EQA – Environmental quality / Qualité de l'Environnement / Qualità ambientale, **18 (2015) 1-9**

SUBMERGED PEDOLOGY: THE SOILS OF MINOR ISLANDS IN THE VENICE LAGOON

Mohammad Wahsha[(1)*], Mandana Nadimi-Goki[(2)], Alba Gallo[(2)], Claudio Cabianca[(3)], Claudio Bini[(2)]

[(1)] Marine Science Station, The University of Jordan, Aqaba branch, Jordan
[(2)] Department of Environmental Sciences, Informatics and Statistics, Università Ca' Foscari Venezia, Italy
[(3)] Fenice Green Energy Park, Padova, Italy

* Corresponding author E-mail: wahsha@hotmail.com

Abstract

Minor islands of the Venice lagoon are part of a delicate ecosystem, with equilibrium that depends on multiple factors deriving from both the aqueous and the terrestrial compartment, and represent useful indicators of the lagoon ecosystem status. Over centuries, some islands emerged, some others disappeared, others are being submerged in consequence of sea level rise, or are dismantled by marine erosion. Ecological survey and soil sampling evidenced rather homogeneous environment and soil characters, likely due to the same genesis from HTM during centuries, and to environmental conditions such as moisture and brackish groundwater. Four of the examined soils are *Inceptisols*, while the others present limited horizon differentiation, and are *Entisols*. All the profiles reflect *udic* or *aquic* conditions, and some of them are submerged for most time. Most soils are moderately alkaline (7.9 <pH< 8.4), with excessive carbonate (> 250 g/kg); organic carbon content at surface is within the normal range (8 <OC g/kg< 12), while at depth it is low (< 8 g/kg). The soils of shallow sandbanks differ from those of the islands having neutral pH (6.6 <pH< 7.3), rather high OC (> 17 g/kg) and carbonates. Moreover, the textural class is generally silty-loam with increasing clay content with depth. Currently, the soils examined present hydromorphic pedo-features, which are the result of the most important pedogenic process in the lagoon. Alternating reduction/oxidation processes would increase as a consequence of sea level rise, determining reducing conditions at bottom, and conversely enhancing salt concentration uppermost, with negative consequences for both pedogenic evolution and vegetation survival.

Keywords: *submerged soils, Venice lagoon, reduction/oxidation processes*

Introduction

Submerged soils are a relatively new frontier in soil science; in recent years, indeed, has raised the idea that sedimentary deposits in shallow water (< 2.5 m), similarly to the supergenic environment, undergo pedogenic processes. Moreover, they may act as substrate for shallow water vegetation (SAV) rooting, and therefore meet the requirements to be designed as soil in the "*Soil Taxonomy*" (2010). The soil concept has evolved with time since the early views of Hans Jenny

DOI: 10.6092/issn.2281-4485/5795

(1941), until Antarctic soils have been included (1975), although cold climate inhibits plant growth, since they present pedogenesis evidence (Ugolini and Bockheim, 2008).
The current definition of the upper limit of a soil is defined as the boundary between soil and air, soil and shallow water, soil and vegetation, soil and undecomposed material. The soil-non soil limit is defined horizontally by the gradual passage to deep water, ice corps, rock, sterile areas (e.g. mine waste). The lower limit, instead, is more difficult to define, since non-soil occurs when sedimentary material is not influenced by the soil-forming factors (cl,o,r,p,t) as proposed by Jenny (1941).
Proposals to include material permanently submerged within the soil taxonomic systems were advanced since the end of '80s, but it was in 1999 that the question was firstly debated, when Demas (1999) reported active pedogenic processes, with additions, losses, translocations and transformations, in permanently submerged substrates. As a consequence of these statements, the state factor equation S= f (cl,o,r,p,t) (Jenny, 1941) has been modified and adapted to soil forming factors in submerged environment, as follows (Demas and Rabenhorst, 2001):

$$Ss = f\ (C,O,B,F,P,T,W,CE)$$

c= climate (temperature); p= parent material; o= organisms; t= time; b= batimetry; w= water column characters; f= hydrological conditions; ce= catastrophic events.

