98.91	0.11	0.98

Table 3

Pseudo-total content of the elements in the studied soils.

Profile	Hor.	Total contents (mg/kg)												
		Al	Ca	Fe	K	Mg	Mn	Na	Cu	Ni	Pb	Zn	Co	Cr
Xuxarantes	A	29,800	263	10,350	1831	1800	89	151	5	12	<25	47	7	7
Cabo Vilano	A1	5540	338	2920	981	480	21	103	<5	<5	<25	6	<5	<5
	A2	15,410	136	7930	1077	790	31	82	<5	5	<25	12	5	5
	Bw	19,180	121	9980	1676	1600	62	123	<5	8	<25	20	5	7
	C	7140	136	3370	931	1400	55	86	<5	5	<25	15	3	5
Muxia	A	2104	248,177	1610	593	3000	33	2075	<5	12	30	10	9	5
	C	2295	244,177	1530	696	3000	32	2008	<5	13	29	10	10	5
	2Ab1	19,440	5407	10,870	2949	1800	85	203	<5	9	<25	24	7	9
	2Ab2	21,450	2777	10,560	3450	2200	97	180	<5	9	<25	34	8	8
	2Bwb1	22,140	3827	10,690	2922	1800	83	151	<5	9	<25	28	7	11
	2Bwb2	29,290	2577	11,690	3722	2400	108	199	<5	10	<25	36	9	10
	2C	38,460	2077	11,780	1789	2800	121	156	<5	15	<25	72	10	8
Cementerio de los Ingleses	A1	1832	575	767	672	260	35	254	<5	<5	<25	6	<5	<5
	A2	1524	275	352	608	87	22	225	<5	<5	<25	<5	<5	<5
	E	760	260	359	315	65	18	140	<5	<5	<25	5	<5	<5
	Bhs	2372	356	1130	363	170	33	144	<5	<5	<25	6	<5	<5
	Bhs2	4574	333	1230	320	200	21	108	<5	<5	<25	7	<5	<5

Fig. 3. Soil profile from Cabo Vilano.

the entire profile (Table 1).

The CEC varied between 5.67 and 1.84 $cmol_c/kg$ and decreased with depth due to the OM content (Tables 1 and 2). The abundance of cations in the CEC has the following sequence Ca > Mg > Na > K, except for the deeper horizons where Mg was the dominant cation due to a mineralogical alteration. In the selective extractions of Fe and Al, the forms linked to OM were greater than those associated with components of low crystallinity (Fep/Feo = 1.08–1.81; Alp/Alo = 1.04–2.49, Table 2). The texture in the upper three horizons was loamy sandy becoming sandy in the saprolite (Table 2). There is a predominance of coarse sands, between 62 and 66 %, maintained throughout the profile, while the finer particles (silts and clays) range from 12 to 18 % (Table 2). The majority concentration in pseudo-total fraction were obtained for Al and Fe (Table 3).

3.3. Soil profile 3. Muxia

The soil profile from Muxia presented two cycles of pedogenesis (Fig. 4). The soil is located a convex slope shape, with a class 1 of slope gradient. There showed a surface with class 1 in rock outcrops and coarse fragments. The main vegetation is characteristic of the gray dune: *Iberis procumbens* Lange*, Medicago marina* L.*, Lagurus ovatus* L.*, Helichrysum picardii* Boiss. & Reut*, Carex arenaria* L.*, U. europaeus, Pinus* spp.*, Rumex bucephaloporus* L.

The upper cycle consists in the formation of two horizons (A, C), in which it is dominated by sedimentation processes. The deposition of sands with aeolian origin indicates the genesis of the two identified horizons. The deposited sands presented mostly a fine size (60.54 %), with a sandy texture and a thickness of more than 40 cm (Table 2). The horizons A and C belong partially to an active dune system, which suffered a setback and stabilization in recent years (Fig. 5).

