SOIL HYDROMORPHISM IN TWO SALINE AND BRACKISH SYSTEM: CLASSIFICATION, INDICATORS AND PEDOGENETIC PROCESSES

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Abstract

The introduction of the "*subaqueous soils*" into the international classification system of the Soil Taxonomy (2010) gives a possibility to soil scientists to use the pedogenetic approach to investigate coastal soils in view of resource protection and valorization. Coastal areas, in fact, are complex and fragile ecosystems whose ecological value is worldwide recognized, but generally highly inhabited and affected by different erosion and pollution phenomena, and flooding problems. The soil science has a great opportunity to contribute to the correct management and protection of coastal soils, by recognizing the value of coastal soils and thus investigating the effect of the water table oscillation and ionic composition to the changes of soil properties and functionality. This work represent a first attempt to describe the *soil continuum* existing from hydromorphic to subaqueous environment, highlighting the evidence of some pedogenetic processes into subaquatic substrates and demonstrating the high ecological values of these pedons.
Keyworks: *subaqueous soils, saline and brackish system, Soil Taxonomy, coastal areas, Grado and Marano lagoon*

Introduction

In most coastal areas, the presence of a saline water gradient, the alternation of freshwater and saltwater aquifer and the tide oscillation level, allow the evolution of particular ecosystems where the development of soil and vegetation patterns is strongly linked to the time of submergence, oxygen diffusion mechanisms, and high salinity levels (Ding et al., 2010; Zuo et al., 2012). The high ecological value of these environments ranges from the regulation of the bio-geo-chemical cycles of nutrients and trace elements, protection of water quality, biodiversity promotion and conservation, fish farming, recreation and many other ecosystem services (Barbier et al., 2011; de Groot et al., 2012). Despite their values, erosion processes of the coastal area, subsidence and saline intrusion are globally threatening these fragile environments, and changes of both climate conditions and hydrological regimes deeply influence their evolution and health (Lotze et al., 2006; Worm et al., 2006; Halpern et al. 2008). The International Panel on Climate Change (IPCC

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AR4 SY, 2007) estimates that the sea level will increase from 18 to 59 cm up to the end of the next century. If so, estuarine and wetland environments will largely expand and the land flooding will cause deep changes to both soil and environmental properties and functionality.

In order to provide useful tools for the management and protection of these environments, it is thus crucial that soil scientists increase their knowledge on the genesis of the soil in these transitional environments and on how soil properties and pedogenic processes can vary depending on the time and entity of water saturation (Surabian, 2007; Erich and Drohan, 2012).

In these areas, *hydromorphic or hydric soils* develop under partial or provisional water saturation conditions (Federal Register, July 13, 1994; Reddy and DeLaume, 2008) and are characterized by the continuous wetting and drying of soil horizons, and by the alternation of aerobic and anaerobic processes which strongly affect soil pedogenesis (Demas and Rabenhorst, 2001), soil properties and processes. On the other hand, the concept that sediments in shallow water environments are capable of supporting rooted plants, and undergo transformation and horizon differentiation, has led soil scientists to consider the hypothesis of a subaqueous pedogenetic process (Demas and Rabenhorst, 1999; Ellis et al., 2002) and to extend the definition of soil upper limit in the USDA Soil Taxonomy classification system, in order properly recognize and classify *subaqueous soils* (Soil Survey Staff, 2010). Demas and Rabenhorst (1999), in fact, found that, in submerged subaqueous environments, soils may develop similarly to subaerial terrestrial ones. In these contests, it has been demonstrated that presence of buried horizons, accumulation of biogenic $CaCO_3$, presence of benthic faunal and of organic components, etc. can be considered common pedogenic additions occurring in subaquatic substrates (Barko et al., 1991; Demas and Rabenhorst, 1999). Similarly to subaerial pedons, pedogenetic losses of nutrients can be observed though the distribution of organic carbon, which usually decreases with depth along the soil profile. In both systems, in fact, the mineralization of organic carbon occurs mostly thanks to the microbial metabolism, even if different degradation processes can be recognized (Roden, 2004; Vodyanitskii and Shoba, 2014) thanks to a different microbial biomass and enzymatic composition. Examples of transfers promoting soil horizons differentiation, include accumulations and depletions of iron and manganese species, diffusion and bioturbation from shellfish and worms (Fenchel and Riedl, 1970; Fanning and Fanning, 1989).

