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Soil properties and plant community relationship in a saltmarsh of the Grado and Marano lagoon (Northern Italy)
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Abstract:	Purpose: The relationship between soil properties and plant communities were investigated in Grado and Marano lagoon saltmarsh (North Italy), where hydrology and micro-morphology strongly influence the features of the ecosystem. A multidisciplinary approach aimed to assess the change of soil properties and plant community in relation to submergence of soil. Methods: Both plant communities and soil profiles survey was carried out along a transect in six sampling sites of the Gran Chiusa saltmarsh (Grado and Marano lagoon). Morphological and physicochemical parameters of soil profiles were investigated and soils were classified according to Soil Taxonomy. Inductively Coupled Plasma-Optical Emission Spectrometry detected macronutrients in both soils and plants. Cluster and linear discriminant analysis were used to assist the dataset interpretation of both plant communities and soils properties, respectively. The bioconcentration factor investigated the relationship of macronutrients between plant community and soil Results: A high, middle and low zone were identified by clustering of plant communities along studied transect. The discriminant analysis showed how the increasing of the soil submergence supported an accumulation of S and Ca content and depletion of Fe and Na. The development of different plant communities were linked to both soil water saturation and to the capacity of halophytes to tolerate anoxic conditions or salinity, by extrusion or bioconcentration strategies. Conclusions: This study demonstrates that tide level plays an important role on pedological development and chemical transformations along a soil hydrosequence.

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Soil properties and plant community relationship in a saltmarsh of the Grado and Marano lagoon (Northern Italy)

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Keywords: saltmarsh, hydromorphic soil, subaqueous soil, plant community, transition, submergence

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Abstract

Purpose: The relationship between soil properties and plant communities were investigated in Grado and Marano lagoon saltmarsh (North Italy), where hydrology and micro-morphology strongly influence the features of the ecosystem. A multidisciplinary approach aimed to assess the change of soil properties and plant community in relation to submergence of soil.

Methods: Both plant communities and soil profiles survey was carried out along a transect in six sampling sites of the Gran Chiusa saltmarsh (Grado and Marano lagoon). Morphological and physicochemical parameters of soil profiles were investigated and soils were classified according to Soil Taxonomy. Inductively Coupled Plasma-Optical Emission Spectrometry detected macronutrients in both soils and plants. Cluster and linear discriminant analysis were used to assist the dataset interpretation of both plant communities and soils properties, respectively. The bioconcentration factor investigated the relationship of macronutrients between plant community and soil

Results: A high, middle and low zone were identified by clustering of plant communities along studied transect. The discriminant analysis showed how the increasing of the soil submergence supported an accumulation of S and Ca content and depletion of Fe and Na. The development of different plant communities were linked to both soil water saturation and to the capacity of halophytes to tolerate anoxic conditions or salinity, by extrusion or bioconcentration strategies.

Conclusions: This study demonstrates that tide level plays an important role on pedological development and chemical transformations along a soil hydrosequence. The vegetation micromosaic can therefore represent a useful index of the hydrological and nutritional status of the underlying soils and be used to predict changes in coastal ecosystems.

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Introduction

Coastal ecosystems are complex and fragile systems which high ecological value is worldwide recognized (Barbier et al., 2011; Reddy and DeLaume, 2008). They harbor high biodiversity levels, providing important habitats for a large number of both migratory and resident birds and support important ecosystem services such as, regulation of the bio-geo-chemical cycles of nutrients and trace elements (de Groot et al., 2012; Gedan et al., 2010; Homann and Grigal, 1996; Ponnamperuma, 1972).

Moreover, about 10% of the global population live in coastal areas (McGranahan et al., 2007; UNEP, 2006), and local economies are often based on fishery, farming and tourism (Beaumont et al., 2007; Worm et al., 2006). The rising of the sea level (IPCC AR4 SYR, 2007) and the overexploitation of coastal areas have led to the increase of erosion processes and to a considerable reduction and degradation of coastal habitats (Halpern et al., 2008; Lotze et al., 2006), in particular those of saltmarshes and mudflats. The degradation of these ecosystems, leads to serious problems linked to land management (Fontolan et al., 2012), protection and maintenance of the inner shore line and for wildlife conservation (Beaumont et al., 2007; Ferrarin et al., 2010).

The consolidation of saltmarshes and mudflats can be considerably improved by halophytes, which foster soil pedogenesis retaining sediments with roots, affecting the redox conditions in the rhizosphere, and providing an important source of organic carbon for microbial communities and soil development (Laanbroek, 2010; Nyman et al., 1993; Reddy and DeLaume, 2008). In this context, the halophytic vegetation appears to be characterized by a micromosaic distribution that can be linked to the properties of the soils underneath (Álvarez Rogel et al., 2001; Van Wijnen and Bakker, 1999). In these environments, soil hydrology has a profound effect on plant colonization, and the inability to define a general evolutionary trend, testify the complexity of the system (Silvestri et al., 2005). In this study, soil properties and plant communities changes were investigated along an increasing gradient of flooding

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and anoxic stress conditions, considering also salinity and nutrients availability (Álvarez Rogel et al., 2001; Van Wijnen and Bakker, 1999). According to the Demas' theory on soil subaqueous soils (Demas and Rabenhorst, 1999), Ferronato et al. (2016) considered the formation and development of *soil continuum* from subaqueous to hydromorphic system.

In this context, the bathymetry, as a proxy of waterlogging, can be considered as one of the main soil forming factor (Demas and Rabenhorst, 2001), which influences several abiotic and biotic factors linked to the hydrodynamic of saltmarshes, such as the variability of soil properties and the occurrence of different pedogenetic processes along a soil hydrosequence.

The number of soil profiles that need to be excavated is a key issue in soil surveys. Decisions are based on the well-known connections between topography and soil substrate on one side and ecological communities, on the other (Wysocki et al., 2012). However, the assessment of variations in a saltmarsh environment, where subtle variations in height (microrelief) have profound effect on soil hydrology, is much more challenging.

In agreement with this view, a soils hydrosequence and the related vegetation cover were studied in the saltmarsh of the Gran Chiusa Isles (Grado and Marano Lagoon, northern Italy). In this study, a cross section of the island, traced from the inner part to the submerged zone, was surveyed. Both plant community distribution and soil survey were carried out with the aim to: i) describe the change of soil properties according to the frequency and length of the soil submergence, and ii) define the relationship among soil position in the hydromorphic sequence, its properties, and plant cover values.

Materials and methods

The study area

The Grado and Marano lagoon (SPA/SAC Nature 2000: IT3320037) is one of the largest Italian lagoons. It extends for 160 km^2 between the Tagliamento and the Isonzo river mouths in the Northern Adriatic Sea. The lagoon is delimited by seven natural barriers, which are

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separated by lagoon inlets (Brambati et al., 1998). The climate of the area is classified as "temperate/mesothermal" (Peel and Bloschl, 2011), characterized by mean annual temperature of 15.1 °C and by 969 mm yr^{-1} of precipitation (OSMER, 2016). Water temperatures range between 5-7°C in winter and 28-30°C in summer and the tide oscillation range between 65 and 105 cm (Ferrarin et al., 2010).

The sampling survey was performed in July 2014 on the main saltmarsh area of the Gran Chiusa Isles, a great complex of saltmarshes of about 0.87 km^2, located in the central part of the lagoon, in the Buso basin. According to the LIDAR models, this area reaches elevations of about 70 cm on the a.m.s.l. on its abrupt canal margin, and presents a gradual depression in the inner part of the saltmarsh. However, the increase of the sea level (ICCP, 2007) and periodical field observations made difficult to establish to establish the exact 0 m a.m.s.l. and the absolute altitudes of the tidal area. Several channels branch out the saltmarsh in all directions, some of them, with straight and regular features, testify the former use of this saltmarsh as a fishing valley.

Sampling method and field analysis

A 70 m long transect was traced from the inner part to the edge of the salt marsh and sampling sites (form GC-a to GC-f) were selected according to six different zones of site-specific topography, hydroperiod (hours per day^{-1}, ISPRA, 2013) and vegetation cover (Figure 1). Notice that the quotes reported in Figure 1 have been corrected according to field observation (Fontolan et al., 2013).