The objectives of this study were:
- to ascertain the physical and chemical characteristics of submerged soils;
- to assess the occurrence of pedogenetic processes in a submerged environment;
- to outline the future soil evolution in relation to climate change.

Materials and Methods

Site location

The Venice lagoon is the widest wetland area in Europe, covering approximately 550 km^2, 67% of the surface is occupied by water, 25% by saltmarshes, and 8% by minor islands. The mean annual temperature is 14.5 °C, and precipitation ranges from 650 mm (south rim) and 850 mm (north rim). The mean depth is 1.2 m, consistent with the current definition of submerged soils, and salinity ranges between 18-30‰, following seasonal variations along a gradient from the lagoon edge to the eastern part, in the proximity of the mouths (Donnici et al., 2011).
In the lagoon there are about 60 minor islands (Venice settlements excluded), with a long history dating since the VII century: natural sandy outcrops, artificial islands (e.g. Tresse), disappeared islands (e.g. Ammiana and Costanciacus), with their monasteries, hospices and hospitals, military batteries, defence fortresses, with frequent abandonments ("the forgotten archipelago", as reported by Caniato and Zanetti, 2005) in coincidence with climate worsening and land paludization (Bini et al., 2012).

Sampling

In the course of a geo-archaeological survey of the lagoon, 10 minor islands and 5 saltmarshes were visited (Fig. 1), and 23 soil profiles were excavated and sampled. Soil features (depth, colour, redoxymorphic features, texture, structure, organic matter, pH and carbonate content) were examined directly in the field, and samples were recovered to the lab for physical and chemical analyses. Routine analyses were carried out on the fine fraction (< 2 mm), and consisted of: particle size (pipette method); total carbonate (gas-volumetric); pH (potentiometer, extract 1:2.5); organic carbon; C.E.C. (titration on $BaCl_2$ extracts); E.C. (conductimeter, extract 1:2.5) according to the methods recommended by Violante and Adamo (2000).

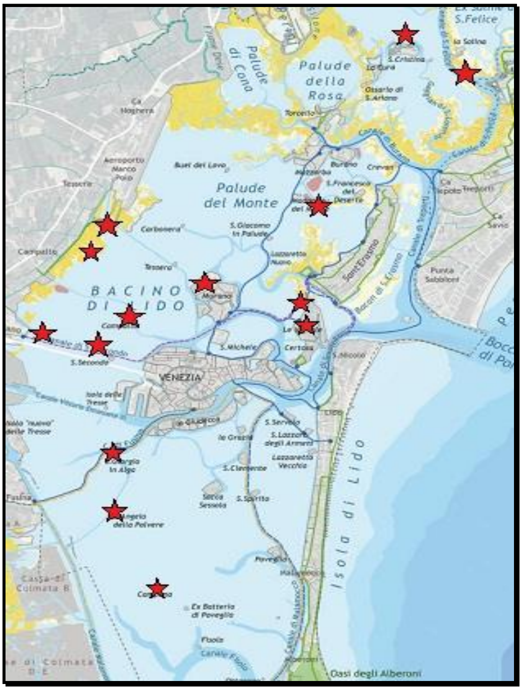

Figure 1
Sampling sites in the lagoon of Venice

Results and discussion

Physical and chemical analyses

Results from the soil analyses show high homogeneity, with marked differences between soils of islands and saltmarshes. The soils of islands are moderately alkaline (average pH 8.2), excessively calcareous (average 278 gkg^{-1}; Fig. 2), with low organic carbon (average 8 gkg^{-1}; Fig. 3) and medium C.E.C. (average 20 $cmolkg^{-1}$). The marshsoils, instead, are neutral (average pH 7.3), moderately calcareous (average 113 gkg^{-1}), with high organic carbon (36 gkg^{-1}) and C.E.C. (31 $cmolkg^{-1}$). The average E. C. is around 4 dSm^{-1} (range 2.40–9.86 dSm^{-1}) and increases slightly with depth. Particle size ranges from sandy or sandy loam

DOI: 10.6092/issn.2281-4485/5795

(mostly in saltmarshes) and silty-loam (in island soils). Soils were classified according to the Soil Taxonomy (2010), and resulted as follows:
- from the islands: Typic Eutrudepts (2); Aquic Eutrudepts (2); Typic Udifluvents (3); Oxyaquic Udifluvents (2); Aquic Udifluvents (4); Typic Udorthent; Lithic Udorthent; Cumulic Udorthent; Typic Udipsamment.
- from the saltmarshes: Typic Psammaquents (2); Typic Fluvaquent; Typic Hydraquents (3).