The reaction in the two horizons (A and C) was alkaline and the OM content were low (Table 1) with a tendency to mineralization (C/N ratios of 8.3 and 9.5, respectively). Total C contents were high with more than 90% of the total being carbonates (Table 1). These carbonates were derived from aeolian deposits with a great abundance of mollusk shells. The CEC was 24 and 33 $cmol_c/kg$, with a non-acid cations saturation of 100 % and Ca as the dominant cation in the exchange complex (95.3–95.6 %, Table 2). The analysis of the Fe and Al forms, obtained from the selective extractions, showed a predominance of the crystalline phases over those of low crystallinity. Moreover, within the non-crystalline phases, the totality was associated with oxides and hydroxides (Table 2). These results agree with those obtained by the thermodynamic modeling of the equilibrium soil solution, where a supersaturation of different Fe and Al oxides and hydroxides was determined, such as Gibbsite, Goethite, Hematite, Diaspora, Lepidocrocite or Boehmite among others. All these solid phases can be formed as secondary minerals from the solution (Table S3).

The second cycle of pedogenesis corresponds to a paleosol in which five horizons were differentiated (2Ab1, 2Ab2, 2Bwb1, 2Bwb2, 2C). The reaction was slightly alkaline in all depth soil profile (Table 1). Although these pH values can indicate the presence of carbonates, this content is less than 1 g/kg (Table 1). Another common characteristic was the presence of 100 % of non-acid cations in exchange complex in all horizons, with Ca being the dominant exchangeable cation (Table 2).

The first and second horizons (2Ab1 and 2Ab2) correspond to a superficial horizon with 72 cm of thickness, dark color (from black (10YR2/1(w)) to very dark brown (10YR2/2(w)), and high OM contents (Table 1; Table S1). The values of C/N ratios were 12.29 and 11.75, respectively. In the first horizon (2Ab1), 59 % of the oxidable C (C_o) was found in more stable forms, while in the second horizon (2Ab2) the labile C forms were the predominant (Table 1). The CEC of the buried surface horizon (2Ab1 and 2Ab2) decreased with the depth (Table 2) being related to the reduction of OM and clays contents. The Ca is the dominant cation followed by Mg, Na and K in exchange complex. The Ca contents are high (Table 2) corresponding to 98 % and 94 % of the total CEC. The selective extractions showed that 50 % of the Fe is associated to non-crystalline forms. In the first 50 cm this fraction is mainly associated with OM (Fep/Feo = 0.79), while the mineral fraction gains relevance at depth as oxides or hydroxides of Fe (Fep/Feo = 0.43; Table 2). For Al, the same distribution pattern was obtained, with an Alp/Alo ratio of 0.65 in $2A_{b1}$ and 0.30 in the 2Ab2 horizon (Table 2).

The third and fourth horizons correspond to a cambic horizon (Bw) with an increase of alteration and release of oxyhydroxides. It's presented from very dark brown to dark brown color in wet (10YR2/2 and 10YR3/3) and from dark yellowish brown to yellowish brown in dry (10YR 4/4 and 10YR5/4) (Table S1). In the third horizon (2Bwb1), the

Fig. 4. Soil profile from Muxia.

OM content is 23.6 g/kg, and the clay content increased compared to the upper horizon (Table 1). This increase of soil colloids explains the values obtained in the CEC in this horizon. The OM presented a tendency to humification (C/N ratios of 15.18) with the labile fraction being dominant (69% of total C), while OM contents in fourth horizon decrease not having active organic compounds (Cp/Ct = 0). For both horizons, the extracted forms of Fe and Al, there was a predominance of non-crystalline forms which were associated with oxides and hydroxides (Table 2).

The last horizon of the second edaphic cycle corresponds to a saprolite from the alteration of a granitic rock (2C). In this horizon, coarse sands predominated over the other particles, with a sandy loam texture, and CEC was low (Table 2) derived, mainly, from the OM (Table 1). The OM presented significant active fraction (83 % of the total C) which was the highest in all the evaluated horizons.

The pseudo-total content of the elements in all the horizons from this pedogenesis cycle were similar, with predominance of high contents of Al and Fe. However, in both horizon from first cycle of pedogenesis the main elements in the pseudo-total fraction were Ca and Mg (Table 3). These elements also were majority in available fraction (Table S2).

