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Hydromorphic to subaqueous soils transitions in the central Grado lagoon (Northern Adriatic Sea, Italy)

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ABSTRACT

The Grado lagoon is among the largest in the Mediterranean sea and is characterized by salt marshes, where tides influenced the development of a complex micromorphology coupled to a micromosaic of vegetation covers. This study represents the first contribution to the understanding of the main processes governing formation, development and spatial transitions between hydromorphic and subaqueous soils in an Adriatic lagoon ecosystem. Physicochemical characteristics and development of soils were investigated in three salt marshes differing for their proximity to the open sea, textural composition and age of formation. Soils of back barrier salt marshes had A/C profiles and were mostly characterized by a sandy coarse texture that allows rapid drainage and subsurface oxygen exchanges. Soil sequences from the inner salt marsh to its submerged border slope or to a brackish waterhole do not simply represent a hydrosequence, but also reflect erosion/sorting/accumulation processes.

The soils in the central part of the lagoon have finer texture and in displayed transition or cambic horizons. Silty clay loam textures and low positions allowed the development of more severe anoxic conditions and accumulation of sulphides. The tide oscillation strongly contributed to formation of redoximorphic features, intensity of anaerobic conditions but also colonization by different plant communities. Discriminant analysis was performed to identify physicochemical properties which discriminate the different soils according to geo-morphological position and prevailing plants. It confirmed that differentiation of plant communities occurred according to distinct morphological and physicochemical soil properties, but also acted as a primary affecting factor of pedogenesis.

1. Introduction

Submerged sediments that originate from deposition of transported materials have been considered for a long time as amorphous deposits not affected by pedogenesis. However, accumulation of organic C, alteration and translocation of materials occur also under submerged conditions and in ways that closely resemble terrestrial soil-forming processes (Erich and Drohan, 2012; McCall and Tevesz, 1982). The concept that sediments are capable of supporting rooted plants, and undergo transformation and horizon differentiation, has led soil scientists to consider the action of subaqueous pedogenetic processes (Bakken and Stolt, 2010; Ellis et al., 2002) and rethink the concept of soil. Accumulation of nutrients and biogenic $CaCO_3$, formation of structural aggregates (Barko et al., 1991; McCall and Tevesz, 1982), marine humus bioturbations, chemical transformation of sulfur and iron in anoxic environments were intensively studied (Bradley and Stolt, 2003; Payne, 2007). Pedologists therefore confirmed that superficial sedimentary deposits do evolve into aquatic soil horizons, leading to formation of subaqueous soil profiles (Demas et al., 1996; Demas, 1998; Demas and Rabenhorst, 1999). On the basis of Jenny's state factor equation, a new model for describing subaqueous soil (SAS) genesis was therefore proposed by Demas and Rabenhorst (2001). These observations have been incorporated by the Soil Taxonomy (Soil Survey Staff, 2014) by introducing two new suborders (*Wassents* and *Wassists*) to classify subaqueous soils (SASs), defined as soils submerged for at least 21 h each day by up to 2.5 m of water.

Estuaries and shallow, semi-enclosed coastal lagoons are

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transitional depositional environments, that cover the boundary between the mainland land and sea (Newton et al., 2014). These landforms represent a continuum of soils with different degrees of hydromorphism, together with large areas of SASs. The combination of these features is fundamental for animal and plant biodiversity, and contributes to the maintenance of equilibrium as well as to a number of ecosystem services, spanning from protection of coastal water quality, to recreation and fish farming (De Groot et al., 2012). SASs may represent important sinks of nitrates and P (Ponnamperuma, 1972) and contribute to C sequestration (Homann and Grigal, 1996), since, under anaerobic conditions, the decomposition of soil organic matter is slow and thick organic-rich horizons may develop (Bradley and Stolt, 2006; Richardson et al., 2001; Stolt and Rabenhorst, 2011). Improving knowledge about SASs can play an important role in devising strategies for the sustainable management of water and coastal resources (Erich and Drohan, 2012). Soil survey may be a very useful key for understanding the formation and evolution of different land units in these very fragile environments (Erich and Drohan, 2012).

The Italian lagoons, and in particular those of the Northern Adriatic Sea, are characterized by salt marshes, sandbanks and subtidal mudflats, which represent important ecosystems for land management and wildlife protection (Ferrarin et al., 2010). The salt marshes, which undergo partial regular flooding at high tide, harbor several halophyte plant species and embody the habitat of several aquatic and migratory birds. Their importance has been highlighted by the European community through the Directive 92/43/CEE "Habitat" and the development of Natura 2000, in which the lagoon is considered as special protection area (SPA) and special area of conservation (SAC).

To our knowledge the investigation and classification of salt marsh soils in Italian lagoons has not been carried out so far.

In this work, we examined physicochemical characteristics of hydromorphic and subaqueous soils profiles in the salt marshes of Grado and Marano lagoon. The lagoon (160 km^2) spans between the Tagliamento and the Isonzo rivers estuaries and is separated from the open sea by a barrier of islets and sandbanks. It is among the largest European shallow lagoons, second only to the Venice Lagoon, in the Mediterranean.

The aim of this study was to investigate how landscape morphology and vegetation influenced transitions from hydromorphic to subaqueous soils. In this ecosystem, salt marshes are characterized by a complex micromorphology coupled to a micromosaic of vegetation covers that is an intrinsic part of the huge biodiversity of these endangered habitats. For this reason, changes of soil properties were investigated in transects between hydromorphic and subaqueous ecosystems, in different salt marshes of the lagoon and under different plant communities. Extending knowledge about the pedogenesis of submerged soils can provide new concepts on the functioning of intertidal and subtidal habitats that can be useful to evaluate and predict future modifications in a perspective of climate change (Erich et al., 2010).