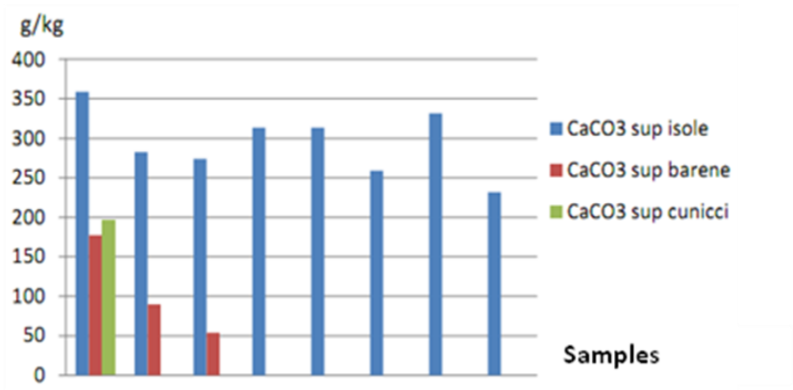

Figure 2
Average content of carbonate in examined samples

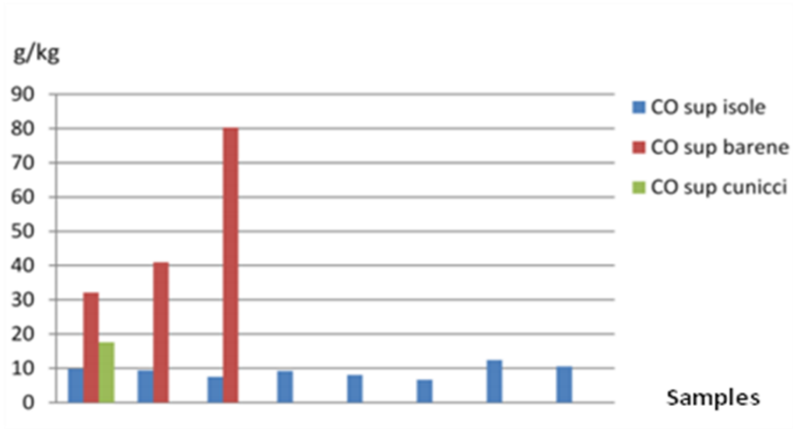

Figure 3
Average content of O. C. in examined samples

A certain difference was ascertained also between abandoned sites and recently man-affected islands that present shallower depth, coarser particle size, higher skeleton content and HTM in comparison to abandoned sites.

Pedogenetic aspects

Emerged soils of minor islands formed from lagoon sediments taken up in the vicinity of the islands and subjected to sea level oscillations. Mollusc shells, typical of lagoon environment with limited water exchange, (e.g. *Bittium reticulatum* and *Cerastoderma cardium glaucum*) are found at different depth in the C horizon, suggesting alternating submersion and emersion periods. As a consequence of such alternating conditions, gleyzation is the most prominent pedogenetic process in the investigated area, as illustrated by blue-grey colour with yellow-brown mottles formation. Alternating redox conditions enhance migration/precipitation of Fe-Mn oxyhydroxides within few days after oxygen diffusion (Breemen and Buurman, 1998). Chemical transformations in redox conditions involve firstly oxygen and nitrogen, followed by Mn, Fe, SO_4^{2-} and CO_2 according to the following reactions (De Laune and Reddy, 2005):

$$
\begin{aligned}
O_2 + 4e^- + 4H^+ &\rightarrow 2H_2O \\
2NO_3^- + 10e^- + 12H^+ &\rightarrow N_2 + 6H_2O \\
MnO_2 + 2e^- + 4H^+ &\rightarrow Mn^{2+} + 2H_2O \\
Fe(OH)_3 + e^- + 3H^+ &\rightarrow Fe^{2+} + 3H_2O \\
SO_4^{2-} + 8e^- + 8H^+ &\rightarrow S^{2-} + 4H_2O \\
CO_2 + 8e^- + 8H^+ &\rightarrow CH_4 + 2H_2O
\end{aligned}
$$