3.4. Soil profile 4. Cementerio de los Ingleses

In this profile, five horizons belonging to a single cycle of pedogenesis were identified, with a total depth of more than 2 m (Fig. 6). The soil is located a convex slope shape, with a class 8 of slope gradient. There showed a surface with class 1 in rock outcrops and class 2 in coarse fragments. The main vegetation is a scrub system dominated by *U. europaeus* and some type species of secondary dune such as *Cistus salviifolius* L.

Apparently, this soil derived from the same starting material of aeolian origin. All the horizons presented a sandy texture with predominance of coarse sands, constituting at least 80 % of the inorganic particles of the soil (Table 2). The reaction in the entire profile was slightly acid (Table 1). The non-acid cations saturation in the exchange complex was lesser than 50 %. Exception was obtained for the first 20 cm where exchange complex was dominated by non-acid cations (90.8 %) with high Ca and Mg contents (Table 2). Another common characteristic of the entire profile was low available P contents (<5 mg/kg; Table 1).

The first and second horizons (A1 and A2) constitute the superficial soil horizon, characterized by an adequate OM content (46.2 and 26.5 g/kg, respectively) and high C/N ratio (17.93 and 30.8) which decreases with the depth. In these two horizons, organic compounds were found in stable forms, while the active organic compounds become more relevant at depth (Table 1).

The next horizon was an eluviation horizon (E) dominated by the loss of organic matter and other properties and its accumulation in the next horizon identified as Bhs. The CEC are related to the low proportion of colloidal fractions. The abundance of the non-acid cations in the CEC was maintained in the same sequence in all the horizons from the profile: Ca > Mg > Na > K, but the exchangeable Al presented a tendency to increase with the depth (Table 2).

The contents of extracted forms of Fe and Al were very low (Table 2), because this soil is sandy with few alterable minerals. It presented a predominance of the non-crystalline forms, except for the E horizon where the Feo/Fed ratio was lesser than 50 % (Table 2). Within the non-crystalline fraction, most of the Fe was identified associated with organometallic complexes, except in the last horizon (Bhs2) in which Fe oxides or oxyhydroxides were the dominant (Alp/Alo = 0.97–1.26) (Table 2). The pseudo-total metal contents were low, without a clear element predominance (Table 3). In equilibrium soil solution, a low contribution of cations to the solution was also obtained, mainly due to the small contribution offered by a soil formed by quartz sands (Table S2).