In each site, the vegetation surveys were conducted in three plots of 4 m^2 (2x2 m) within each area. Plant communities were described referring to the most abundant species (percentage of cover), following the nomenclature reported in Biondi et al. (2014). Nomenclature of plant taxa followed the latest Italian check list of vascular plants (Conti et al., 2005). In each site,

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samples of the most representative and abundant species were collected in plastic cases, and stored at 4° C until analysis.

In each site, a soil profile was excavated or collected using a Beeker vibracore sampler (Eijkelkamp, NL) equipped with a polyethylene tube with a diameter of 6 cm. Soil profiles were described in field according to the guideline of McVey et al. (2012) and of Schoeneberger et al. (2012), including the H_2O_2, and colour change and soil incubation test for the detection of sulphidic materials (Fanning et al., 2002; McVey et al., 2012). Each soil profile was further classified according to the USDA Soil Taxonomy (Soil Survey Staff, 2014). In order to avoid oxygen infiltration, samples were immediately sealed with a tight stopper and stored at 4 ° C, until laboratory analysis.

Soil and plant samples analysis

For the physicochemical characterization, samples were air-dried and sieved at 2 mm and soil particle size distribution was determined by pipette method (Gee and Bauder, 1986). The pH (pHmeter, Crison, Germany) and the electrical conductivity (EC; conductimeter Orion, Germany) of each sample were measured on 1:2.5 (w:v) soil:distilled water suspension. The content of total carbonates ($CaCO_3$) were quantified by volumetric method (Loeppert and Suarez, 1996), while the total organic carbon (OC) and total nitrogen (TN) were measured by Dumas combustion with a CHN elemental analyser (EA 1110 Thermo Fisher, USA) after dissolution of carbonates with 2 M HCl.

For the detection of total macro elements content, samples were finely grounded and digest with *aqua regia* solution in a microwave oven (Milestone, 1200). Inductive Coupled Plasma-Optic Emission Spectroscopy (ICP-OES, Ametek, Germany) processed the mineralized soil solution.

Plant samples were washed in deionized water in order to remove soluble salts and sediment deposited on the tissues and then oven-dried at 60°C for 48h. The content of total macro

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elements was determined by Inductive Coupled Plasma- Optic Emission Spectroscopy (ICP-OES, Ametek, Germany) after digestion of the finely grounded dry biomass in microwave oven with a solution of H_2O_2 and HNO_3 (2:6 v:v) according to Vittori Antisari et al. (2011). All analyses were performed in duplicate; reference materials (BCR-320R and BCR 062) and reagent blanks were used to check the accuracy of the measurements and the agreement was typically 10%.

Data analysis

Differences between the chemical composition of soil samples were evaluated with one way analysis of variance (ANOVA) and post-hoc tests (Tukey test, $p<0.05$), whereas a Student's t test was applied to check for plant samples composition difference. Normality of data was verified using the Shapiro's test for normality ($p>0.05$), while the homogeneity of variances was tested using the Bartlett's test ($p>0.05$).

A multivariate approach was used to assist the interpretation of the dataset. A hierarchical cluster analysis, using the Bray-Curtis dissimilarity as distance matrix and the complete link method for the clustering, was performed to describe the sites plant communities. A discriminant analysis (DA) with forward stepwise method was performed to identify the key variables that discriminate the different soil profiles according to their vegetation cover (Wilk's lambda<0.0009; $p<0.001$). The standardized canonical discriminant coefficients were evaluated to rank the importance of each variables while the structure matrix was used to assign meaningful labels to the linear discriminant functions (LD). The soil-plant relationships were investigated through the calculation of the bioconcentration factor (BCF) of macronutrients in each plant community. The BCF was calculated as the ratio between the total element concentration in plant (mg kg^{-1}) and in the soil (g kg^{-1}) according to Li and Zheng (2011).

Results

Vegetation pattern along the hydrosequence

The characterization of plant communities along the hydrosequence was performed by a cluster analysis. The analysis of the dendrogram (Figure 2) showed the presence of two cut levels (i.e. 0.98 and 0.70). The first indicated three main clusters (clusters 1, 2, 3), corresponding to the high (cluster 2), middle (cluster 3) and subaqueous (cluster 1) part of the saltmarsh. The latter was characterized by green algae cover (cluster 1), whereas in cluster 2 and 3, further five different subclusters were identified (namely, A, B, C, D, E).

Within cluster 2, subcluster B referred to the vegetation class of *Juncetea maritimi*, representing the mediterranean perennial salty and brackish grasslands; subcluster C encompassed both GC-b and GC-c zones, referred to *Sarcocornietea fruticosae* class, that includes pioneer, perennial, hyperhalophilous, succulent, woody and semi-woody plant communities. In subcluster B, the most abundant plant, occurring in all plots, was *Juncus maritimus* (80% on average), followed by *Limonium narbonense* (27%) *Sarcocornia fruticosa* (23%) and *Atriplex portulacoides* (12%), while in the latter (subcluster C), the most aboundant species were *L. narbonense* (65%), *S. fruticosa* (13%) and *Spartina maritima* (13%).

Similarly, also cluster 3 can be interpreted as a combination of two different vegetation patterns found in the middle zone (Figure 2, subcluster D and E). The subcluster D showed a mean cover of 95% of *Sp. maritima* and was ascribed to the *Spartinetea glabrae* class, which include all pioneer vegetation of perennial formations that grow on muddy brackish soils inundated for long period. The subcluster E showed the prevalence of *Salicornia patula* (72%) and referred to the class *Thero-Suaedetea splendentis*, encompassing all pioneer communities of annual species of the genus *Salicornia*, in temporarily inundated saltmarsh sites and in saltpans.

Classification and properties of soil hydrosequence

The morphological description of soil profiles (Table 1S) highlighted that all soils were little developed with a silty or silty loam texture, generally showing an A/AC/C pedosequence, except for the presence of BC horizons in the GC-a profile, and of a L (limnic) horizon in the GC-f pedon. (Table 1S).

Figure 3 summarizes some of the morphological features of soil profiles. The pedons in the high zone (GC-a, GC-b and GC-c, cluster 2) presented many roots sheaths in the topsoil and some shell fragments in the deeper C horizon. Conversely, the pedons located in the submerged zone (GC-d, GC-e and GC-f, cluster 3 and 1, respectively) presented common shell fragments in the A horizons and organic films and concentrations in the deeper one. Sulphidic materials were detected in the topsoil of the highest pedons and in the subsoil of submerged profiles, and increased from the inner part of the saltmarsh to its edge (Figure 3). Despite the accumulation of these materials in the investigated pedons, *sulfic* horizons were not detected because of the lack of pH failure during aerobic incubation (McVey et al, 2012).

All the soil profiles collected in GC-a, GC-b, GC-c and GC-d zones showed evidence of aquic conditions, due to periodic saturation and reduction processes, while GC-e and GC-f pedons had a positive water potential at the soil surface for more than 21 hours per day (ISPRA, 2013; Soil Survey Staff, 2014) and were thus ranked into the *Wassent* suborder. Soil profiles in the high part of the saltmarsh (GC-a, GC-b and GC-c, Cluster 2) were classified as *Typic Endoaquent,* while in the middle part (cluster 3), the classification of GC-d and GC-e fell into the *Typic Hydraquent* and *Typic Hydrowassent* great groups respectively. In the lowest part of the saltmarsh (Cluster 1), GC-f pedon was classified as *Typic Fluviwassent*.

Table 1 reports the main physicochemical characteristics of each genetic horizons and the significant differences among the mean values of the investigated pedons.

Among the different profiles, the subaqueous GC-f soil presented significant higher pH values and lower EC values than GC-c pedon (p=0.018 and 0.006 respectively). Irregular $CaCO_3$

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distribution along the soil profile was mainly due to intercalation of shell fragments in several layers (Table 1). The OC and TN content decreased along the soil profiles, with exception of the subaqueous *Fluviwassent* profile (GC-f), where organic-enriched layers were recorded along the soil profile. Moreover, the post-hoc test highlighted a significant higher content of OC in GC-c (*Typic Endoaquent*) than the pedons located in the low part of the salt marsh ($p<0.05$). Significant higher EC value and Na content in GC-c pedon than those in GC-f was also detected (*p*=0.011). Among the investigated profiles, the macronutrients content (e.g. K, Fe Al) in the subaqueous soils was significant lower than that in GC-a pedon. Conversely, Ca and S amount was significantly higher (Table1).