Highly reducing conditions (anaerobic) occur at Eh values ranging from -300 and -200 mV; moderately reduced conditions occur in the Eh range -100/+300 mV; oxidized conditions (aerobic) occur at Eh> 400 mV (De Laune and Reddy, 2005).
Besides gleyzation, ferrolysis and pyrite formation may occur during reduction phases:

$$Fe_2O_3 + 4SO_4^{2-} + 8CH_2O + 1/2O_2 = 2FeS_2 + 8HCO_3^- + 4H_2O$$

Water saturation, anoxic conditions, Eh lowering are hydromorphic features that allow grouping the studied soils as gley soils, partly submerged (during high tide), and partly emerged (during low tide).

Soil evolution and taxonomy

The above described features allow highlighting the general soil evolution in the lagoon, as reported in Table 1.
According to the revised WRB classification (WRB and Berlin Technical University, 2006) the soil evolution in the lagoon islands is the following:

CAMBISOLS ⇨ REGOSOLS ⇨ GLEYSOLS ⇨ MARSHSOLS

Some studied soils do not meet the requirements for the above classification, due to heavy human activity (e.g. S. Secondo, Murano) or for natural causes (e.g. Madonna del monte 2), and may be described as Entisols (USDA, 2010). According to the revised WRB classification (WRB and Berlin Technical University, 2006), these soils meet the requirements for Anthrosols, Arenosols and Gleysols (Table 2). Most examined soils in the lagoon are formed from HTM recovered in the island surroundings during last centuries. The last human intervention has likely occurred 50-20 years ago.

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Table 1. *Soil taxonomy and main characters at different sites in the Venice lagoon*

Taxonomy	Soil features	Location
TYPIC EUTRUDEPT	- located in top position - above water level - cambic horizon - udic soil moisture regime	*Campalto1*
AQUIC EUTRUDEPT	- soils in the presence of oscillating water level - Bg horizon - redox features. - udic soil moisture regime	*Campalto2* *Campalto3*
TYPIC UDIFLUVENT	- located in bottom position - no horizonation - little profile development - fine texture - irregular O.C. trend - udic soil moisture regime	*S.Giuliano 1* *S.Giuliano 2* *Vignole*
OXYAQUIC UDIFLUVENT	- depth> 1 m - redox features within 100 cm - udic soil moisture regime	*La Salina* *S.Giuliano 3*
AQUIC UDIFLUVENT	- depth < 1 m - redox features within 50 cm - udic soil moisture regime	*S.Giorgio in alga* *S.Angelo della polvere* *Campana* *Madonna del monte 1*
TYPIC FLUVAQUENT	- strong reducing conditions close to surface - little soil development - aquic soil moisture regime	*Madonna del monte 3*
TYPIC HYDRAQUENT	- partly submerged - anoxic conditions close to surface - aquic soil moisture regime - n value> 0.7	*Barena di S.Erasmo* *Barena aeroporto 2* *Barena aeroporto 3*

Table 2. *Soil taxonomy and main characters at sites affected by human activity in the Venice lagoon islands*

CUMULIC UDORTHENT	**TYPIC UDIPSAMMENT**	**LITHIC UDORTHENT**	**TYPIC PSAMMAQUENT**
- HTM over buried soil - little soil development - no horizonation - udic soil moisture regime	- high sand content - little soil development - no horizonation - udic soil moisture regime	- shallow - little soil development - no horizonation - udic soil moisture regime	- depressed topography - coarse particle size -- little soil development - no horizonation - aquic soil moisture regime
S.Secondo 1	S.Secondo 2; Madonna del monte 2	Murano-Sacca S.Mattia	Barena aeroporto 1
Terric Anthrosol	**Haplic Arenosol**	**Urbic Anthrosol**	**Arenic Gleysol**

