Geoderma 265 (2016) 141–151

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Chemical and pedological features of subaqueous and hydromorphic soils along a hydrosequence within a coastal system (San Vitale Park, Northern Italy)

Chiara Ferronato [a,*], Gloria Falsone [a], Marco Natale [a], Denis Zannoni [b], Alessandro Buscaroli [b], Gilmo Vianello [a], Livia Vittori Antisari [a]

[a] Department of Agricultural Sciences (Dip.SA), University of Bologna, Viale Fanin 40, 40100 Bologna, Italy
[b] Biological, Geological, and Environmental Sciences (BiGeA), University of Bologna, Via S. Alberto, 163, 48123 Ravenna, Italia

ARTICLE INFO

Article history:
Received 30 January 2015
Received in revised form 11 May 2015
Accepted 14 November 2015
Available online 4 December 2015

Keywords:
Subaqueous soil
Water table
Coastal system
Hydrosequence
Soil catena

ABSTRACT

Transitional systems are complex and fragile ecosystems where the water table oscillation plays a fundamental role in soil and landscape development. Due to global climate change, by the end of the next century a large part of these environments will be affected by water flooding, causing deep changes to soil properties and functionality. Increasing the knowledge on the genesis and properties of these soils can be fundamental for providing useful tools for the correct management of this natural resource. The transition from wetland to hydromorphic interdune system in the coastal area of the S. Vitale park (Northern Italy) represents a unique soil hydrosequence characterized by soils which undergo continuous or partial, permanent or periodic saturation and reduction. These hydrosequences offer a great opportunity to investigate how soil properties change in the transition from subaqueous to hydromorphic soils and to understand which pedogenetic processes mostly characterize the soil development under different water saturation conditions. In this study, the soil transition through the hydrosequence was recognized by the evaluation of some morphological (e.g. Munsell color) and chemical (organic carbon, sulfur ratio, $CaCO_3$ content) soil properties that could trace the extent of sulfidization and decarbonation processes along the soil sequences. The presence of salts of marine origin characterized the subaqueous pedons, while nutrients accumulation (i.e., phosphorous) increased with soil emersion.
These hydrosequences represent a soil continuum where the duration of water saturation and the oscillation of the water table along the soil profiles strongly affect some specific soil-forming processes that involve S redox transformation, P accumulation, $CaCO_3$ depletion and salt accumulation.

1. Introduction

Research in soil science examining aquatic substrates in the last decades identified the occurrence of some pedogenic processes, and these evidences have led to the reclassification of these substrates as subaqueous soils (SASs; Demas and Rabenhorst, 1999, 2001; Erich et al., 2010). In fact, pedogenetic processes in SASs have been observed to be similar in concept to those occurring in terrestrial soils (Bradley and Stolt, 2003; Demas and Rabenhorst, 2001; Ellis et al., 2002; Payne, 2007; Vaughan et al., 2008). These processes include nutrients, humus and biogenic $CaCO_3$ accumulation (Barko et al., 1991; McCall and Tevesz, 1982), horizon differentiation, aquatic bioturbation, chemical transformations linked to the sulfidization process, and formation of sulfidic horizons (Balduff, 2007; Bradley and Stolt, 2003). Recently, subaqueous soils have been introduced into the USDA soil classification system, and at present they can be accurately classified in two new suborders, *Wassents* and *Wassist* (Soil Survey Staff, 2010).

Subaqueous soils are usually found in estuaries and wetland systems, or in transitional environments that span between terrestrial, hydromorphic and aquatic environments (Cowardin, 1979). These systems are characterized by areas where both shallow and ground-water table oscillations cause the presence of aquic soil regime and the alternation of anaerobic and aerobic conditions along the soil profile. In these areas, the soil surface is recurrently saturated and pedons can be defined as hydromorphic soils (van Breemen and Buurman, 1998). On the other hand, in areas where a water column of up to 2.5 m is present, or where the dynamics of both shallow and ground-water induces a positive water potential for at least 21 h each day, soils are permanently saturated and are defined as subaqueous soils (SASs).

Transitional environments are fundamental in the ecosystem: they are important nutrient sinks, they regulate the equilibrium and services of ecosystems, promote biodiversity, improve water quality, provide flooding control, and offer habitats for fish and marine biota (Barbier

* Corresponding author at: Department of Agricultural Sciences (Dip.SA), University of Bologna, Viale Fanin 40, 40401270, Bologna, Italy.
E-mail address: chiara.ferronato2@unibo.it (C. Ferronato).

http://dx.doi.org/10.1016/j.geoderma.2015.11.018
0016-7061/

et al., 2011; de Groot et al., 2012; Reddy and DeLaume, 2008). It is well known, however, that these environments are fragile: erosion processes of the coastal areas, subsidence and salt water intrusion often threaten these ecosystems (Antonellini et al., 2008; Buscaroli and Zannoni, 2010; Cochard et al., 2008; Mollema et al., 2013) and the changes of both climate and hydrological regime deeply influence their evolution and healthiness (Halpern et al., 2008; Lotze et al., 2006; Worm et al., 2006).

Studies on the effects of climate change have estimated that the sea level will increase from 18 to 59 cm by the end of the next century (IPCC AR4 SYR, 2007). 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 (Castañeda et al., 2015; Rossi and Rabenhorst, 2015). From the point of view of soil forming processes, the soil sequence characterized by continuous/partial, permanent/periodic water saturation (i.e., soil hydrosequence) can be considered as a "*soil continuum*" and the role of the water table level on soil development can be investigated. The reclassification of the aquatic substrates as soils (i.e., SASs) and their introduction into the USDA soil classification open a new frontier to soil science as they allow us to investigate the change in physicochemical properties and pedological processes that occurs in the soils of these transitional environments (Ferreira et al., 2007).