2. Materials and methods

2.1. Study area

This study focused on three salt marsh transects (Fig. 1), in the middle section of the lagoon (Buso and Grado basins). The salt marsh bars differ for their proximity to the open sea, textural composition and age of formation. The Marina di Macia site (MM) was located on a back barrier salt marsh, which was part of the old longshore bar that separated the Grado basin from the sea. The sampling transect was traced from the inner salt marsh, nowadays protected by a shallow sand ridge (MM-Lim1 and 2, 60 to 50 cm height above mean sea level), to the marsh border slope (MM-Zos, −50 cm below m.s.l.). The Isole della Gran Chiusa site (GC) was located in the Buso basin, on a channel fringing marsh that has evolved from an ancient enclosed fish farm that had been abandoned long ago, re-invaded by waters and reverted to wilderness. The transect was sampled between a prevalently emerged (GC-Sar 1, 40 cm above m. s. l.) and a more frequently submerged part of the salt marsh (GC-Sar 2, 30 cm above m. s. l.). The third study site (MD) was located in a salt marsh parallel to the Mosconi dike road, which formed from the dredged sediments derived from the excavation of the dike and adjacent Belvedere channel (1902–1920). The transect was sampled in a mostly submerged area (MD-Sp1, 15 cm above mean sea level) and in a permanently submerged internal waterhole (MD-Sp2, 5 cm above men sea level). Altimetric data and ortophotos were obtained from LiDAR cloud points.

2.2. Vegetation structure analysis

Vegetation communities types were individuated observing presence and coverage of prevalent species. Nomenclature of plant species follows the latest Italian check list of vascular plants (Conti et al., 2005).

2.3. Climate and tides

Mean annual temperature is 13.1 °C, while annual precipitation is 1106 mm yr^{-1}. According to the Köppen-Geiger system, the area's climate is classified as "temperate/mesothermal" (Peel and Bloschl, 2011), characterized by the moderating effect of the sea (Michelutti et al., 2003). Climatic data were obtained from the meteorological station of Grado (0 m m.s.l.; about 5–10 km from the study sites). In the lagoon, the tidal mean range is 65 cm, with a spring range of 105 cm. The average salinity of sea water ranges from 20 mg L^{-1} near the mainland to 35 mg L^{-1} near the sea (ARPA, 2008). Water temperatures are comprised between 5 and 7 °C in winter and 28–30 °C in summer (Covelli et al., 2009; D'Aietti and Altobelli, 2007; Ferrarin et al., 2010).

2.4. Sampling

Sampling was carried out in summer 2013, during low tides periods. Soil profiles were excavated and genetic horizons described according to Schoeneberger et al. (2012). Samples were sealed in polyethylene bags and stored at 4 °C until analysis.

SASs samples (MM-Zos and MD-2) were collected using a vibracore Beeker sampler, (Eijkelkamp, NL), equipped with a 6 cm polyethylene tube (McVey et al., 2012). The cores were sealed with a tight stopper to avoid oxygen infiltration and stored at 4 °C.

2.5. Analyses of soil profiles

2.5.1. Water analysis

Analysis of sea water were carried out in the field for pH, dissolved oxygen (DO), salinity (SAL) and temperature (T) with portable electrodes (Hach-Lange Instruments). Water samples were collected in pirex glass bottles and analysis where replicated in the laboratory.

2.5.2. Physical and chemical analysis of soils samples

Soil columns were extracted on a suitable support and each genetic horizon was described for its depth, boundary, Munsell color, coats/films and redoximorphic features, organic fragments, fluidity class. Accumulation of sulphides (sulfidization) was observed through color change after adding 3% H_2O_2 (McVey et al., 2012) and odor description (Fanning and Fanning, 1989; Fanning et al., 2002).

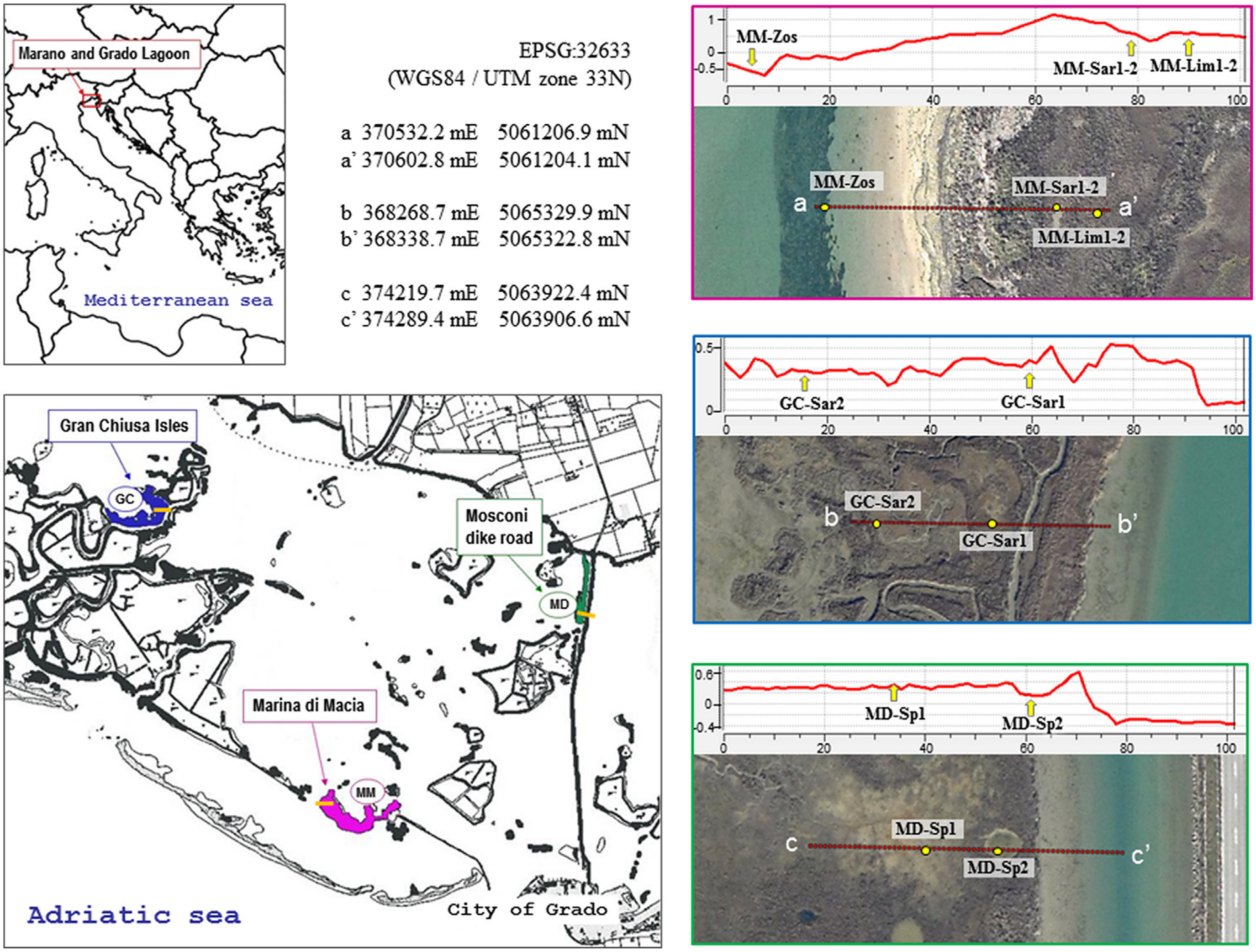


Fig. 1. Geographical location of study area and altimetric profiles of sampled transects in the three different salt mash bars examined: MM = Marina di Macia, GC = Gran Chiusa, MD Mosconi dike. Altimetric data and ortophotos were obtained from LiDAR cloud points.