A discriminant analysis (DA) was performed on three *a priori* groups of soils, chosen according to the results of the cluster analysis (cut level=0.98), using the soil physicochemical parameters above described (Figure 4) as independent variables. The canonical structure matrix (Table 2) was used to discuss the most relevant variables which compose the discriminant functions (greater than 0.3).

The first Linear Discriminant function (LD1) separated the subaqueous *Fluviwassent* (GC-f) soil properties from those of the pedons in the middle and high zone of the saltmarsh (clusters 2 and 3, respectively). Notably, cluster 3 included both hydromorphic (GC-d, *Hydraquent*) and subaqueous soils (GC-e, *Hydrowassent*), while cluster 2 was only composed by hydromorphic *Endoaquent* soils. The canonical structure matrix (Table2) showed that among the relevant variables of LD1, EC, CEC, Na, Fe and Al increased from the subaqueous to hydromorphic system, while S and Ca content followed the opposite trend.

The variables involved in LD2 separated the soils of cluster 3 in the middle zone of the saltmarsh (covered by *Spartinetea glabrae* and *Thero-Suaedetea splendentis* classes), from those of cluster 2 in the highest zone (covered by *Juncetea maritimi* and *Sarcocornietea fruticosae*). The driving variables were pH, S and Ca amount, which were higher in cluster 3 soils (*Typic Hydraquent* and *Typic Hydrovassent*); conversely, EC, Na, P, OC content and

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C/S ratio decreased from the *Endoaquent* pedons (cluster 2) to *Hydraquent* and *Hydrowassent* ones (cluster 3).

Soil-vegetation relationship

Table 3 presents the main macronutrients concentration measured in the plants corresponding to the two groups obtained from the cluster analysis (cut level=0.98, cluster 2, 3). Cluster 3 (GC-d/e sites located in the middle zone of the transect), mostly covered by *Spartina maritima* and *Salicornia patula*, had a significantly higher content of Ca (p=0.050), K (p=0.011) and Fe (p=0.008) than that determined in the plant tissues of the cluster 2 (GC-a/b/c sites, located in the highest zone). Notice that these last two plant communities types were characterized by dominance of *Juncus maritimus* (GC-a) the first and of *Limonium narbonense* and *Sarcocornia fruticosa* (GC-b/c) the second. In addition, the content of the other macronutrients in plant tissues (Mg, Na, P, S) were slightly higher in cluster 3 than that in cluster 2, but no significant difference was detected.

In order to assess the different capacities of plant communities to absorb nutrients from soil, the bioconcentration factor (BCF) of macronutrients, with respect to soil, was calculated for all the plant samples of cluster 2 and 3. As shown in Figure 5, some statistical significant differences were found between the two groups.

K (*p*= 0.004) and Fe (*p*= 0.016) BCF were significantly higher in the plant communities adapted to survive in more frequently submerged areas (cluster 3, GC-d/e sites) than those located in the high zone of the saltmarsh. On the contrary, plants of these communities (*Spartinetea glabrae* and *Thero-Suaedetea splendentis* classes) showed a significant low BCF for S (p=0.150) in comparison to specimens referring to *Juncetea maritimi* and *Sarcocornietea fruticosae* classes (cluster 2).

The other macronutrients did not show a significant differences; however, the BCF of P, Mg and Na appeared higher in cluster 3, while BCF of Ca showed an opposite trend.

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Discussion

The vegetation survey, in the Gran Chiusa saltmarsh, identified three main vegetation groups and a high variability of features within the pedological sequence, which highlighted the system transition from the subaqueous to the hydromorphic environment.

The macro areas separated by cluster analysis (high, middle and low zone), reflected the distribution of some important physicochemical parameters of soils groups, as highlighted by the discriminant analysis.

The highest soil profiles of the hydrosequence (GC-a, b, c) showed a relatively weaker signs of reduction than the other soils, due to a shorter period of submerge, and they were soluble salt-enriched. Accumulation of Na and soluble salts noted in superficial horizons of these soils, are probably linked to continuous flooding/evaporation processes and to other oxidation processes (Ferronato et al., 2016; Salama et al., 1999). These phenomena were more evident in the GC-c pedon. Furthermore the C:S ratio, which is an indicator of anoxic pedogenesis (Ferronato et al., 2016; Ivanov et al., 1989), being larger in anoxic environment, increases in these soils with respect to the profiles in the lower part of the saltmarsh .

Indeed, the low C:S ratio of the submerged soils and soil horizons, and detection of strong sulphidic odour during the profile description, indicate that in the permanently saturated zones of the saltmarsh, the soils are characterized by accumulation of reduced S compounds, OC enrichment and anoxic pedogenesis (Demas and Rabenhorst, 1999; Ferronato et al., 2016). The sulfidization is a typical pedogenetic process of marsh soils (Fanning and Fanning, 1989; Fanning et al., 2002) where the chemical and microbiological reduction of SO_4^{2-} into HS^-, lead to the formation of iron-sulphide compounds, that define the sulphidic horizons (Demas and Rabenhorst, 1999; Fanning and Fanning, 1989). In the soils transect of the Gran Chiusa saltmarsh, the formation of these horizons was not possible, because although layers with accumulation of sulphides were observed where soil was permanently saturated (e.g. in the C

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horizons of GC-a/b/c highest profiles, and in the A horizons of GC-d/e/f lowest pedons), the expected consequent acidification was not detected. For this reason, according to the Soil Taxonomy (Soil Survey Staff, 2014), these horizons were not considered as diagnostic *sulfic* horizons. Because the sulphides accumulation reflects important pedogenic pathways in the saltmarsh pedons, the lack of acidification during the aerobic pH detection must be ascribed to the buffering action due to high carbonate and Ca content in investigated soil (Vittori Antisari et al., 2016).

In the middle position of the investigated hydrosequence, *Typic Hydraquent* (GC-d) and *Typic Hydrowassent* (GC-e) coexist, reflecting a typical transition zone in micro-morphologically depressed areas within the saltmarshes.

According to the physicochemical data and to the DA, the physicochemical features of these soils are similar to those of *Endoaquent* mainly due to the increase of EC and other macronutrients, but also to those of *Fluviwassent* for their moderate content of S and Ca, due to water saturation. *Spartina maritima* and *Salicornia patula*, for 95 and 72%, respectively, cover these transition pedons, suggesting that these species are particularly adapted to growth under severe conditions, such as low oxygen availability, soil salinity and water saturation (Zhang et al., 2006; Zuo et al., 2012). The species adaptation in saltmarshes depends on a number of edaphic factors that act at both macro and micro-morphological scale, such as the bathymetry, the oxygen availability, the redox status of the soil, the life cycle of the species, and their capacity to adapt and tolerate severe environmental conditions (Génin et al., 1998; Pedersen et al., 2013). In this paper, we suggest that the nutrients content of the plant tissues and the bioconcentration factor (BCF) could be useful tool to depict the interaction between soil-vegetation cover systems.

The higher content of Fe, K and Mg in the plants living in low saltmarshes communities (*Spartinetea glabrae* and *Thero-Suaedetea splendentis* classes), with respect to other species established in highest saltmarsh areas can be ascribed to anaerobic conditions, which

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determines the reduction and mobility of several nutrients e.g. Fe, K, Ca (Julie and Siobhan, 2001).

At micro-edaphic scale, the results also confirm that the plants uptake depends on both soil properties (e.g. soil salinity and water saturation) and by specie-specific factors linked to the plant metabolism and adaptation (Silvestri et al., 2005). For example, the highest Na content in plant tissues was recorded in the class *Thero-Suedetea splendentis*, where the salt resistant *S. patula* was the most abundant species (Ushakova et al. 2005, Sajna et al. 2013).