We think that the pedological approach can be a very useful tool for understanding the main biotic and abiotic processes that regulate the soil formation in coastal area; for this reason, mapping these resources from a soil classification and soil use point of view, can be the first step for a sustainable planning of the coast management in view of environmental protection and valorisation.

The aim of the study was to investigate soils affected by a different submergence level in two different pedo-climatic areas, in order to i) verify if there is a *soil continuum* between hydromorphic and subaqueous environment; ii) recognize differences and similarities among soil pedogenetic process, soil physicochemical properties and organic carbon store.

Materials and Methods

The study area

The Grado and Marano lagoon (SPA/SAC Nature 2000: IT3320037) is a saline system which extends between the Tagliamento and the Isonzo rivers estuaries in the Northern part of the Adriatic sea. The lagoon is separated from the open sea by 760 ha of islets and sandbanks which separate the inner lagoon from the open sea and which have a very important role for the protection form coastal erosion and for biodiversity conservation (Fontolan et al., 2012). Two different soil transects were investigated in this area, in two distinct salt marshes located in the inner and sea-exposed part of the lagoon, according to their typical vegetation cover as shown in Figure 1. The San Vitale park is a protected area of 1222 ha, which stands in the southern part of the Po Estuary Regional Park (Northern Italy).

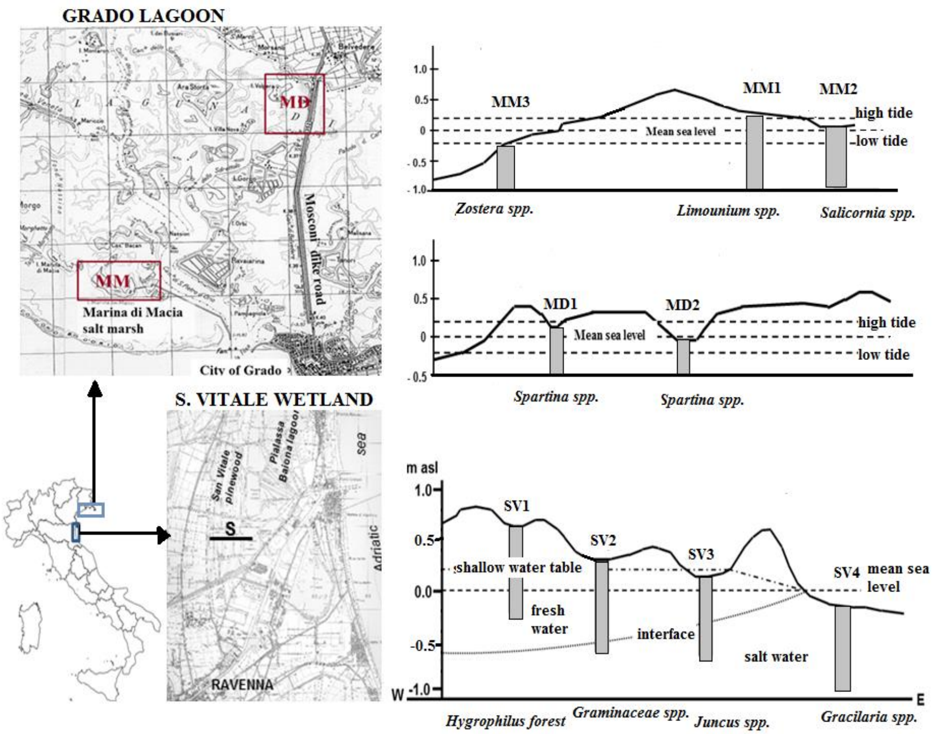

Figure 1. *Map of the two study area: Grado Lagoon and S. Vitale Wetland (Northern Italy)*

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A long sedimentation process allowed for the evolution of a dune/intra-dune coastal system and of an alluvial wetland called "*Pialassa*", which span the boundary between the main land and the open sea and it is crossed by several canals which serve as drainage of the inland waters (Veggiani, 1974; Buscaroli et al., 2011). Rainfalls, temperature oscillations, and evapotranspiration phenomena deeply affect the groundwater level and the magnitude of saline intrusion in the deep aquifer (Castiglioni et al., 1999; Amorosi et al., 2005). Moreover, the exploitation of freshwater aquifer for agricultural purposes has caused a rise of the fresh *vs* salt water interface and consequently the increase of saline intrusion problems (Buscaroli and Zannoni, 2010). A soil transect was traced from the hydromorphic inner and higher part of the wetland to the lower zone of the area and soil profiles were excavated and studied according to their typical vegetation cover as shown in Figure 1.