Effects of reducing conditions on soil color (gleyfication) were investigated by field observations (H_2O_2 test and Munsell color recording). Measurement of pH after soil incubation (16 weeks) was carried out on SASs to detect pH lowering due to acid sulfate oxidation (Bradley and Stolt, 2003; Soil Survey Staff, 2014).

Electrical conductivity (EC) and pH were measured on 1:2.5 w:v (hydromorphic samples) or 1:1 w:v (SASs) (McVey et al., 2012) on moist samples. Soil samples were air-dried and sieved (<2 mm) when required to carry out the following analysis. Particle size distribution was determined by the pipette method (Gee and Bauder, 1986) and total carbonates quantified according to the Dietrich-Fruhling method. Total Organic Carbon (TOC) and Total Nitrogen (TN) were measured with an EA 1110 Thermo Fisher CHN elemental analyzer after dissolution of carbonates with 2 M HCl. Total Fe and S were quantified by ICP-OES (Ametek, Germany) after aqua regia digestion in a Millestone 1200 microwave oven (Vittori Antisari et al., 2011). The cation exchange capacity (CEC) was determined by shaking 2.5 g of soil for 2 h with 50 mL of 0.05 N $[Co(NH_3)_6]Cl_3$ (Ciesielski and Sterckeman, 1997). Samples were filtered (Watmann 42 filter paper) and CEC (cmol kg^{-1}) was estimated measuring the Co^{2+} remaining in solution by ICP-OES (Aran et al., 2008).

2.6. Statistical analysis

Discriminant Function Analysis (DFA) was performed following a forward stepwise approach to discriminate soils according to their location and prevalent vegetation cover. The statistical significance of the discriminant function was checked with Wilk's lambda test. The standardized canonical discriminate coefficients (SCDC) were used to rank the importance of each variable and the canonical score plot displayed the different samples according to the two dimensions that best separate the three groups.

3. Results

3.1. Soil climatic and morphological characterization

For permanently emerged soils in this area (not examined in this study), the water balance (Black, 2007), shows a limited deficit from July to August. Processing of climatic data by the Newhall Simulation Model (Cornell University, 1991; Newhall, 1972; Van Wambeke, 2000) defines a *Mesic* temperature regime (annual average soil temperature between 8 and 15 °C, with a difference between summer and winter above 5 °C) and a *Udic* soil moisture

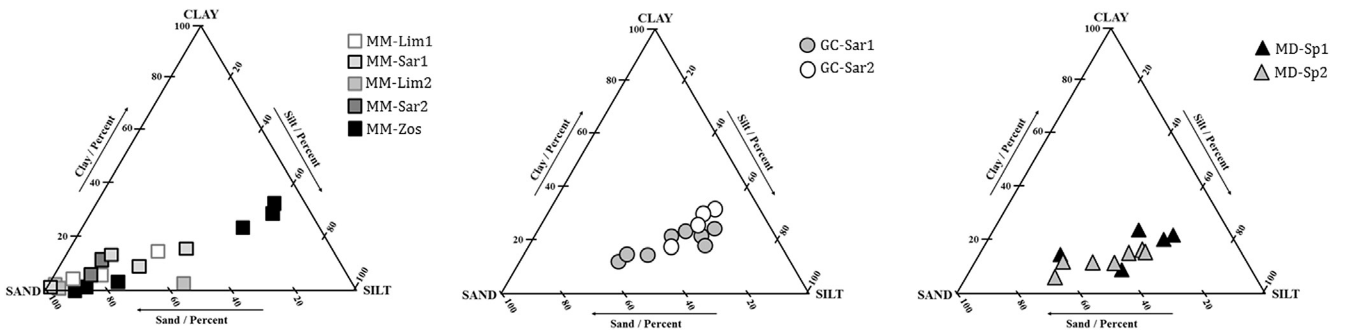


Fig. 2. Textural triangle representation of the textural distribution of soil profiles in the three different salt marshes. GC = Gran Chiusa, MD = Mosconi dike, MM = Marina di Macia.

Table 1
Mean chemical properties of the Marina di Macia salt marsh (MM) soil profiles.