Conversely, the plant communities located in the high zone need to face a high Na concentration and they adopt several mechanisms to tolerate Na, such as the development of epidermal glands able to secrete salt from leaves (e.g. in *Limonium* genus) or the increase of leaf or stem succulence (e.g. *Sarcocornia* genus). Furthermore, the capacity of *Sp. maritima* and *S. patula* to colonize transition areas and anoxic soils, where sulphides and other reductive species are found, can be ascribed to their capacity to avoid passive S^{2-} uptake (Havill et al., 1985), as confirmed by the low BCF of S.

Conclusion

This paper points out the existence of a significant relationship in saltmarshes between soil types and plant communities along soil hydrosequences. The vegetation micromosaic can therefore represent a useful index of the hydrological and nutritional status of the underlying soils. Indeed, the soil classification scheme and the vegetation clustering were able to reflect the micro-morphology of the area and the evolution of different soil-forming processes linked to the lack of oxygen in soil, such as sulfidization processes and nutrients mobilization. The distribution of the vegetation pattern along the hydrosequence largely depend on the capacity of plants to adopt resistance strategies to colonize the different environmental and soil conditions.

This study demonstrates that tide level plays an important role on pedological development and chemical transformations along a soil hydrosequence. A multidisciplinary approach has been successfully used to describe the pedogenetic and vegetation diversity and variability in such a peculiar environment. Furthermore, this interdisciplinary approach can be a powerful tool to predict future changes in case of subsidence or increase of flooding events, due to rise in the sea mean level subsequent to ongoing climate changes.

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Table

Table 1. Physicochemical characterization of soil profiles. Pairwise post-hoc Turkey test results are reported with different letters on the statistically different groups.

Profile	Master	Depth	pH*	EC* mS cm^{-1}	CaCO$_3$	OC*	TN	K*	P	S* g kg^{-1}	Al*	Fe*	Mn	Mg	Ca*	Na*	C/S*
	A	0-12/13	7.6	22.1	107.2	43.8	4.9	11.7	0.50	2.3	35.9	20.2	0.5	23.6	30.4	20.5	19
	A2	12/13-21/22	7.8	16.8	131.3	25.4	2.2	11.4	0.40	1.3	35.3	21.4	0.7	25.9	33.3	15.3	20
	BC	21/22-36	7.9	16.2	150.3	21.8	2.1	12.2	0.33	1.6	37.8	17.8	0.2	24.6	31.4	14.3	14
GC-a	C1	36-45/47	7.9	14.1	178.6	13.1	1.1	11.8	0.30	1.3	37.0	18.1	0.1	24.9	32.3	11.7	10
	C2	45/47-54	7.9	15.1	142.9	nd	nd	11.8	0.23	6.3	35.7	17.1	0.3	24.4	50.0	12.3	nd
	Mean		*7.8*	*16.8*	*142.1*	*26.0*	*2.6*	*11.8*	*0.4*	*2.5*	*36.3*	*18.9*	*0.4*	*24.7*	*35.5*	*14.8*	*15.8*
	SD		*0.1*	*3.1*	*26.2*	*12.9*	*1.6*	*0.3*	*0.1*	*2.1*	*1.0*	*1.8*	*0.2*	*0.8*	*8.2*	*3.5*	*4.6*
	Pairwise post-hoc		*ab*	*ab*	*ns*	*ab*	*ns*	*b*	*ns*	*a*	*b*	*b*	*ns*	*ns*	*a*	*ab*	*b*
	A1	0-18/20	7.5	23.9	154.7	41.5	3.9	12.5	0.41	2.3	37.4	18.9	0.3	22.6	28.5	20.9	18
	AC	18/20-24/30	7.9	14.2	110.5	19.2	1.8	10.5	0.24	9.9	31.0	17.4	0.2	26.2	54.5	11.1	2
GC-b	C1se	24/30-49/50	8.2	14.3	44.2	16.4	1.5	9.7	0.23	10.2	27.9	17.3	0.4	24.1	57.1	11.4	2
	C2se	49/50-60	8.3	22.6	147.4	16.3	1.6	10.6	0.26	10.1	31.5	18.5	0.5	24.5	54.8	12.2	2
	Mean		*8.0*	*18.8*	*114.2*	*23.3*	*2.2*	*10.8*	*0.3*	*8.1*	*32.0*	*18.0*	*0.4*	*24.4*	*48.8*	*13.9*	*5.8*
	SD		*0.4*	*5.2*	*50.5*	*12.2*	*1.1*	*1.2*	*0.1*	*3.9*	*3.9*	*0.8*	*0.2*	*1.5*	*13.5*	*4.7*	*8.3*
	Pairwise post-hoc		*ab*	*ab*	*ns*	*ab*	*ns*	*ab*	*ns*	*a*	*ab*	*ab*	*ns*	*ns*	*ab*	*ab*	*ab*
	A	0-8/10	6.9	40.2	19.3	94.0	8.6	11.3	0.45	4.2	29.4	16.1	0.2	15.3	15.7	37.4	22
	A2g	8/10-15/16	5.2	39.3	119.1	80.8	6.5	12.8	0.38	6.2	36.0	16.0	0.1	13.5	10.5	38.8	13
	AC1se	15/16-22/23	7.6	19.2	218.8	28.6	2.5	10.9	0.24	13.9	31.2	19.5	0.2	24.2	45.0	18.2	2
	AC2se	22/23-41/42	8.1	16.4	229.5	26.6	1.5	10.3	0.21	7.6	29.8	16.1	0.3	24.2	50.2	12.7	3
GC-c	C1g	41/42-58/59	8.0	15.3	269.6	34.9	1.3	9.3	0.20	9.6	26.2	15.6	0.4	24.3	65.3	11.1	4
	C2g	58/59-76	8.2	11.9	197.0	33.0	0.6	7.3	0.16	7.0	18.8	11.1	0.3	28.8	83.2	7.4	5
	Mean		*7.3*	*23.7*	*175.6*	*49.6*	*3.5*	*10.3*	*0.3*	*8.1*	*28.6*	*15.7*	*0.3*	*21.7*	*45.0*	*20.9*	*8.2*
	SD		*1.2*	*12.6*	*91.3*	*29.7*	*3.3*	*1.9*	*0.1*	*3.3*	*5.7*	*2.7*	*0.1*	*6.0*	*28.1*	*13.8*	*8.0*
	Pairwise post-hoc		*a*	*b*	*ns*	*b*	*ns*	*ab*	*ns*	*ab*	*ab*	*ab*	*ns*	*ns*	*ab*	*b*	*ab*
	Ag	0-11	7.9	15.9	223.3	23.3	1.9	10.6	0.24	15.9	31.5	22.8	0.2	24.0	45.9	12.8	1
	ACg	11-24	8.0	15.6	173.4	18.9	1.8	11.6	0.27	4.5	35.7	19.5	0.1	22.3	29.7	13.2	4
	ACse	24-32/33	8.1	12.7	44.7	16.0	1.4	11.1	0.22	6.7	32.6	17.4	0.2	25.8	56.9	10.2	2
GC-d	C1g	32/33-60/63	8.1	12.0	35.7	13.1	1.1	9.1	0.18	8.5	24.5	14.3	0.3	27.3	74.8	8.1	2
	C2g	60/63-68	8.2	12.6	55.8	nd	nd	9.5	0.19	10.4	26.4	16.1	0.3	26.3	67.6	9.4	nd
	Mean		*8.1*	*13.8*	*106.6*	*17.8*	*1.6*	*10.3*	*0.2*	*9.2*	*30.1*	*18.0*	*0.3*	*25.2*	*55.0*	*10.7*	*2.4*
	SD		*0.1*	*1.8*	*85.9*	*4.3*	*0.4*	*1.0*	*0.0*	*4.3*	*4.6*	*3.3*	*0.1*	*2.0*	*17.9*	*2.2*	*1.3*
	Pairwise post-hoc		*ab*	*ab*	*ns*	*a*	*ns*	*ab*	*ns*	*ab*	*ab*	*ab*	*ns*	*ns*	*ab*	*ab*	*ab*
	Ag	0-4	8.0	18.7	58.1	39.4	5.4	11.4	0.34	9.2	33.6	17.9	0.2	19.5	48.1	15.8	4
	A2g	4-16/17	8.0	20.0	154.7	32.8	3.4	11.6	0.28	11.5	33.4	18.2	0.3	20.9	57.6	16.3	3
	A2se	16/17-23	8.1	13.0	154.7	19.1	2.1	10.6	0.23	11.0	31.3	18.4	0.3	25.1	55.4	11.4	2
GC-e	ACse	23-39/40	8.1	14.5	31.3	16.8	1.6	12.7	0.27	5.0	40.5	20.3	0.2	24.7	33.7	12.8	3
	C1g	39/40-49/50	8.1	12.9	88.4	13.6	1.2	10.0	0.20	7.6	28.2	15.9	0.3	26.8	63.7	9.8	2
	C2g	49/50-60	8.3	12.1	75.2	13.9	1.3	10.1	0.19	10.2	28.0	16.0	0.3	27.6	68.0	8.8	1
	Mean		*8.1*	*15.2*	*93.7*	*22.6*	*2.5*	*11.1*	*0.3*	*9.1*	*32.5*	*17.8*	*0.2*	*24.1*	*54.4*	*12.5*	*2.6*
	SD		*0.1*	*3.3*	*51.0*	*10.9*	*1.6*	*1.0*	*0.1*	*2.4*	*4.6*	*1.7*	*0.1*	*3.2*	*12.3*	*3.1*	*1.1*
	Pairwise post-hoc		*ab*	*ab*	*ns*	*a*	*ns*	*ab*	*ns*	*ab*	*ab*	*ab*	*ns*	*ns*	*ab*	*ab*	*ab*
	Lse	0-4	8.4	11.8	189.6	19.3	2.0	9.9	0.28	13.5	29.2	16.8	0.3	24.1	61.7	9.5	1
	Ase	4-16/18	8.2	11.0	221.1	15.8	1.4	9.9	0.24	15.2	28.5	15.8	0.3	26.4	62.1	8.0	1
	AC1g	16/18-30	8.1	10.8	204.1	24.3	1.4	10.4	0.23	18.1	29.9	16.3	0.3	26.3	63.3	7.9	1
GC-f	AC2g	30-40	8.2	10.4	200.9	21.4	1.1	9.3	0.22	17.1	26.4	15.8	0.4	26.3	65.7	7.6	1
	C2g	40-63	8.4	10.1	57.5	23.6	1.0	7.6	0.21	13.7	21.1	13.3	0.4	28.2	72.0	7.0	2
	2AC1g	63-82/84	8.5	9.5	128.8	21.5	1.0	8.3	0.21	13.1	22.6	12.9	0.3	27.6	72.9	6.5	2
	2AC2g	82/84-91	8.5	9.2	176.9	23.3	1.0	8.9	0.22	12.8	24.6	13.5	0.3	27.3	72.2	6.8	2
	Mean		*8.3*	*10.4*	*168.4*	*21.3*	*1.3*	*9.2*	*0.2*	*14.8*	*26.0*	*14.9*	*0.3*	*26.6*	*67.1*	*7.6*	*1.5*
	SD		*0.1*	*0.9*	*57.0*	*2.9*	*0.4*	*1.0*	*0.0*	*2.1*	*3.4*	*1.6*	*0.0*	*1.3*	*5.1*	*1.0*	*0.3*
	Pairwise post-hoc		*b*	*a*	*ns*	*a*	*ns*	*a*	*ns*	*b*	*a*	*a*	*ns*	*ns*	*b*	*a*	*a*