Soil sampling and morphological description

The pedological survey on both systems was carried on during summer season 2013 and 2014. Hydromorphic soil profiles were excavated up to 1 m depth and each genetic horizon was described in field according to Schoeneberger et al. (2012). The morphological features recorded, included horizon depth, boundary, Munsell colour (wet), consistence of the matrix, presence of coats/films and redoximorphic features, roots and biological concentration. Samples were then sealed in polyethylene bags and stored at 4°C until analysis.

Subaqueous soil profiles were collected using a vibracore Beeker sampler, (Eijkelkamp, NL), equipped with a 6 cm polyethylene tube (McVey et al., 2012). Sample cores were immediately sealed with a tight stopper to avoid oxygen infiltration and stored at 4 °C until any morphological and analytical manipulation. Soil columns were extracted in laboratory on a suitable support and each genetic horizon was described for its depth, boundary, Munsell colour (wet), coats/films and redoximorphic features, organic fragments, fluidity class (McVey et al. 2012). The presence of monosulphides was observed though the colour response of the matrix after adding some drops of 3% H_2O_2 (McVey et al. 2012) and by recording the odour description of each soil horizon (Fanning and Fanning 1989; Fanning et al. 2002). Effects of reducing conditions on soil colour (gleyfication) were investigated by field observations (Munsell colour recording and redoximorphic feature description).

Soil physico-chemical characterization and statistical analysis

All soils samples were air-dried and sieved at 2 mm before analysis (Balduff, 2007). Electrical conductivity (EC) was measured on 1:2.5 w:v. Particle size distribution was determined by the pipette method (Gee and Bauder, 1986). Total Organic Carbon and Total Nitrogen were measured with an EA 1110 Thermo Fisher CHN elemental analyser after dissolution of carbonates with 2M HCl. The pseudo-total concentration of S and Fe was detected by Inductive Coupled Plasma – Optic Emission Spectroscopy (ICP-OES, Ametek, Germany) after treating samples with aqua regia (6ml HCl and 2ml HNO_3 suprapure, Fluka) in microwave oven (Millestone, 1200) according to Vittori Antisari et al. (2011). All analysis were performed in duplicate and BCR Reference Standard Materials (BCR 320 and BCR 142) were used to check the accuracy of the measures.

Results

Soil Classification

Both hydromorphic and subaqueous soils showed little development and no diagnostic horizon was identify. For this reason, all soil profiles were ascribed to *Entisols* order and, according to the Keys of Soil Taxonomy 12th edition (Soil Survey Staff, 2014). The soils characterized by aquic conditions at a depth between 40 and 50 cm were ranked into *Aquent* suborder (MM1, MM2, SV1, SV2), while those distinguished by a positive water potential at the soil surface for more than 21 h of each day in all years were ranked into *Wassent* one (MM3, MD1, MD2, SV3, SV4).

As shown in Figure 2a, in the Grado lagoon, the fringing salt marsh (MM) was characterized by sandy soils with few intercalation of silt material (MM1, MM2: *Psammaquent*), and some important silty clay one in the subaqueous one (MM3) which didn't allow this pedon to enter in the *Psammowassent* group. On the contrary, in the back barrier, MD salt marsh soils were composed by finer material and were classified as silty loam and loamy pedons.

In S. Vitale wetland all pedons had sandy parent materials, with some intercalation of sandy loam and silty loam horizons along the soil profiles (SV1, SV2: *Psammaquent;* SV3: *Psammowassent*). The only exception was SV4 pedon, where some clay and silty clay loam horizons were also present.

The colour of the soil matrix, as presented in Figure 2b, ranged from Reddish colours (10YR) to yellowish (2.5Y) and Gley one (generally 10Y, 5GY and N) according to the level of the water table oscillation (either considering the groundwater table and the tide variation).