Future evolution

There is currently International concern on global change, with particular reference to climate. The recorded trend of climate change in the last 100 years suggests that there should be a noteworthy impact on soil development in the lagoon islands. Since 1872, until 2010, there has occurred a 30 cm sea level raise (1.5-2 mm/year); within 100 years most islands, whose elevation above the sea level is 60-80 cm, could be submerged. It is likely that current soils, with hydromorphic features below 50 cm depth, will be interested by gleyzation and salinization of the whole soil column. Submerged and saline soils similar to those present today on the lagoon margins, such as water-saturated Gleysols and Marshsols (WRB and Berlin Technical University, 2006) would form. As a consequence of saturation, soil colour would change to greysh-bluish, organic matter would decompose slowly, pH decreases to sub-acid values and salinity increases; vegetation too would change, with development of halophytes, while wave movement would induce erosion of bench. The sea level raise would induce a "marinization" process causing:

- organic matter rich marshsols covered with low organic matter marine sediments;
- increased carbonate content at surface (within 5 cm) caused by sea water contact;
- decreased fine particles content by marine erosion;
- increased salinity;
- decreased areas covered by common reed, with loss of biodiversity.

Further consequence of sea level raising is the possible release of nutrients and potentially toxic substances from submerged soils and sediments. Indeed, Eh decrease enhances Fe and Mn solubility and Pb, Zn, Al as well (Miao, 2006).

Previous studies on the morphology of the lagoon margin (Bonometto, 2003; Bondesan, 2004) showed that natural saltmarshes, originally shallow margins of coastal plain, populated by common reed, have been highly modified by human activity (e.g. river deviation and conterminous areas delineation), that provoked soil salinization, erosion on one side and sedimentation on the other, enhancing changes in vegetation structure:

- hygrophilous (poplar, willow) and nitrofilous (*Urtica*, *Rumex*)
- invasive plants (*Robinia*, *Ailantus*, *Hedera*, *Parietaria*)
- common reed
- halofilous (*Salicornia*, *Sarcocornia*, *Puccinellia*, *Limonium*)
- submerged vegetation.

In the opposite case of sea level regression, with oxidation prevailing over reduction, soils would undergo pedogenetic evolution, with formation of cambic and even argillic horizons. Therefore, Inceptisols and possibly Alfisols would replace Entisols, as it occurs in the conterminous mainland.

Saltmarsh areas would increase organic matter content and total soil depth, initially forming Mollisols, which afterwards would turn to Inceptisols at oxidative and acid conditions, forming redoximorphic features, salt washing and vegetation change from hygrophilous to shrubby and even arboreal population.

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Conclusions

The Venice lagoon is a very delicate ecosystem in fragile equilibrium depending on several factors linked to both aquatic and terrestrial compartments. Minor islands proved good indicator of the ecosystem health. During centuries some islands emerged, others were submerged or disappeared owing to erosion and sea raise. Since more than 1000 years, humans operated to preserve lagoon ecosystem and the whole environment, avoiding paludization and flooding, cultivating new areas, reclaming some others.

The results of our survey showed nearly homogeneous soil conditions, possibly due to common parent material taken in the proximity of the islands, and to environmental conditions (soil moisture and saline water close to surface).

Physical and chemical analyses showed that most soils are moderately alkaline, with moderate carbonate and OC content. Some differences, however, have been recorded between natural and man-affected soils of islands and those of saltmarshes. Some islands (e.g. S.Secondo, S.Giorgio in Alga) showed soils with high accumulation of HTM, heterogeneity and discontinuity in the profile, likely due to works connected with military purposes.

Gleyzation is the main soil forming process in the lagoon islands, accompanied by salt capillary raise and soil salinization. Redox conditions would be enhanced by sea level raise, as expected in consequence of climate change. This would determine bank erosion, capillary raise, change of the vegetation cover, loss of natural and cultural heritage.

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DOI: 10.6092/issn.2281-4485/5795