Profile	Horizon	Depth cm	pH		EC dSm^{-1}	$CaCO_3$	TOC	TN	S	Fe	CEC mol^{+} kg^{-1}	C/N	OC/S	Fe/S
			Initial	Final		g kg^{-1}								
MM-Lim1	*Oe*	3–0	nd	6.7		35	99.8	7.6	nd	nd	nd	13.0	nd	nd
	A1	0–5	nd	7.7	16.5	374	12.3	1.4	5.2	26.2	38.0	8.6	2.4	5.0
	A2	5–10	nd	7.8	30.9	108	48.1	3.8	1.2	10.0	10.7	12.5	39.1	8.1
	Ab	10–17	nd	8.0	8.5	366	15.5	1.9	2.8	26.0	15.0	8.2	5.5	11.0
	C	17–30	nd	8.3	6.1	759	2.7	0.8	0.4	2.2	5.8	3.4	6.6	5.4
	Cg1	30–80	nd	8.3	5.3	800	1.6	0.2	0.4	1.7	7.1	8.4	4.1	4.3
	Cg2	80–100	nd	8.1	4.7	443	2.5	0.7	2.4	7.3	4.7	3.5	1.1	2.6
MM-Lim2	*Oe*	1.5–0	nd	7.2		nd	98.8	7.6	nd	nd	nd	13.0	nd	nd
	A1	0–3	nd	7.6	35.0	227	46.6	5.2	2.9	13.0	24.6	8.9	16.1	4.5
	A2	3–6	nd	7.5	16.5	664	5.2	1.1	0.6	3.9	8.5	4.6	8.8	6.7
	Ab	6–20	nd	8.0	8.5	357	13.5	1.9	1.3	9.6	14.4	7.1	10.6	7.6
	C	20–35	nd	8.3	6.1	759	2.4	0.8	0.4	2.3	5.7	2.9	6.5	6.3
	Cg1	35–70	nd	8.3	5.3	800	1.3	0.2	0.4	1.7	6.2	6.2	3.6	4.7
	Cg2	70–100	nd	8.1	4.7	422	2.7	0.7	0.4	1.8	4.9	4.1	6.6	4.4
MM_Sar1	*A1*	0–0.5	nd	7.7	41.3	195	73.2	6.1	5.1	17.1	18.5	10.3	14.3	3.3
	A2	0.5–1.5	nd	7.6	37.6	299	30.3	3.4	4.3	14.6	10.0	8.9	7.1	3.4
	C	1.5–15	nd	8.4	5.9	348	0.7	0.6	0.3	3.2	3.4	1.3	2.3	10.3
	AC	15–20	nd	7.5	27.7	141	26.5	2.6	2.3	20.4	17.4	10.3	11.5	8.9
	ACse	20–35	nd	7.7	22.0	151	22.8	2.6	3.2	17.5	14.2	8.9	7.1	5.4
	Cg	35–65+	nd	7.9	9.3	699	1.9	0.5	0.7	3.0	6.3	4.1	2.9	4.5
MM-Sar2	*A1*	0–0.5	nd	7.0	46.4	294	74.1	6.3	4.7	8.0	19.2	11.7	15.9	1.7
	A2	0.5–1.5	nd	7.5	39.7	324	47.3	4.2	3.5	10.3	7.5	11.1	13.3	2.9
	C	1.5–20	nd	8.4	3.5	802	1.3	0.2	0.3	1.8	5.8	5.4	4.8	6.8
	ACse	20–32	nd	7.3	28.3	170	34.4	2.7	3.7	12.9	17.7	12.6	9.2	3.4
	Cg1	32–35	nd	8.2	6.0	750	1.7	0.4	0.4	2.8	6.7	3.9	4.0	6.8
	Cg2	35–70+	nd	8.2	6.0	750	1.4	0.2	0.5	2.9	6.6	6.4	2.5	5.2
MM-Zos	*Oig*	0.2–0	nd	nd		613	97.8	8.1	nd	nd	nd	12.0	nd	nd
	Ase	0–12	8.3	7.0	6.14	618	33.0	5.1	2.1	4.9	7.0	6.5	15.9	2.4
	ACse	12–22	8.2	7.1	3.42	170	40.0	4.3	3.1	5.7	8.2	9.3	12.9	1.8
	O/Cg1	22–37	8.6	7.5	3.30	80	53.2	7.3	3.9	22.9	17.1	7.3	13.8	5.9
	O/Cg2	37–52	8.5	7.6	4.05	90	66.1	8.5	3.9	28.3	20.0	7.8	17.1	7.3
	Cg1	52–63	8.4	7.5	4.60	609	71.0	9.1	3.5	20.7	17.6	7.8	20.2	5.9
	Cg2	63–67+	8.1	7.4	4.12	52	22.0	7.2	0.8	4.7	8.2	3.1	25.9	5.5

CEC = cation exchangeable capacity.

regime (Soil Survey Staff, 2014) with more than 90 days of non-cumulative rainfall.

The soils were poorly developed, being characterized by A/C profiles, except for the soils at the Gran Chiusa (GC-Sar1 and GC-Sar2), in which transition or cambic horizons (Bg) were also recognized. All soils were characterized by organo-mineral A horizons, ranging from 8 to 22 cm, which in some cases were covered by thin organic horizons. The morphological characterization of hydromorphic and submerged soil profiles are shown respectively in Tables 1S and 2S of Supplementary Materials.

Clay content was below 40% and silt below 60% at all sites in all soil horizons (Fig. 2). Sand predominated in the deeper horizons of the MM hydromorphic soils, even if layers enriched with silt were observed at different depths. In these soil profiles (MM-Lim1-2 and MM-Sar1-2), the sand content was larger than in the submerged profiles (MM-Zos) of the same transect, in which deposited silt and clay associated with accumulation of organic materials, overlay the deeper carbonatic sand layer (Table 1). The Gran Chiusa and Mosconi Dike soils had silty clay textures, with sand intercalations in some of the horizons (Fig. 2).

At Marina di Macia (MM), proceeding along a transect from the inner part of the bar to the edge of the sea inlet, the vegetation cover is represented by three different plant communities. The MM-Lim1 and MM-Lim2 soil profiles were collected in areas flooded only twice a day, during the high tides, where *Limonium narbonense* was the dominant species, having the largest percentage cover. On the contrary, *Sarcocornia fruticosa* shows higher coverage in MM-Sar1 and MM-Sar2 sites, situated in slightly lower areas (see profile in Fig. 1). In the adjoining submerged area (MM-Zos), the eelgrass *Zostera noltii* was dominant, in association with few

Table 2
Mean chemical properties of the Gran Chiusa salt marsh (GC) soil profiles.