The San Vitale park is a natural area on the Adriatic sea coast, near Ravenna (Northern Italy) and is strongly influenced by the surrounding freshwater and saline aquifers. The park ranges from wetland areas to a sandy dune and interdunal system and represents a natural heritage of biodiversity conservation (Barbarella et al., 2012). For these reasons, the park has been classified as a special protection and conservation area by the European Community (SPA/SAC IT4070003, Nature 2000). The San Vitale park was thus chosen to investigate the soil development along a soil sequence from wetland to hydromorphic interdune system, aiming to: (i) characterize distinct pedons along the hydrosequence formed by subaqueous pedons and those affected by water table oscillation; (ii) identify the soil chemical properties that can discriminate soils, in order to assess how the soil processes change along this "*soil continuum*".

2. Materials and methods

2.1. The study area

San Vitale park is a protected area of 1222 ha which stands in the southern part of the Po Estuary Regional Park (Northern Italy). The area emerged between the 10th and 16th centuries from alluvial deposits of an ancient branch of the Po river and of some Apennine watercourses, and it acquired its present appearance before the last intervention of canalization during the 20th century (Ferronato et al., 2014).

The long sedimentation process allowed the evolution of a dune/interdune coastal system and of an alluvial wetland called "*Pialassa*", which was originated by a sea loch inclusion during the 18th century (Buscaroli et al., 2011; Veggiani, 1974). The San Vitale park is characterized by a sub continental temperate climate with about 600 mm of annual rainfall, mainly concentrated in autumn and spring (200 and 150 mm month^{-1} respectively), while mean temperatures range from 24 °C in July to 3 °C in January (Pinna, 1978; Zannoni, 2008). Rainfalls, temperature oscillations, and evapotranspiration phenomena deeply affect the groundwater depth and the magnitude of salt water intrusion in the deep aquifer (Amorosi et al., 2005; Castiglioni et al., 1999; Laghi et al., 2010).

The northern part of the study area is influenced by Lamone river while the southern part is crossed by the Cerba canal, which serves as collector of agricultural and landfill discharges of the surrounding area. The study area was affected by intense subsidence phenomena from World War II until the 1970s. Then, the construction of new public aqueducts using surface water during the late 1970s and 1980s significantly reduced the subsurface water consumption and the settlement rates to the pre-war values (Teatini et al., 2005). At present, the southern part is topographically lower than the northern part (Gambolati, 1998; Teatini et al., 2005; Zannoni, 2008).

The soil survey was carried out in both the northern and southern parts of the park, and the studied soil profiles were chosen according to their topographic position and to the estimated depth of the groundwater level on the soil profile. (Fig. 1). Two hydrosequences were thus studied (N and S, in the northern and southern parts respectively) and both were formed by four soil profiles (N1–4 and S1–4, respectively). The N1 and S1 soil profiles (at about 0.7–0.8 m a.s.l.) were opened in interdunal areas, characterized by sporadic water flooding of the soil surface, and colonized by hygrophilous species (e.g. *Fraxinus oxicarpa*, *Populus alba*, *Ulmus minor*) and mesophilous species (e.g. *Quercus robur* and *Quercus pubesens*). The N2 and S2 soil profiles (at about 0.5–0.4 m a.s.l.) were opened on interdunal areas that are seasonally affected by flooding phenomena and mainly covered by Graminaceae family and *Juncus* spp. The N3, N4 and S3 subaqueous soils (at around 0 m a.s.l.) were collected in the wetland area characterized by the presence of brackish waterholes and colonized by *Juncus* spp. and halophyte species such as *Arthocnemus fruticosum*. A further subaqueous soil profile, S4 (at about −0.2 m a.s.l.), was collected in the *Pialassa* wetland and was characterized by the presence of red algae of *Gracilaria* spp. According to the historical cartography of the Military Geographical Institute (IGM, 1890), the N3–4 and S3–4 soil profiles developed on permanent subaqueous environments.

2.2. Sampling survey and field measurement

Hydromorphic soil samples (N1–2 and S1–2) in the interdunal sites were opened and each genetic horizon has been described in field. The morphological features have been coded according to Schoeneberger et al. (2012).

Subaqueous soil profiles in the wetland area (N3–4 and S3–4) were collected to a depth of 1.5 m using a Beeker vibracore sampler (Eijkelkamp, NL), equipped with a polyethylene tube with a diameter of 6 cm. The depth of the water column upon the soil surface was recorded before column extraction. Samples cores were immediately sealed with a tight stopper to avoid oxygen infiltration and stored at 4 °C until laboratory analysis. Soil profiles were extracted on a suitable support and each genetic horizon has been described according to McVey et al. (2012). The presence of monosulfides were observed though the color response of the matrix after adding some drops of 3% H_2O_2 and by recording the odor description of each soil horizon (Fanning and Fanning, 1989; Fanning et al., 2002). Each soil profile has been classified according to USDA Soil Taxonomy system (Soil Survey Staff, 2014).

2.3. Physicochemical characterization of soil profiles

All soils samples were air-dried and sieved to 2 mm before analysis (Balduff, 2007). A wet subsample of each genetic horizon of SASs was immediately aerobically incubated for 16 weeks in 1:1 (w:v) soil:distilled water, in order to detect the lowering of pH due to acid sulfate weathering oxidation in soil horizon which contain reduced sulfides (Bradley and Stolt, 2003; Soil Survey Staff, 2010). For all soil samples, Electrical conductivity (EC; conductimeter Orion) and pH (pH meter, Crison) measures of all samples were performed on 1:2.5 (w:v) soil:distilled water suspension. Soil particle size distribution was determined by pipette method (Gee and Bauder, 1986). Total