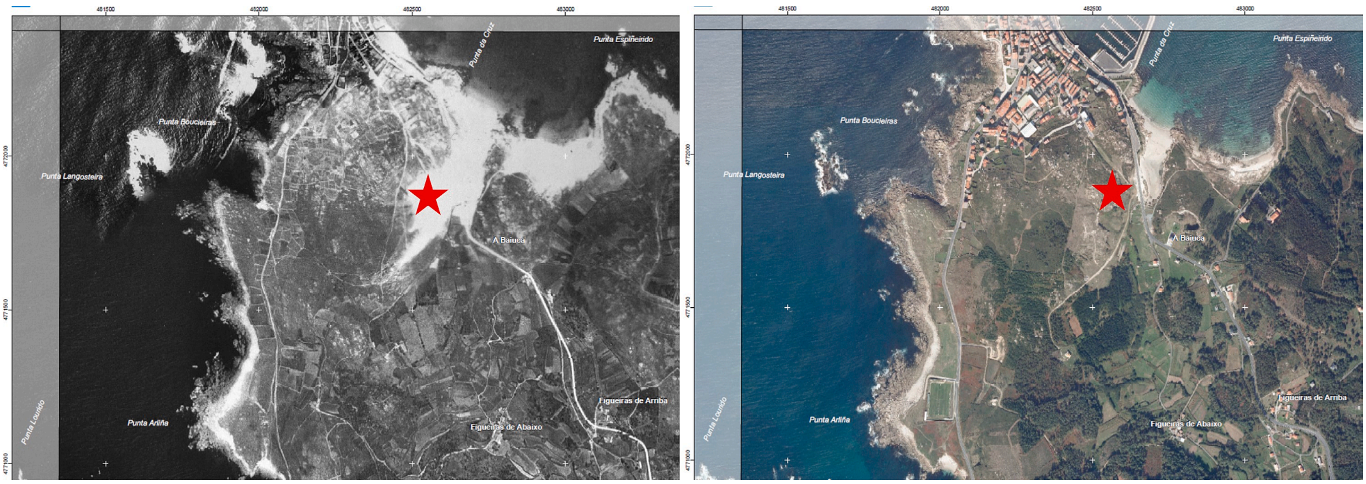

Fig. 5. Comparison of the state of the dune system where the Muxia soil profile is located: Orthophoto of the American USA flight (1956) vs PNOA (2009–2010).

Fig. 6. Soil profile from Cementerio de los Ingleses.

4. Discussion

4.1. Soil profile 1. Xuxarantes

This profile represents a soil developed from granitic materials without any influence of the processes of aeolian sedimentary contribution. Therefore, this soil was selected as a control profile since the other studied soils were developed from same parental material and under similar climatic conditions. In general, the characteristics of this soil (e.g., pH, thickness, CEC, OM, pseudo-total contents) were typical for soils developed on granitic materials from Galicia (Álvarez Rodríguez et al., 1993; Calvo de Anta et al., 1992; López Mateo et al., 2002; Macías et al., 1993; Macías and Calvo de Anta, 2009; Rubio and Gil-Sotres, 1997).

The main process of pedogenesis was the OM accumulation (melanization) in the superficial mineral horizon and settle directly on the parent material. The mineral alteration is limited, which implies no release of cations and, consequently, a very low saturation of non-acid cations with a predominance of Al in the exchange complex. According to the IUSS Working Group WRB (2022), this soil is classified as Endoleptic Umbrisol (Loamic, Hyperdystric, Hyperhumic, Pachic), which presents an umbric surface horizon that contacts with the continuous rock at 100 cm of the soil surface. In addition, the relevant Group II qualifiers were: Loamic due to the presence of a sand loamy texture at depth, Hyperdystric associated with a saturation of non-acid cations of less than 50 % in the exchange complex of the total thickness (between 20 and 100 cm from the soil surface) and Hyperhumic due to its high content of organic C ($\geq$5%) in the mineral soil surface. Finally, this soil was also characterized by having an umbric horizon $\geq$ 50 cm thick, obtaining a Pachic character. This Pachic qualifier is similar to many Galician Umbrisols located at the foot slope where colluvial materials have been accumulated and the climatic conditions promote the humification as well as the stabilization of OM with Al, Al-humus complexes, and inhibition of microbial activity (Calvo de Anta et al., 2015; Macías et al., 2004; Macías and Camps Arbestain, 2020; Turrión et al., 2009; Verde et al., 2005).

4.2. Soil profile 2. Cabo Vilano

This soil present one more phase of evolution of a soil developed on granitic materials, compared to the soil profile from Xuxarantes, adding the characteristic of the displacement of the alteration front and obtaining of a mineral alteration front, a cambic horizon. As in the Xuxarantes profile, the superficial horizon had a high content of organic matter accumulated and stabilized by organometallic complexes, mainly with Fe and Al (Macías et al., 2004; Macías and Camps Arbestain, 2020).

The contents of Ca and Mg in the exchange complex were higher than those found by other authors for the forest soils from Galicia (Álvarez Rodríguez et al., 1993), while the contents of Mn, Cu, Ni, Pb, Zn, Co, and Cr in pseudo-total fraction and available fraction in all depth of profile were within the normal ranges for Galician soils and developed on granite materials (Macías and Calvo de Anta, 2009; Álvarez Rodríguez et al., 1993; Calvo de Anta et al., 1992). Two specific pedogenic processes were observed in this soil. There were processes of OM accumulation in the superficial horizon (melanization) with humic (≥1% organic C) and pachic character (60 cm of umbric horizon), and of browning in the subsurface horizon (Bw) with a greater structural development (Carballas et al., 2016). This soil was classified as Haplic Umbrisol (Arenic, Humic, Pachic) (IUSS Working Group WRB, 2022).