Profile	Horizon	Depth cm	pH (H_2O)		EC dSm^{-1}	$CaCO_3$	TOC	TN	S	Fe	CEC $mol^+ kg^{-1}$	C/N	OC/S	Fe/S
			Initial	Final		g kg^{-1}								
GC-Sar1	*Oe*	1–0	nd	7.2		52	61.1	5.1	nd	nd	nd	12.0	nd	nd
	A1	0–5	nd	7.0	26.7	23	43.5	3.9	2.6	42.0	22.1	11.2	17.0	16.4
	A2	5–10	nd	7.6	16.9	72	14.0	1.4	1.0	33.1	14.6	10.2	14.3	33.6
	Bg	10–25	nd	7.8	12.9	124	7.1	1.3	0.8	34.8	17.0	5.3	9.3	46.0
	AC	25–50	nd	7.9	12.5	106	7.4	1.0	1.0	35.3	16.9	7.6	7.5	35.7
	Cg1	50–60	nd	7.8	13.9	103	9.1	1.2	2.3	34.6	21.8	7.4	3.9	15.0
	Cg2	60–80	nd	7.7	15.0	75	11.8	1.3	5.7	35.9	20.8	9.2	2.1	6.3
	Cse3	80–110	nd	7.8	17.5	72	12.3	1.3	9.4	42.1	24.0	9.1	1.3	4.5
	Cse4	110–120+	nd	7.4	16.6	71	21.5	1.8	11.9	38.4	23.7	11.7	1.8	3.2
GC-Sar2	*A1*	0–0.5	nd	7.3	33.4	29	37.1	3.6	3.9	37.0	15.7	10.3	9.5	9.5
	A2	0.5–5	nd	7.2	17.8	38	28.5	3.0	1.6	40.5	25.4	9.6	17.6	24.9
	Bg	5–10	nd	7.7	12.0	48	13.2	1.6	0.8	42.3	21.4	8.4	17.1	54.5
	AC1	10–18	nd	7.8	9.5	76	8.1	1.2	0.6	43.2	19.8	6.9	12.5	66.3
	AC2	20–55	nd	7.9	9.9	100	6.2	1.1	0.6	39.5	17.3	5.8	10.3	65.6
	Cg1	55–75	nd	7.8	13.9	100	8.7	1.0	1.6	31.5	20.9	8.6	5.3	19.2
	Cse2	75–85	nd	7.7	15.0	81	11.1	1.2	4.1	32.8	21.3	9.3	2.7	7.9
	Cse3	80–95+	nd	7.8	17.5	79	12.2	1.3	9.3	42.7	24.1	9.0	1.3	4.6

CEC = cation exchangeable capacity.

Table 3
Mean chemical properties of the Mosconi Dike Road salt marsh (MD) soil profiles.

Profile	Horizon	Depth cm	pH (H_2O)		EC dSm^{-1}	$CaCO_3$	TOC		S	Fe	CEC $mol^+ kg^{-1}$	C/N	OC/S	Fe/S
			Initial	Final		g kg^{-1}								
MD-Sp1	*0/Ag1*	0–8	7.0	6.3	4.72	38	56.1	5.4	6.6	27.7	25.7	13.7	8.5	4.2
	Ag2	8–13	7.6	7.2	9.69	194	15.9	1.9	4.6	17.6	19.0	8.3	3.4	3.8
	Cg1	13–30.5	7.6	7.3	8.10	248	13.1	1.5	8.7	17.7	18.6	8.6	1.5	2.0
	Cg2	30.5–41	7.6	7.3	5.91	270	13.5	1.5	6.9	16.5	17.6	9.0	2.0	2.4
	Cg3	41–46	7.9	7.5	7.35	323	9.1	1.0	7.6	14.7	14.0	8.8	1.2	1.9
	Cse4	46–66.5	7.7	7.5	4.73	199	13.7	1.6	10.1	18.8	19.4	8.8	1.3	1.8
	Cse5	66.5–80	7.7	7.5	6.74	181	18.4	1.8	12.9	22.0	22.8	10.1	1.4	1.7
	Cse6	80–87+	7.7	7.6	7.60	200	21.3	2.2	12.4	21.0	23.9	9.6	1.7	1.7
MD-Sp2	*Oig*	0.5–0	nd	nd		nd	92.7	7.9	nd	nd	nd	11.7	nd	nd
	Ag1	0–1.5	7.9	7.1	9.58	111	29.3	3.1	10.4	37.8	8.6	9.5	2.8	3.6
	Ag2	1.5–4.5	7.9	6.9	9.38	56	55.7	5.0	12.5	42.6	17.0	11.2	4.4	3.4
	Ag3	4.5–8	7.7	6.5	9.93	68	52.8	4.7	17.2	47.6	17.0	11.2	3.1	2.8
	A/Cg	8–11	8.0	7.3	6.88	196	6.0	0.9	5.4	20.0	12.7	6.7	1.1	3.7
	Cse1	11–15.5	8.8	7.3	4.57	150	14.6	2.0	10.8	36.1	19.0	7.4	1.3	3.3
	Cse2	15.5–27.5	7.9	7.3	6.34	173	13.5	1.9	11.7	36.7	19.0	7.0	1.1	3.1
	Cse3	27.5–60+	7.9	7.3	6.55	198	15.5	1.7	12.3	39.4	19.0	9.1	1.3	3.2

CEC = cation exchangeable capacity.

species of both red (e.g., *Gracilaria* genus) and green algae (e.g. *Ulva* genus).

At the Gran Chiusa salt marsh (GC), *L. narbonense* was the dominant species in the GC-Sar1 site, whereas the GC-Sar2 showed a slight different species composition, with a similar abundance of both *L. narbonense* and *S. fruticosa*.

At the Mosconi dike salt marsh (MD), sampling concerned areas having the lowest maximum height with respect to the mean sea level among all the hydromorphic soils examined. The dominant species on the MD-Sp1 soil was *Spartina maritima*, while the MD-Sp2 profile refers to a confined brackish waterhole (*chiaro*). In this site with some *S. maritima* individuals and below shallow water, a thin (0–0.2 cm) dense orange-red film of organic fibers (fibric material) covered the surface.

3.2. Physicochemical characterization

The physicochemical characteristics of hydromorphic and SASs soils profiles of MM, GC and MD salt marshes are respectively shown in Tables 1–3.

In all soils, pH at sampling ranged between 6.7 and 8.6; in SASs the pH values determined after 16 weeks of wet incubation decreased up to 1.3 pH units. Electrical conductivity decreased with depth in both hydromorphic and submerged soils. In the deeper horizons (C and Cg) of the hydromorphic soils low EC is determined by infiltration of non-saline waters, whereas in the upper horizons of hydromorphic soils accumulation of salts is driven by surface evapotranspiration. Total carbonates content was larger in MM soils, which are located nearer to the lagoon inlets, being associated with the carbonatic sands deposited by the Adriatic sea. Generally, total organic C and N decreased with depth, but in MM soils, intercalations and accumulations of organic matter were observed at different depths along the soil profiles. In the MM-Lim profiles, a consistent accumulation of organic materials derived from the decomposition of roots and biomass residues (Tables 1 and 1S) was observed in the A2 and 2Ab horizons at depths between 5 and 20 cm, whereas in the MM-Sa profiles it occurred in past surface horizons (AC and ACse horizons of a buried soil) between 15 and 32 cm. In the MM-zos soil, TOC peaked between 52 and 63 cm below the surface. The C/N ratio ranged from 10 to 14 in all superficial horizons, independently from the soil vegetation cover. Generally the C/N ratio decreased with depth, although not always in a regular way.