In some horizons, black colours were also associated to the presence of sufuric materials (MM3, MD1, SV4, *Sulfiwassent*). Moreover, the pedogenetic horizons affected by aeration during low tide, generally displayed the presence of redoximorphic features (Figure 2a), characterized by reddish concentration and/or black nodules and masses due to the effect of Fe and Mn oxidation and reduction. Presence of fine roots and organic fragments were also detected in most of these horizons and in subaqueous pedons, different intercalations of low decomposed organic matter were observed along the soil profiles.

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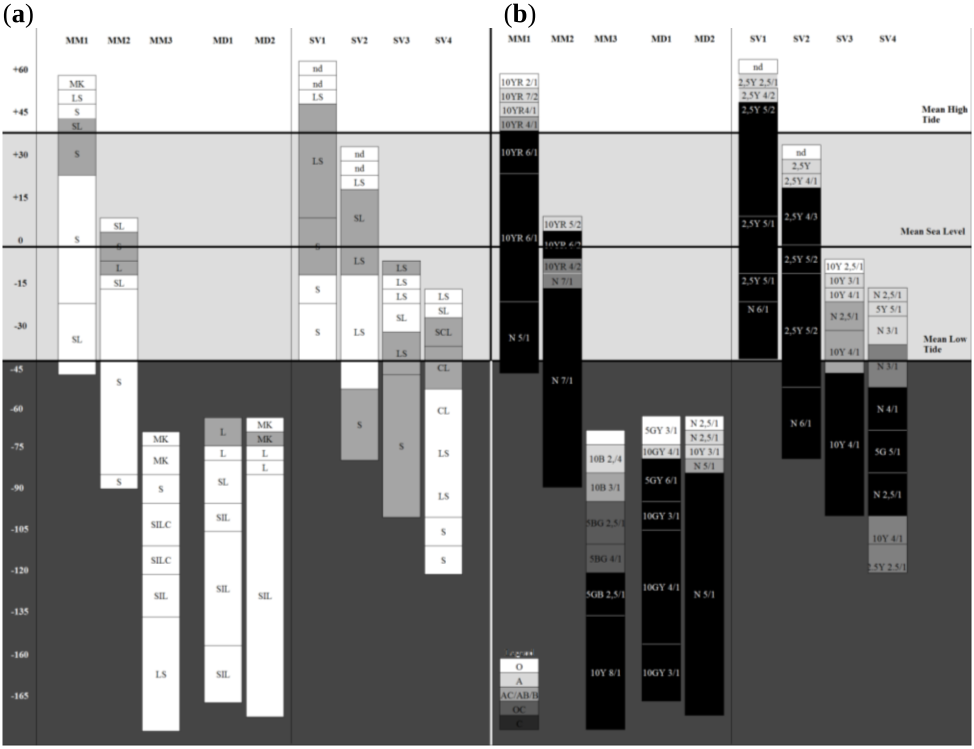

Figure 2. *Schematic representation of soil texture and redoximorphic features* (**a**) *and soil matrix colour* (**b**).
S= Sandy; SL=Sandy loam; LS= Loamy sand; SIL= Silty loam; SILC= Silty Clay Loam; CL= Clay; L= Loam; MK= Mucky. Grey colour: redoximorphic features

Soil features and physicochemical properties

Soil salinity, in both systems, was evaluated through the measurement of the Electrical Conductivity (EC), and it was compared to the trend of organic carbon (OC) along each soil profile, as shown in Figure 3.

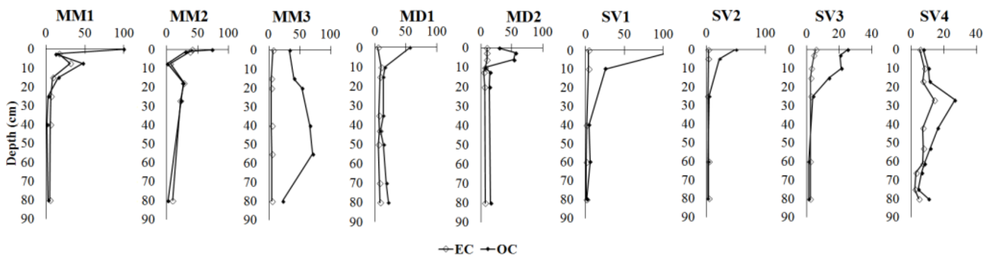

Figure 3. *Distribution of EC (mS cm^{-1}) and OC (g Kg^{-1}) detected along each soil profiles.*