*=p<0,05; ns=non significant

Table 2. Canonical structure matrix of LD1 and LD2 showing the correlation between the values of the explanatory variables and those of the discriminant functions. Important variables were greater than 0.30.

	LD 1	LD 2
pH	-0.3	0.4
CE	0.4	-0.4
CaCO$_3$	-0.3	-0.3
OC	0.1	-0.4
TN	0.3	-0.3
CSC	0.4	-0.2
K	0.5	-0.1
P	0.3	-0.4
S	-0.6	0.4
C/S	0.3	-0.6
C/N	-0.2	-0.2
Al	0.5	-0.1
Fe	0.5	0.1
Mn	-0.2	-0.3
Mg	-0.3	0.2
Ca	-0.4	0.4
Na	0.4	-0.4

Table 3. Mean macronutrient concentration found in the different plant communities. Minimim (min), maximum (max) values and standard deviation (SD) is also reported. Data are expressed as g kg^{-1}, with exception of P (mg kg^{-1}).

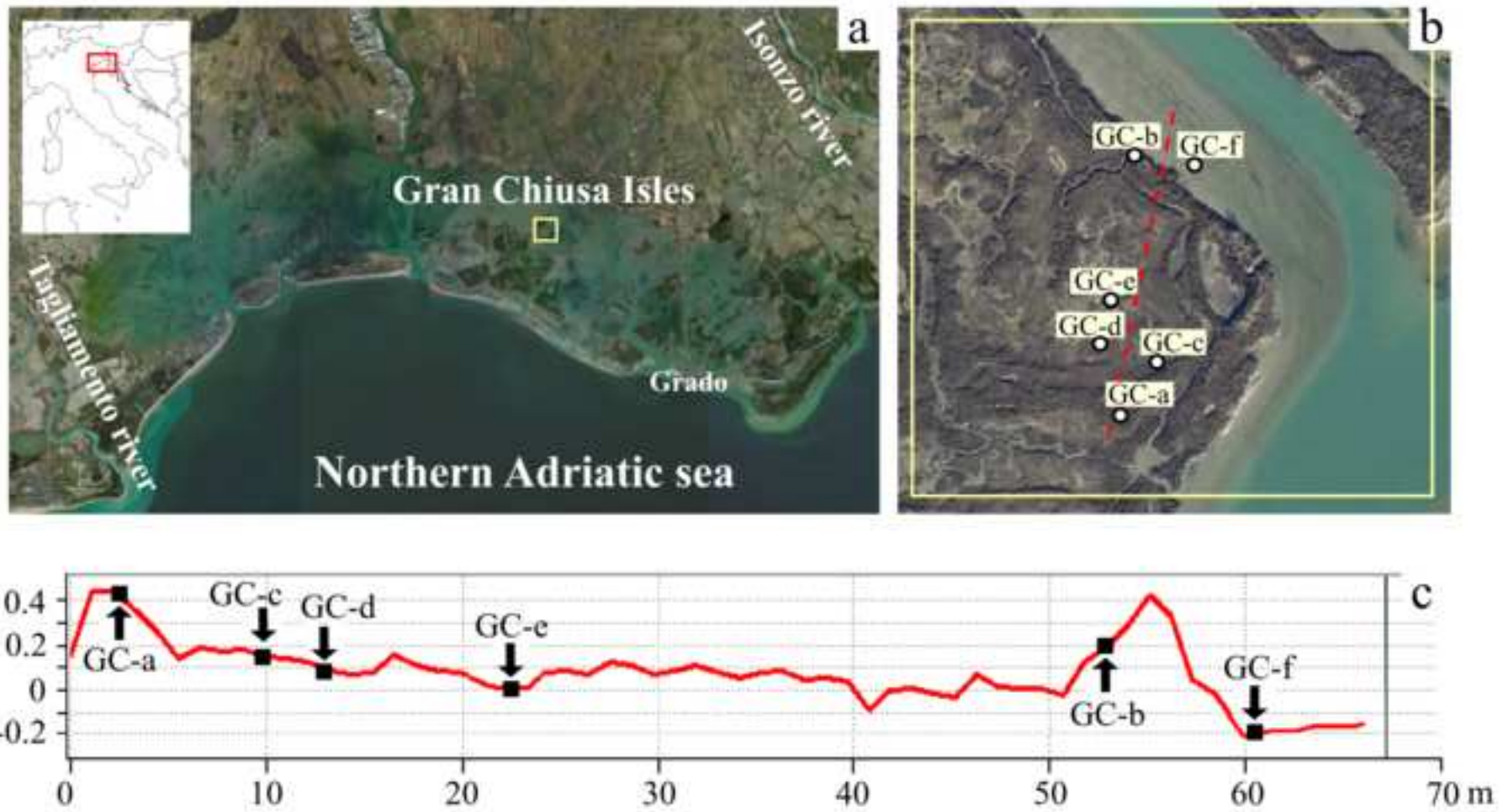|		Cluster 2 (GC-a/b/c)	Cluster 3 (GC-d/e)
Ca*	Mean	2.8	5.4
	SD	1.3	2.3
	Min	1.0	3.1
	Max	3.9	8.1
K*	Mean	5.4	6.0
	SD	0.3	0.3
	Min	5.0	5.7
	Max	5.8	6.2
Mg	Mean	4.6	6.5
	SD	3.5	2.0
	Min	0.9	3.6
	Max	10.4	8.1
Na	Mean	41.6	88.7
	SD	38.3	57.0
	Min	3.8	44.4
	Max	105.2	167.8
Fe*	Mean	0.3	2.9
	SD	0.1	0.9
	Min	0.1	1.6
	Max	0.4	3.4
P	Mean	0.6	0.8
	SD	0.3	0.5
	Min	0.3	0.4
	Max	1.1	1.4
S	Mean	3.6	4.0
	SD	2.6	1.4
	Min	0.6	2.4
	Max	6.7	5.3