4.3. *Soil profile 3. Muxia*

The soil profile from Muxia has two cycles of pedogenesis and some interesting characteristics for the paleoenvironmental reconstruction. It is a process of fossilization of a soil by an aeolian mantle which, in turn, is at the beginning of pedogenic process, and influencing through leachates to the soil buried.

The buried soil has the characteristics of having been initially formed as Umbrisol with a cambic horizon developed by in situ alteration on granitic rocks. In fact, the pseudo-total contents of the elements, especially Al, Fe, and K, were similar to other Umbrisols developed on the same type of geological material (Macías and Calvo de Anta, 2009) and the studied profiles of Xuxarantes and Cabo Vilano. In addition, the non-acidic cations of CEC (except Ca) are within the normal ranges for Galician soils (Calvo de Anta et al., 1992; López Mateo et al., 2002).

This buried soil has been covered by aeolian materials of carbonate nature, which have modified its characteristics through soil solution. According to Arribas et al, 2010, the main composition of Galician Holocene sands has a homogeneous mature quartzofeldspathic petrofacies, while aeolian deposits with modern carbonates are represented by bioclasts, mainly from molluscs, and their contribution suggests a progressive influence of marine supplies, such as the present deposit. Therefore, in this buried soil was observed combined characteristics between the process before burial and those influenced by the later sedimentary input. This buried soil presented high organic matter content, alkaline reaction, and a high CEC (11 – 24 cmolc/kg), which is dominated by Ca, classifying it as mollic horizon (IUSS Working Group WRB, 2022). The non-existence of carbonates in all the horizons of the second pedogenetic cycle and the alkaline reaction suggest that it is an indirect effect of the leachates originated in the first cycle. These leachates would imply a process of neutralization of the acidity of the original soil and a process of Ca enrichment. Thus, according to IUSS Working Group WRB (2022) this buried soil was classified as Haplic Phaeozems (Endoloamic). Several authors have shown that the contribution of aeolian material was able to modify the physicochemical properties of the soils, both present soils and paleosols, affecting their paleoclimatic interpretation (D'Amico et al., 2023; McAuliffe et al., 2018; Varga et al., 2016).

The first pedogenetic cycle of this Muxia profile consists of two horizons (A, C) in which sedimentation processes predominate. The presence of a horizon A is due to the beginning of pedogenic processes with the stabilization of the deposit in the last years and the increase of the dune vegetation, which led to an increase of organic matter. The dominant elements of this upper cycle are pseudo-total of Ca (244–248 g/kg) and carbonates (≈ 50 g/kg), which, as indicated in the study of Arribas et al. 2010, are due to modern sedimentary deposits with high mollusc content. The pseudo-total metal contents, except for Pb, are in the same range of variability of soils developed on sedimentary materials (Macías and Calvo de Anta, 2009). This upper pedogenetic cycle was classified as Aeolic Calcaric Arenosol (Ochric – Novic).

Until this moment, no dating was carried out between the two cycles of pedogenesis consequently it not possible specify in which time period these changes occurred. In any case, this upper deposition must not have been very fast since the physicochemical conditions of the lower cycle have been intensely modified throughout the profile. Also, the quantification of carbonates at the beginning of deposition is unknown, so with the data from this study it was not possible to appreciate either the intensity or the speed of the decarbonation processes.

4.4. *Soil profile 4. Cementerio de los Ingleses*

The physicochemical characteristics of the soil profile of Cementerio de los Ingleses showed that the soil is developed on an aeolian deposit, a dune system where several pedogenic processes occurred. The main process identified was podsolization, which has also been described by other authors in this type of deposits (Bressolier et al., 1990; García-Rodeja and Macías, 1978; Jungerius, 1990; Martínez Cortizas et al., 1997; Nornberg, 1977; Pollmann et al., 2020; Schwartz, 1986; Sevink, 1991; Wilson, 1992). Therefore, this soil has a spodic horizon that begins within 200 cm of the surface and is characterized by the presence of an albic horizon with a thickness of about 30 cm. The sandy texture was dominant in all depths of the profile, considering Pantoarenic as qualifier (IUSS Working Group WRB, 2022).