In both Grando and S. Vitale study areas, all hydromorphic soils showed an accumulation of soluble salts on their soil surface, followed by a rapid decrease in the deeper horizons, especially in the sandy C horizon of MM2, characterized by low content of organic matter between 5 and 15 cm. On the other hand, the subaqueous pedons showed relative low levels of EC and a quite homogeneous distribution along the soil profile, with exception of SV4 pedon, where a very irregular decrease of EC was detected. As expected, the EC level in the salt marshes of the Grado Lagoon was generally higher than that of S. Vitale wetland: in the latter, the salinity generally increased from the subaqueous to the hydromorphic system and in some pedons (e.g. SV2, SV4) an increase of soil EC in the deep C horizons was also recorded.
In MM hydromorphic pedons of Grado Lagoon, the distribution of both EC and OC along the soil profiles followed the same trend, while in the subaqueous profiles, OC accumulation were detected at different depth (MD2: *Fluviwassent*), without showing any correlation with the EC. Notably, in all pedons of S. Vitale wetland, the EC increase corresponded to OC accumulations, and this was more evident in the subaqueous pedons (SV3 and SV4) than in the hydromorphic one, where a very high content of OC was detected in the superficial organo-mineral horizons (118 and 49 g Kg^{-1} in SV1 and SV2 respectively).

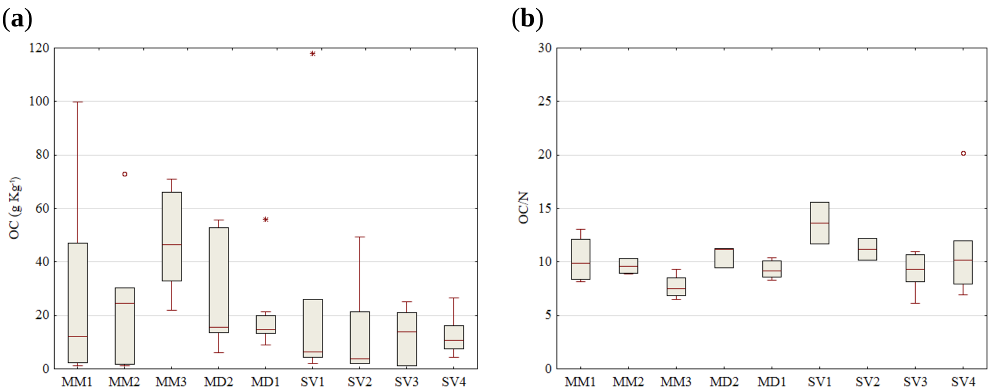

Figure 4. *Quartile distribution of the Organic Carbon* (**a**) *and of the C/N ratio* (**b**) *in each soil profiles.*

The quartile distribution of the organic carbon (OC) along the soil profiles is shown in Figure 4a and it shows that salt marshes soils had a higher content of OC than wetland one (p=0.049). In the organo-mineral soils of Grado Lagoon, in fact, the OC content ranged between 12 and 73 g Kg^{-1} with a hotspot of 100 g Kg^{-1} in MM1 organic horizon, while in S. Vitale wetland soils it ranged between 7 and 49 g Kg^{-1}, with a hotspot of 118 g Kg^{-1} in the organic horizon of SV1 pedon. By

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considering only organo-mineral O and A horizons, the statistical differences between the two system was even more significant (*p*=0.005).
The OC/N ratio was quite similar in all soil profiles, ranging meanly between 9 and 8 in the hydromorphic and the subaqueous pedons respectively. In this case, by considering only the organo-mineral horizons of the pedons, which represent the pedogenetic active part of the pedon (Figure 4.b), the C/N ratio ranged between 11 and 9 in the two different groups, showing a slight decrease in the subaqueous soils (*p*>0.05).