In the GC and MD soils, dark sulphide bearing materials were

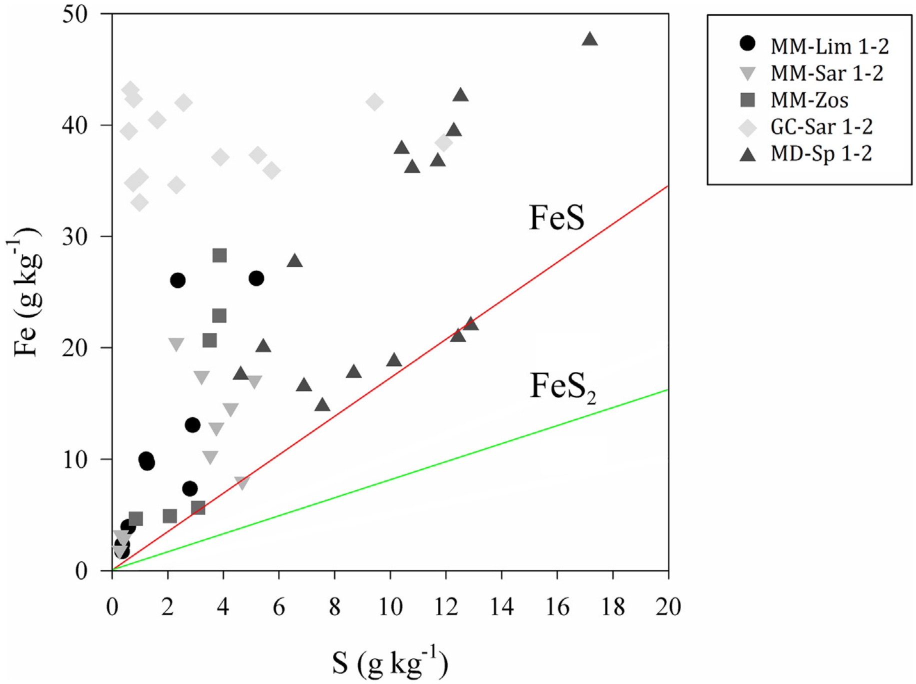


Fig. 3. Scatterplot between total sulfur (S) and iron (Fe), expressed as g kg^{-1}, considering all soil profiles examined.

detected, upon treatment with H_2O_2, in horizons laying below the mean low tide level. Their depth varied with soil elevation and in the submerged MM-Zos, they were also present in the top soil. Total S content ranged from 17.7 to 1.1 g kg^{-1} in the present superficial layers (e.g. A, Ag horizons) and in those belonging to buried surfaces of old soils (Ase horizons) and from 12.2 to 0.2 g kg^{-1} in deeper ones (e.g. C, Cg and Cse horizons). C/S ratios varied with depth and were larger at the surface in hydromorphic soil profiles, whereas in the MD-Spa2 and MM-Zos pedons larger values were found deeper along the profile. Plotting Fe and S contents of soil horizons (Fig. 3) yielded a strong linear correlation ($R^2 = 0.72$) for the MM and MD soils (including both submerged soils) which highlights a link in the accumulation of these two elements. The strongest S accumulation was found in MD soil horizons. A large excess of iron (Fig. 3) was detected in the GC pedons, which displayed Fe concentrations ranging between 32 and 43 g kg^{-1}.

3.3. Classification of hydromorphic and SASs profiles

According to their water saturation regimes, the soil profiles ranked into the *Aquents* and *Wassent* suborders (Soil Survey Staff, 2014). Nearer to the open sea, MM-Lim1 and 2 soils displayed the same sequence of horizons (O/A/Ab/C) and were classified as *Typic Psammaquents*, because of their sandy texture and presence of less than 35% of rock fragments. MM-Sar1 and Sar2 were characterized by accumulation of sulphides within 50 cm of the mineral soil surface as testified by their strong rotten egg smell and soil color change tests carried out in the field. These soils did not show any pH change upon exposure to oxygen, due to the buffering of carbonates, so they had to be classified as *Typic Psammaquents*, in spite of the large presence of sulphides. On the same salt marsh bar, the MM-Zos soil was classified as a *Typic Fluviwassent* because of a positive water potential during more than 21 h per day. This soil was characterized by the presence of a 41 cm thick buried layer enriched in organic materials (Table 1).

At the Gran Chiusa salt marsh, both GC-Sar1-2 pedons were classified as *Typic Fluvaquents* due to an irregular TOC profile within a depth of 25 cm. They were also characterized by the presence of sulphide bearing materials within 50 cm from the mineral soil surface (Table 2).

In the inner part of the Mosconi dike salt marsh bar, soil MD-Sp1 displayed an irregular decrease in organic C between 25 cm and a depth of 100 cm, and sulphide bearing materials with a combined thickness of at least 15 cm within 50 cm of the surface, was classified as *Typic Hydrowassents* because of its longer daily submergence. In the lowest part of the transect, MD-Sp2 was again classified as *Typic Hydrowassents*, since it has an irregular decrease of organic C. This soil has horizons with a combined thickness of a least 15 cm within 100 cm of mineral surface that contain sulphide bearing materials (Table 3), which do not exhibit pH changes upon exposure to oxygen.

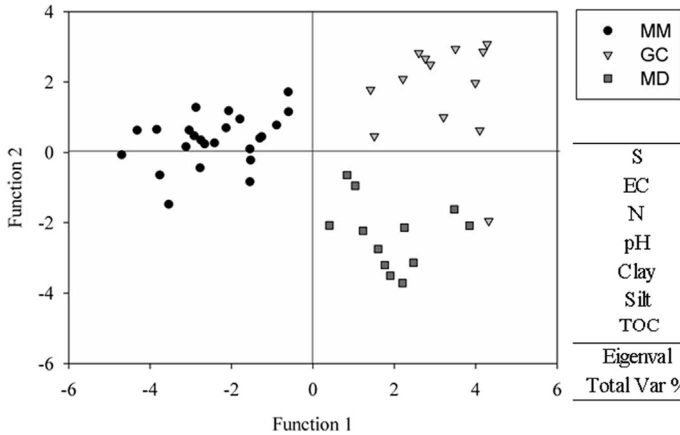
3.4. Characterization of salt marshes ecosystems

Discriminant function analysis was performed to identify the continuous variables related to the physicochemical properties which could discriminate the different soils according to their geomorphological position in the lagoon and their prevailing vegetation cover.