The superficial horizon showed a high organic C content (14.9 – 26.8 g/kg) and a thickness of 60 cm. Although the first 20 cm has the characteristics of a mollic horizon as result of a superficial enrichment of carbonates materials (1.50 g/kg C-CO3), which lead to base saturation >50%, the remaining 40 cm presented a base saturation < 50 %, classifying it as an umbric horizon. The abundance of the non-acid cations in the CEC was similar to those obtained by Martínez Cortizas et al. (1997). In this case, the qualifier mollic should be used to define a relevant characteristic of this Podzol. However, the IUSS Working Group WRB (2022) only considers between anthromollic or umbric, considering that the changes and increases in base saturation are a result of human processes or activities and not, as in the present situation, derived from a surface enrichment of aeolian depositions with carbonate containing materials.

Another characteristic common to the whole profile was P deficiency (<5 mg/kg), values that agree with those reported for Galician soils (Fernández Marcos et al., 1994). Similarly, the pseudo-total elements contents were small and lower than those obtained by Macías and Calvo de Anta (2009) for soils developed on sandy sediments. In the equilibrium soil solution was also obtained a low concentration of cations (Álvarez Rodríguez et al., 1993), due to the small contribution offered by quartz sands.

The studied soil was classified as Albic Umbric Podzol (Pantoarenic) and constitutes one more step in the evolution of aeolian deposits (first cycle of pedogenesis in the Muxia profile). This situation was the result of various edaphic processes: initially the intense decarbonation and decalcification of the sediments, followed by a subsequent acidification, and finally, the podzolization process, or starting from sands without carbonates that would favor the acidification and podzolization process. Possibly this last edaphic process was a consequence of the effect of lateral leachates, from the highest areas, rather than of vertical illuviation processes.

4.5. *Edaphic evolution relations of soil profiles*

The studied soils showed an edaphic variability and interrelationships of coexisting processes over time. Besides, incipient soils on granitic materials and their subsequent evolutionary step with the development of alteration horizons, due to weathering processes, are presented. The effect of aeolian deposition on these soils leads to a variability of processes, which can affect pre-existing soils or on these new materials. If they have a low acid neutralization capacity, acidification processes can be accelerated, but if these materials have an excess of organic acids, podzolization process are enhanced (Macías and Camps Arbestain, 2020). This genesis of spodic horizons is favored by the mobility of organic components in the absence of clays and with the low Fe and Al reactive contents present in these soils, as well as, for presenting a very acidic parent material, quartz materials of granitic origin, with good vegetation cover and abundant precipitation (Jenčo et al., 2018) The time of formation of Podzols from aeolian deposits in different regions such as Norway, Finland, Canada, Sweden, among others, can vary from 200 years to more than 3000 years (Mokma et al., 2004; Sauer et al., 2008; Singleton and Lavkulich, 1987). This variation in formation times derives from the starting material, the presence of carbonates in the aeolian deposits, as well as the position, existing vegetation, and climatic conditions. For the soil profile from Cementerio de los Ingleses, located less than 10 km from the Traba sedimentary deposits, whose origin was dated at about 5000 years (Arribas et al., 2010). The composition of these sediments presented carbonates of biogenic origin, mainly mollusks, so a sedimentary process of the same temporality would be expected. Thus, the soil processes included the decarbonation, decalcification, acidification and, finally, podzolization. Previous study on composition of the sandy beaches in Galicia also showed that the area from Traba to Cementerio dos Ingleses presents sands up to 32% carbonates (Flor et al., 2004).

Through the equilibrium soil solution of the different studied soils, the trends and processes involved in their genesis were differentiated and they indicate the sequence of alteration and neoformation. For in situ alteration soils, the proximity to the sea leads to the decrease of the rate of acidification, with enrichment of the electrical conductivity and concentration of cations with special relevance of Ca, of biogenic origin. This element comes from the aeolian transport of shell fragments of different mollusks (Table S2).