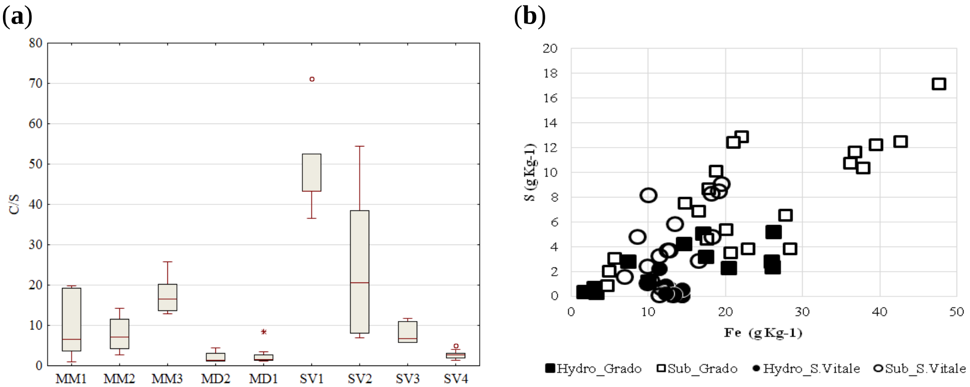

Figure 5. *Quartile distribution of the C/S ratio in each soil profile* (**a**), *and linear correlation between total Fe and S* (**b**).

The ratio between OC and S (Figure 5a) was calculated to describe the occurrence of anoxic phenomena, and it shows how in both systems, the index was lower in the subaqueous soils than in the hydromorphic one (*p*< 0.001), with exception of MM3 pedon. Subaqueous pedons (MD1, MD2 and SV4), in fact, presented a C/S ratio always lower than 5 while SV3 subaqueous pedon showed a C/S ratio between 5 and 12. Generally, the soil horizons affected by low C/S ratio, were those where the changing of the matrix colour and the smell of the soil, drove the classification of *sulphuric* horizons. The positive correlation between Fe and S showed in Figure 5b highlighted the high content of these elements in both hydromorphic and subaqueous pedons, especially in subaqueous soils of Grado Lagoon, which presented the highest content of both Fe and S.

<u>Discussion</u>

Both S. Vitale wetland and Grado Lagoon salt marshes have been formed by different processes linked to centuries of riverine and marine deposits sedimentation, and by different human interventions in the coastal areas of the Adriatic sea, such as land canalization in S. Vitale area, and dredging operations in Grado Lagoon (Buscaroli and Zannoni, 2010; Fontolan et al., 2012).

Although a different entity of marine *vs* riverine depositions, a different hydrogeological background, a different morphology of the coast and a different vegetation pattern, all hydromorphic and all subaqueous soils showed some common characteristics in terms of pedogenetic features, chemical properties and soil development.

In fact, in both areas, soils were little developed showing an A/C pedosequence and only in some cases a thin organic O horizon was recorded. The appearance of gley colours in the soil matrix and the presence of redoximorphic features, in all studied pedons, clearly indicate the *gleyfication* processes due to prolonged water saturation of the soil, and to the effect of water table oscillation along the soil profiles. This phenomena results in the alternation of wet/dry cycle of soil horizons and induce the reduction, translocation and/or oxidation of iron and manganese oxides (Schaetzl and Anderson 2005). The development of redoximorphic features, as shown in MD1 and MD2 profiles, is also due to the presence of plants roots, which strongly contribute to diffuse oxygen and prevent anoxic conditions (Génin et al. 1998; Richardson et al. 2001). Only in SV3 profile, redoximorphic features were detected in deeper horizons were no living roots were found, suggesting that the presence of a loamy sandy layer above a sandy horizons, allows the water retention in the upper saturated horizon, followed by a rapid drainage in the deeper one, allowing the formation of oxidized masses of Fe^{3+}.

Generally hydromorphic soils (*Aquent*) were characterized by a sandy texture and a different intensity of superficial accumulation of salts due to marine aerosol depositions, precipitations, evapotranspiration phenomena and retention of salts by the organic matter (Salama et al. 1999; Rose and Waite 2003; Cidu et al. 2013), while anoxic phenomena occurred only rarely (MM2). These soils, in fact, were classified as *Sodic Psammaquent* (SV1 and SV2), *Typic Psammaquent* (MM1), *Sulfic Psammaquents* (MM2).