Differences among salt marsh soils were investigated, according to two independent functions and both standardized coefficients included in the model and the canonical score plot: Fig. 4 provides an evaluation of the separation of the different salt marsh soils according to their position.

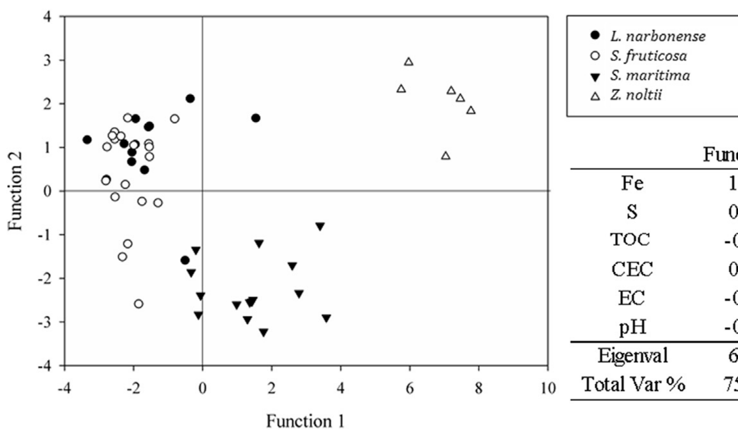
Function 1, was driven by TOC and N as positive SCDC and by EC and clay as negative factors. This allows to discriminate the older MM pedons, more rich in TOC, from those of the CG and MD salt marsh bars, which were characterized by larger total S and clay contents. Function 2 discriminated CG pedons from MD ones: total S content and EC were respectively identified as negative and positive coefficients. The analysis underlines the strong differentiation among the three salt marshes.

The second discriminant analysis highlights the influence of vegetation (Fig. 5). Function 1, mainly driven by EC in the positive



	Function 1	Function 2
S	0,10	-1,26
EC	-1,71	0,66
N	1,23	0,72
pH	0,67	0,93
Clay	-0,64	-0,18
Silt	0,30	0,23
TOC	1,03	0,36
Eigenval	8,26	2,22
Total Var %	76,77	20,63

Fig. 4. Canonical score plot of discriminant function analysis (DFA) among the main physicochemical variables of the representative soil profiles and profile locations.



	Function 1	Function 2
Fe	1,04	0,49
S	0,16	-1,01
TOC	-0,98	-0,35
CEC	0,30	0,36
EC	-0,76	1,10
pH	-0,85	0,90
Eigenval	6,94	2,31
Total Var %	75,03	24,97

Fig. 5. Canonical score plot of discriminant function analysis (DFA) among the main physicochemical variables of soil profiles and dominant plant species.

sector and by TOC as the negative one, outlined the separation of a great group characterized by the dominant coverage of *S. fruticosa* and *L. narbonense* from soils with either submerged or prevalently submerged species. Moreover, according to Function 2, the soil covered by *Z. noltii* (MM-Zos) was discriminated from the sites with dominant *S. maritima* in the MD salt marsh bar by EC in the positive sector and by S and TOC contents in the negative one.

Again according to Function 2 a distribution of soils both above and below the central line appears associated to the dominant presence of *S. fruticosa,* whereas *L. narbonense* was mainly confined in the positive according to Function 2 (EC) and in the negative according to Function 1 (TOC).

4. Discussion

The formation of salt marshes in the Grado and Marano Lagoon, occurred since the 4th century AD and originated from different marine and riverine sedimentation processes (Brambati, 1970). During time, some areas became permanently emerged, while others are now constantly submerged, contributing to the formation of tidal channels and subtidal zones (Ferrarin et al., 2010). In the study area, which lays far from riverine input sources, the distance from the open sea influences soil texture and soil development as highlighted by the first discriminant analysis (Fig. 4).

The back barrier MM salt marsh lies parallel to the sea and was formed by accumulation of calcareous sand deposits of marine origin, which are the main components of the parent material in C horizons. Based on discriminant analysis, the low Fe content and the high EC in the superficial horizons confirm both the influence of marine water intrusion and the accumulation of salts near the soil surface due to evaporation (Cidu et al., 2013; Rose and Waite, 2003). This trend is enhanced at the surface of soils located at higher position in the salt marsh microrelief.

The soil development from the SAS (MM-Zos) to the hydromorphic soils (MM-Sar and MM-Lim) is linked to an increasing accumulation of TOC on the topsoil, which ended with the formation of a thin organic O horizon in the upper soil profiles covered by *L. narbonense.* However, the discontinuous distribution of TOC, the presence of mottles, coats and organic fragments in deep horizons of MM soils, suggest that an intense combination of erosion-sedimentation events has occurred in the past (Bellucci et al., 2007).

This hypothesis is confirmed by C/N ratios which, in all soils, are little affected by plant cover and decrease irregularly along the soil profile. This index, which is a typical indicator of organic matter transformation, highlights that in these soils microbial activity is intense and that humification occurs more similar to well aerated soils (C/N = 10) than to anaerobic freshwater organic soil environments (C/N > 30). Even the deeper horizons of the MM-Zos soil display low C/N ratios which suggest that organic matter underwent decomposition before the occurrence of some dramatic subsidence or erosion/translocation event.

This hypothesis is further supported by CEC values of organic materials in mineral horizons, calculated from linear regressions (see Fig. 1S of supplementary materials) between CEC and TOC of the hydromorphic soils of the MM saltmarsh, where soils contain very little clay. Regression ($r^2 = 0.83$) for the MM-zos soil yielded a CEC of 274 $cmoles_{c+}$/kg TOC very close to that (283 $cmoles_{c+}$/kg TOC calculated for the hydromorphic soils of the same saltmarsh ($r^2 = 0.72$).