In soils with allochthonous material, there was an important difference in relation to pH values. In the incipient development of the Arenosols, the pH was high and controlled by the presence of Ca-carbonates and, to a lesser extent, Na and Mg. The evolution of this hyperquartz material leads to decarbonation and decalcification, favoring the acidification processes and subsequent podzolization with the formation of thick spodic horizon, whose genesis appears to have associated to lateral enrichment processes with waters rich in soluble C. The absence of clays and low Fe and reactive Al contents allowed the mobilization and enrichment of the deeper horizons, as also observed in tropical Podzols or podsols developed on coastal systems and dunes in other countries (Rizzato et al. 2010a,b; Monteiro et al., 2015).

The in situ alteration soils were dominated by hydroxylated forms, mainly $Al(OH)_2^+$. There was no relevant species in the soils of recent aeolian contribution, and only in the podzolic systems these hydrolysed cationic forms appear again in the spodic and superficial horizons, with a relevant value of Al^{3+} activity in the albic horizon. The Ca^{2+} is the most important species of this element, but also with situations where the formation of ionic pairs with sulfates was favoured, such as $CaSO_4$, especially in the Arenosol of incipient evolution (Table S3).

The presence of the marine influence is reflected in the high activities of chlorides and Na^+ in all soils and horizons. Also, the abundance of sulfates and the distribution of Mg^{2+} indicated that they come, mostly, from the contributions of marine splashes, as well as from the mists and rains of this origin. In terms of plant growth, the relatively high activity of nitrates and its constancy in all soils stand out despite the differences in its reaction and edaphic evolution, which seems to indicate that it is fundamentally related to the contributions of precipitation.

In the possibilities of secondary neoformation minerals controlled by the saturation indices (SI), it was observed the presence of 2:1 nontronite-type phyllosilicates in the in situ alteration soils, followed by 1:1 kaolinite-type phyllosilicates (Table S4). This data is not in accordance with observed in most Galician soils, where the new solid phases are of the kaolinite type (Macias et al., 2005). This effect is due to the higher activity of the non-acid cations. This same behavior was obtained for the Arenosol of incipient contribution and even in the buried horizons of in situ alteration (soil profile from Muxia), with high saturation indices for the 2:1 mineral, and even for some trioctahedral silicates such as tremolite or talc, for which reason there is an influence on the whole profile of the activity of alkaline and alkaline earth cations. The process is maintained, although to a lesser extent, in podzolic soil (Table S3).

5. Conclusions

The studied soils showed an influence of aeolian deposits on pedogenic processes and characteristics of coastal soils. The in situ alteration soils without contribution of aeolian deposits presented an enrichment of non-acid cations in exchange complex and secondary minerals of neoformation, mainly, phyllosilicates 2:1 (versus 1:1, kaolinite type). For these soils, the main pedogenic process were melanization and browning.

The contribution of aeolian sedimentary materials lead to the appearance of various pedogenic processes, which caused intense modifications of the soils buried by these deposits or pedogenic process on them. The main processes in the incipient pedogenesis of the sands were acidification, decarbonation and decalcification. These processes can modify the characteristics of buried soils, causing some on their properties or characteristics to change. Subsequently, the intensification of these processes over time leads to a more advanced pedogenesis process, the podzolization of the quartz-sandy sediments, resulting in podzolic soils.

The results of this study allow to demonstrate an influence of wind deposits and to highlight the main mechanisms that influence the processes of genesis or modification of properties in buried soils. However, these processes need to be evaluated in more detail in deposits with different ages and compositions in order to understand the speed of the processes and their limitations with respect to the nature of the sediments. In the present study, it is not possible to address the dating between the mentioned cycles which is a point of improvement in the future in the understanding of the identified processes. On the other hand, it also shows that the effects of changes in the depth of buried soils must also be considered in paleoenvironmental reconstruction studies in these areas.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2023.107465.

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