*= $p < 0.05$

Figure 1. (a) Grado and Marano Lagoon and location of the studied transect. **(b)** Position of the sampling points; coordinates (WGS84/ EPSG:3857) are: GC-a - 5737165.6N 1481450.3E; GC-b - 5737252.0N 1481455.3E; GC-c - 5737184.2N 1481462.3E; GC-d - 5737189.6N 1481443.3E; GC-e - 5737204.0N 1481447.6E; GC-f -5737249.6N 1481475.0E. **(c)** Elevation profile of the study transect.

Figure 2. Hierarchical clustering based on vegetation surveys (Bray-Curtis, complete link method). Tree main clusters (cut level=0.98, clusters 1, 2, 3) represent the main saltmarsh areas based on height; a further separation (cut level=0.70, subclusters A, B, C, D, E) regards vegetation classes characterization.

Figure 3. Scheme of the morphological description of the soil profiles, displaying the intensity of sulphidic material and biological concentration (codes according to McVey et al, 2012).

Figure 4. Canonical score plot of Discriminat Analysis (DA). Wilks' Lambda: 0.0009 p< 0.001.

Figure 5. Boxplots representing macronutrients bioconcentration factors (BCF) in the two main clusters (*=p<0.05). BCF was calculated as the ratio between nutrient concentration in plant samples and in the soil (mg kg^{-1}).

Figure1

Figure2

Figure3

S=sulphurous; N=none; SL=slight, MD=moderate, ST=strong. Biological concentrations: RSB=root sheaths, SFB=shell fragments; OSF=organic strains;. f=few, c=common, m=many

Figure4

Figure5
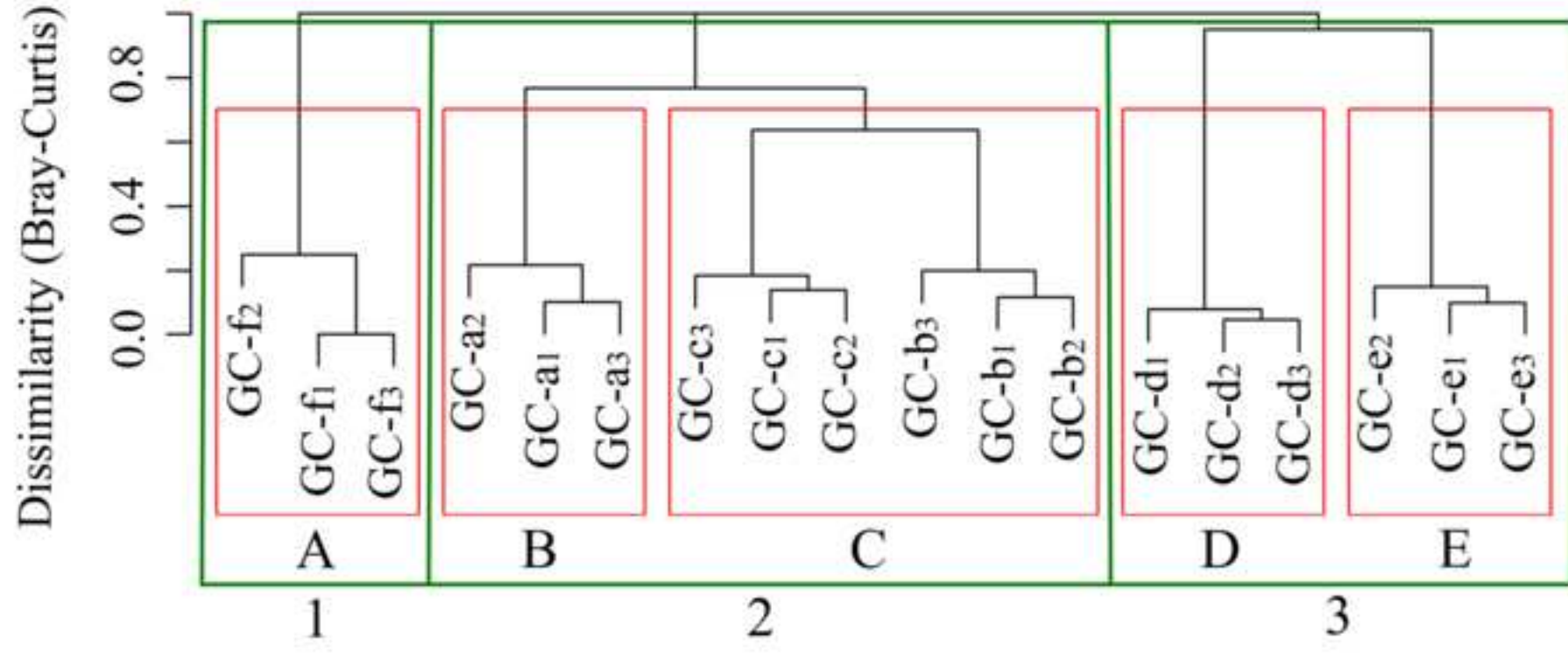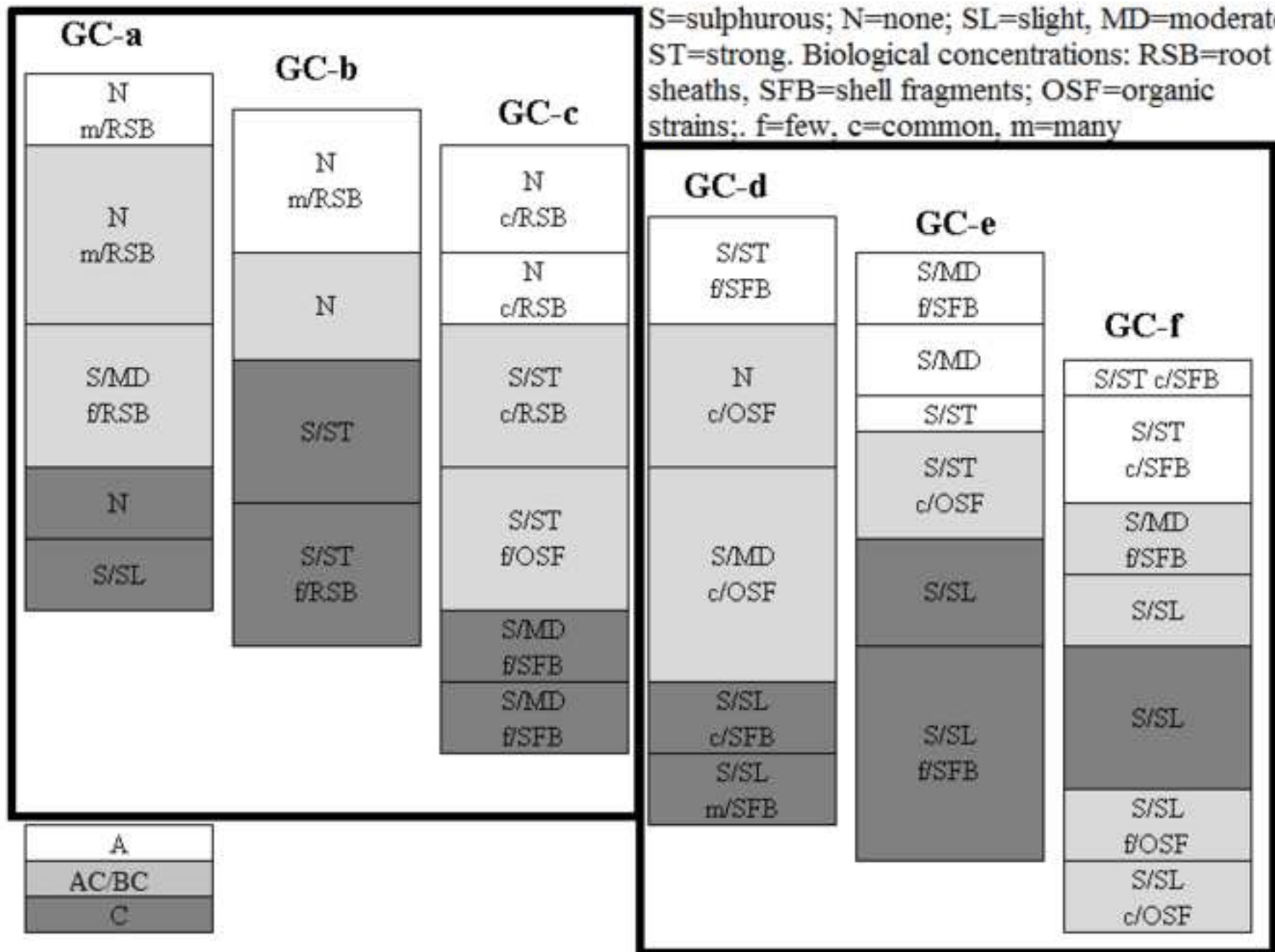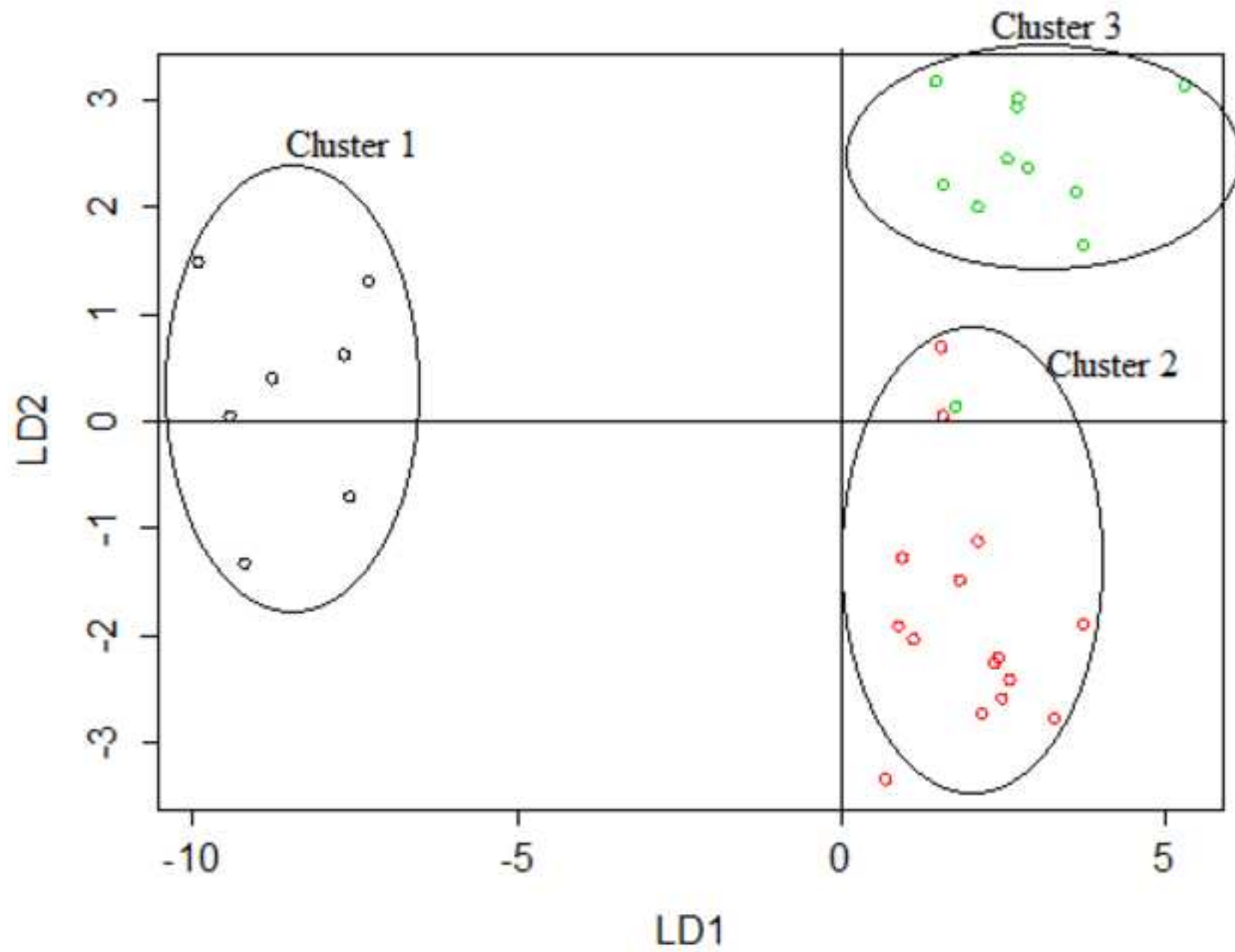
Table1S. Morphological features of investigated soils profiles. Codes according to Schoeneberger et al. (2012) and McVey et al (2012).