The strongly reduced (gley) C horizons of MM and GC hydromorphic soils as well as all the horizons in MD-Sp1-2 are characterized by C/S ratios below 5. Ivanov et al. (1989) pointed out that soils under recurrent or permanent anaerobic conditions have low C/S ratios that indicate accumulation of reduced sulfur forms. At present Soil Taxonomy does not provide for a way to recognize soils that have accumulated mineral iron sulfide phases, but which also contain substantial carbonates that would neutralize the acidity generated during oxidation. For this reason, in spite of the fact that sulphides accumulation reflected important pedogenic pathways, within these profiles, the GC-Sar1-2 pedons could not be classified in the sulfic great groups nor the MD-Sp2 pedon in the *Sulfiwassent* suborder.

The submerged MM-Zos, was the only pedon which featured large C/S ratios in horizons with bluish black to bluish gray color (Gley 2) in the deeper part of the profile. This feature can be explained by occurrence of footslope accumulation of upslope eroded materials, rich in organic matter and by the soil's mostly coarse sandy texture which permits diffusion of fresh water from the phreatic zone. The sequence from the inner MM salt marsh to its edge may not simply represent a soil hydrosequence, but reflects erosion/sorting/accumulation processes as in the Milne's second type of catena (hillslope with more than one type of parent rock). The evaluation of these phenomena, however, is made difficult by the on-going process of allochthonous sand sedimentation from the sea running from the MM-Zos surface to the MM-Sar and MM-Lim profiles (see Supplementary materials).

The silty clay loam texture and the high Fe content in GC soils suggest their formation was more influenced by sedimentation of re-suspended silt deposits of riverine particulates (Poulton, 2002) and soils are enriched in Fe due to weathering processes (Krachler et al., 2005). These soil sequences show pronounced accumulation processes linked not only to the reduction of sulfate, but also to the reductive dissolution of iron. The clay-silty texture of these soils, in fact, affects the diffusion of oxygen, allowing the onset of more severe anaerobic conditions, which are testified by accumulation of dark bluish-black sulphide bearing materials. These conditions, allow the formation of cambic horizons of at least 15 cm characterized by an increase of the Fe/S ratio, due either to a depletion of S above Cg and Cse horizons (in GC-Sar1) or to coatings of sesquioxides linked to the presence of redoximorphic features without any apparent Fe losses (GC-Sar2). The presence of many redoximorphic features up to 50 cm highlights the effect of the tide oscillation which induce the alternation of oxic/anoxic conditions, whereas in the deepest and permanently anoxic horizons, a stronger accumulation of sulphides occurs as a consequence of the reaction between sulphides and different reduced forms of Fe (Rickard and Morse, 2005).

At the MD salt marsh sites, the long submergence periods and finer clay-silty texture promote permanently anoxic conditions and accumulation of sulphide bearing materials in horizons deeper than respectively 46 cm (MD-Sp1) and 11 cm (MD-Sp2). MD-Sp2 in fact lays in one of the micro closed round basins (waterholes, *chiari*), which originate from subsidence due to structural failures associated to ground water fluctuations (Wysocki et al., 2012) and are typical of this type of salt marsh bars. The transition from the MD-Sp1 to the MD-Sp2 soil, highlights a much finer stratification derived from repeated accumulation of sorted materials, carried by surface flow of tidal or rain water. Permanently submerged conditions lead to enhanced TOC, Fe and S accumulation in the submerged profile compared to the surrounding hydromorphic soil.

It is well known that submerged mineral soils develop redoximorphic features due to the reduction, translocation and/or oxidation of iron and manganese oxides. Gley Munsell colors are associated to pale green reduced forms of Fe(II) in silicate minerals (Vepraskas and Fulkner, 2001) and are present in all soils starting from the level of the high tide. Redoximorphic features, associated with living roots, were observed in some gleyed horizons, confirming the great power of some plants to release oxygen and prevent anoxic conditions in the rhizosphere (Génin et al., 1998; Richardson et al., 2001).

The presence of several fragmented vegetation patterns in salt marshes is attributed to the degree of soil hydromorphism and sea water level (Silvestri et al., 2005).

Discriminant function analysis (Fig. 5) points out TOC and N as strong positive driving factors in the differentiation of soil properties following plant communities distribution. This highlights the action of feedback mechanisms among salt marsh soils and vegetation cover. Colonization by *L. narbonense* allows the development of well-structured organic and C-rich organo-mineral superficial layers, and strongly affects hydromorphic soil conditions through evapotranspiration, improved drainage and oxygen translocation to the root system. In soils submerged by shallow water, *S. maritima* contributes to differently characterize the submerged environment. Contrary to *L. narbonense*, the root system of *S. maritima* favors oxygen diffusion only near the surface because of its shallow root development (Pedersen et al., 2013; Zhang et al., 2006; Zuo et al., 2012).

On the other hand, its felt root system still allows for accumulation of poorly humified organic matter (Ding et al., 2010; Vann and Megonigal, 2003) and, according to its lower ability to accumulate C (Tables 1 and 3) and to diffuse oxygen (Pedersen et al., 2013; Zhang et al., 2006; Zuo et al., 2012), trigs a slower pedogenetic process.

5. Conclusions

Distinct pedogenetic processes affect the formation of closely located micro-environments on salt marshes due to a complex interaction of morphological, physical, chemical and biological factors.

The sandy coarse texture, which characterizes some back barrier saltmarshes, allows a more rapid drainage and subsurface oxygen exchange, and leads to less developed profiles in comparison to the silty-clay textured soils located farther from the sea. The genesis of soils in the Grado and Marano lagoon depends only in part on sediment type and length of submergence periods: the particular salt marsh morphology and the specific contribution of the vegetation are strong effecting factors that contribute to differentiate soils. Transitions from hydromorphic to submerged soils are particularly made complex by erosional/depositional processes that are acting also at micromorphological levels. Accumulation of sulphide bearing materials is a relevant pedogenetic process in these soils, but at present the Soil taxonomy, which focuses on the acidification potential of these materials, does not provide satisfactory ways to differentiate soils which also contain substantial carbonates.

Our study shows that vegetation plays an important role in the development of soils, also in these environments, by affecting organic matter accumulation and its distribution along the soil profiles. At the same time, a clear relationship exists between vegetation species and hydromorphology, confirming that these are non-independent variables of the system. The biodiversity observed within the same salt marsh is due to a very complex feedback mechanism: hydromorphic features influence the colonizing vegetation, which is subsequently modified by biologically driven factors as evapotranspiration, accumulation of C, transfer of oxygen to roots, stabilization and improvement of soil structure.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ecss.2016.02.004.

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