On the other hand, subaqueous one (*Wassent*) presented different intercalations of fine materials (silt or clay) and of organic carbon, due to the continuous effect of sediment transportation and erosion by water, and to the low decomposition rate of organic matter under anoxic conditions (Reddy and DeLaume 2008). Moreover, subaqueous soils were characterized by a lower salinity level than the hydromorphic one, due to salt leaching processes though the marine flow (Friedman 2005; Bennett et al. 2009), and by the presence of sulphuric materials, due to the reduction of sulphur from SO_4^- present in the saline waters, to S^{2-} forms. The *sulfidization* process, in fact, is very common in anoxic soils and sediments (Fanning et al. 2002; Meyer and Kump 2008), thanks to the presence of a source of sulphate, a source of reactive Fe^{2+}, organic matter as microbial substrate and anaerobic conditions (Demas and Rabenhorst 1999). The occurrence of sulfidization in subaqueous soils, was also confirmed by the evaluation of the C/S ratio, which is commonly used to identify the evolving of anoxic conditions in soils and sediments, together with the occurrence of pyrite precipitation (Demas and

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Rabenhorst 1999). The values of C/S ratio obtained from our soil samples, highlight the significant difference between hydromorphic and subaqueous pedons, highlighting a specific pedogenetic transformation process occurring in tidal marshes and shallow water environments affected by estuarine and marine waters. The subaqueous E*ntisols*, therefore, were classified as *Sulfic Psammowassent* (SV3), *Fluventic Sulfiwassent* (SV4), *Thapto-histic Fluviwassent* (MM3), *Sulfic Fluviwassent* (MD1) *and Fluventic Sulfiwassent* (MD2).

The analysis of the distribution of Organic Carbon reveals that these systems act as important C sink (Reddy and DeLaume 2008), highlighting their important role for the environmental sustainability and protection. Despite the presence of a dense pinewood ecosystem in S. Vitale park (Marinari et al. 2012), the OC amount of its soils was lower than that of Grado Lagoon, where only halophitic vegetation was present. These species, in fact, have a shorter life cycle than that of the arbor species of S. Vitale, and probably for this reason a larger amount of biomass can be deposited on the soil surface every year. Moreover in lagoonal systems, during winter seasons, or during extraordinary high tides and raining events, the mean tide levels rises and cover all the salt marshes surface (ARPA 2008; Fontolan et al. 2012), allowing a slower degradation of the organic matter, but also providing a continuous supply of C compounds on the salt marshes soils.

Notably the C/N ratio is commonly used to evaluate the microbial decomposition of organic matter. At the time of our sampling survey, the C/N ration observed in the organo-mineral soils were similar to those of terrestrial soils (Demas and Rabenhorst 1999). These results, highlight that there is no significant difference between hydromorphic and subaqueous soils organic microbial degradation, and suggest that the C/N ratio can be used to evaluate the transformations of fresh organic matter to other humic substances even in subaqueous soils. However, further investigations should be carried on, to evaluate the rata and the quality of subaquatic humification process.

Conclusion

The analysis of two different coastal system aimed to investigate the existence of a soil continuum from a hydromorphic to a subaqueous environment. In the two study areas, S. Vitale coastal wetland and Grado lagoon salt marshes, it was possible to classify different kind of *Entisols*, and to highlight some common features occurring in tidal soil ecosystems. All coastal soils, in fact, reveals the same gleyfication process, and the presence of redoximorphic features along the soil profiles, highlights the role of both the water table oscillation and of living roots on the chemical transformation of Fe and Mn oxides. The analysis of organic carbon and of the C/N reveals that these soils are someway similar to terrestrial soil and further investigations should focus on the qualitative composition of the sub-aquatic organic matter.

However, this study highlighted some distinct pedogenetic processes affecting soils along the hydrosequence. The presence of several intercalation of fine materials within sandy parent materials and of organic carbon, indicate the influence of sedimentary processes affecting mostly subaqueous soils, but also the presence of pedogenetic transfer occurring in terrestrial systems as well as in subaqueous substrates. These latter are well characterized by sulfidization processes, which strongly contribute to mineral transformations mediated by both chemical and microbial processes in SO_4^- rich aquatic environment. On the other hand, the emergence of coastal soils, results in salt accumulation processes, which may induce sodicity problems.

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