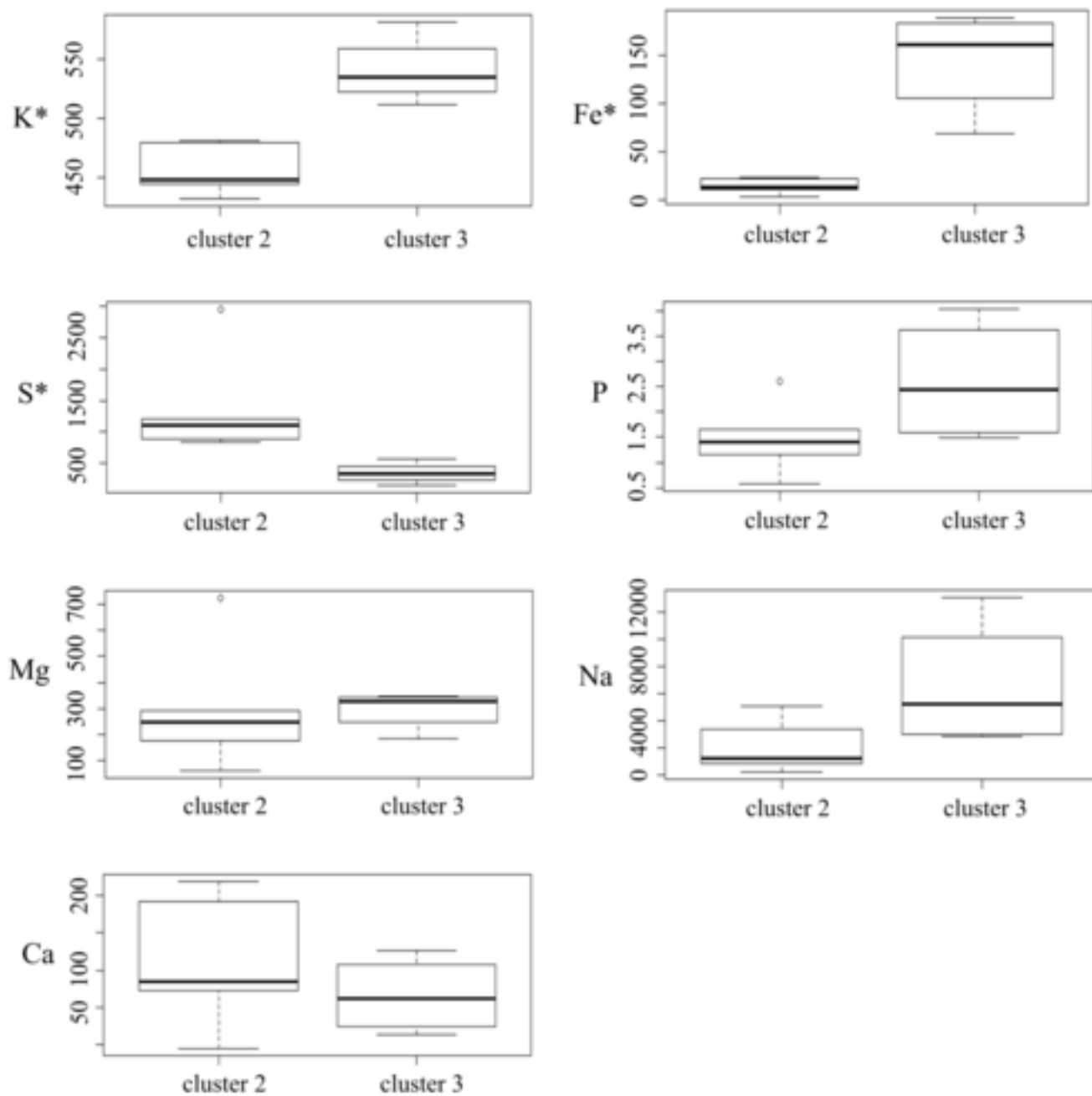| Soil profile/ time of sumbergence (h day^{-1})*	Master	*Depth*	Boundary	Matrix Color	Mottles	Texture	Consistance	Coats/Films and redoximorphic features	Roots	Biological concentration	H$_2$O$_2$ color change	Odor	Origin
GC-a (5±0,6)	**A**	*0-12/13*	D	10Y 5/1		L	so/ps	m/OSF/ 2.5YR 4/8	c/co; m/vf	m/RSB	Y	N	
	A2	*12/13-21/22*	D	10Y 5/1		SIL	ss/ps	m/OSF 2.5YR 4/8	c/m	m/RSB	Y	N	SMD
	BC	*21/22-36*	D	10Y 5/1		SIL	ss/p	f/OSF 2.5YR 4/8		f/RSB	Y	S/MD	
	C1	*36-45/47*	C	10Y 4/1	c/f/ 5Y 6/4	SILC	ss/pv	f/OSF N 6/1			N	N	
	C2	*45/47-54*	U	N 4/1		SIL	so/pv	f/OSF N 6/1			Y	S/SL	
GC-b (8±0,8)	**A1**	*0-18/20*	C	10 Y 6/1	c/f 2,5 YR 5/3	SIL	s/p	c/ OSF/ 2,5 YR 5/3	m/m;f	m/RSB	Y	N	
	AC	*18/20-24/30*	D	5Y 3/1		SIL	s/pv	c/ OSF/ 2,5 YR 5/3	m/vf		Y	N	SMD
	C1se	*24/30-49/50*	A	10Y 3/1		SIL	s/pv	10Y 4/1			Y	S/ST	
	C2se	*49/50-60*	U	10Y 3/1		SIL	s/pv	N 3/1		f/SFB	Y	S/ST	
GC-c (16±1)	**A**	*0-8/10*	C/W	10Y 5/1			s/po	m/OSF/2.5YR 5/8	m/vf/m	c/RSB	Y	N	
	A2g	*8/10-15/16*	C/W	10Y 5/1			s/po	m/OSF/2.5YR 3/2	m/vf	c/RSB	Y	N	
	AC1se	*15/16-22/23*	C/W	10Y 2,5/1		SIL	ss/po	c/OSF/2.5YR 6/2	c/f	c/RSB	Y	S/ST	SMD
	AC2se	*22/23-41/42*	A/S	10Y 2,5/1		SIL	so/p		f/m	f/OSF	Y	S/ST	
	C1g	*41/42-58/59*	A/S	10Y 4/1		SIL	ss/p			f/SFB	Y	S/MD	
	C2g	*58/59-76*	U	10Y 3/1		L	ss/p			f/SFB	Y	S/MD	
GC-d (18±1)	**Ag**	*0-11*	C/W	10Y 2,5/1		SIL	s/po	c/d/10Y 1/3	c/vf	f/SFB	Y	S/ST	
	ACg	*11-24*	C/W	10Y 2,5/1		SIL	ss/ps	f/F2M/OAF/2.5 6/6		c/OSF	Y	N	
	ACse	*24-32/33*	D/I	10Y 4/1		SIL	ss/ps	f/F2M/OAF/2.5 6/6	c/vf	c/OSF	Y	S/MD	SMD
	C1g	*32/33-60/63*	D/I	10Y 4/1		L	s/ps		c/f	c/SFB	Y	S/SL	
	C2g	*60/63-68*	U	10Y 2,5/1		SIL	vs/ps			m/SFB	Y	S/SL	
GC-e (22±0,3)	**Ag**	*0-4*	C	N2,5/1			ss/ps		m/f; vf	f/SFB	Y	S/MD	
	A2g	*4-16/17*	C	10Y 3/1		L	ss/ps		m/f; vf		Y	S/MD	
	A2se	*16/17-23*	D	10Y 3/1		SIL	ss/ps		f/vf	c/RSB	Y	S/ST	SMD
	ACse	*23-39/40*	A	N 4/1		SICL	s/ps	c/OSF/ 10Y 1/5		c/OSF	Y	S/ST	
	C1g	*39/40-49/50*	A	10Y 4/1		SIL	ss/p				Y	S/SL	
	C2g	*49/50-60*	U	10Y 4/1		SIL	ss/p			f/SFB	Y	S/SL	
GC-f (23±0,2)	**Lse**	*0-4*	A/W	N 2,5/1		SIL	mf		m/mf/f	c/SFB	Y	S/ST	
	Ase	*4-16/18*	A/I	N 2,5/1		SIL	mf		f/f	c/SFB	Y	S/ST	
	AC1g	*16/18-30*	A/W	N 3/1		SIL	mf	f/OSF N 6/1	f/f	f/SFB	Y	S/MD	
	AC2g	*30-40*	C/W	N 4/1		LS	sf	f/OSF N 6/1			N	S/SL	SMD
	C2g	*40-63*	C/W	N 4/1		L	sf				N	S/SL	
	2AC1g	*63-82/84*	D/I	N 3/1		SIL	sf	f/OSF N 4/1		f/OSF	Y	S/SL	
	2AC2g	*82/84-91*	U	N 3/1		L	sf	c/OSF N 4/1		c/OSF	Y	S/SL	

*= ISPRA, 2013; 2014. **Legend:** Horizon master: g = strong gleying, se = presence of sulphides. Horizon boundary. D) Distinctness: A = abrupt, C = clear, G = gradual, D = diffuse / (T) Topography: S = smooth, W = wavy, I = irregular - U = unknown. Mottles: (Q) Quantity: f = few, c = common / (C) Contrast: f = faint, d = distinct. Structure. (T) Type: GR = granular, ABK= angular blocky, SBK = subangular blocky, PL = platy, SG = single grain / (G) Grade: 0 = structureless, 1 = weak, 2 = moderate. Texture. Field estimation: MK = mucky, L = Loam, LS = Loamy Sand, S = sand, SL = Sandy Loam, SCL = Silty Clay Loam, SIL = Silt Loam. Consistence. (S) Stickiness: so = non-sticky, ss = slightly sticky, s = moderately sticky, sv = very sticky / (P) Plasticity: po = non-plastic, ps = slightly plastic, p = moderately plastic, pv = very plastic; NF = non fluid, SF = slightly fluid, MF = moderately fluid, VF = very fluid. Coats/films. (Q) Quantity: f = few, c = common, m = many / (K) Kind: FED = iron depletions, FEF = ferriargillans, F2M = reduced iron FeS, OAF = organoargillans, OSF. Roots. (Q) Quantity: f = few, c = common, m = many / (S) Size: vf = very fine, f = fine, m = medium, co = coarse. Biological concentrations. (Q) Quantity: f = few, c = common, m = many / (K) Kind: RSB = root sheaths, SFB = shell fragments. Odor. (K) Kind: N = none, P = petrochemical, S = sulphurous – (I) Intensity: SL = slight, MD = moderate, ST = strong. Origin. SMD = salt marsh deposits, LGD = lagoonal deposits.