Report on the geomorphological setting of the Italian site

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1. Introduction

The Interreg Italy-Croatia project MoST (Monitoring Sea-water intrusion in coastal aquifers and Testing pilot projects for its mitigation) aims at testing solutions against saltwater intrusion in agricultural areas, a worldwide problem exacerbated by human activities and climate changes. The regions of interest of the MoST project are the Veneto Region coastal plain, south of the Lagoon of Venice (Italy), and the Neretva river mouth (Croatia).

MoST WP3.1 Action (Sites characterization) aims at the detailed characterization of study sites from the geologic, hydrogeological, and agricultural points of view on the basis of the available knowledge and previous studies.

The aims of this report are (1) to contextualize the Italian pilot site within the regional geological framework; (2) to provide the geomorphological characterization of the Italian study area.

The geomorphological characterization of the Italian site is the Deliverable D_3.1.1 “Report on the geomorphological setting of the Italian site” planned to be issued by the WP3 “Studying”.

2. Materials and methods

The Italian study area is part of the Padano-Venetian coastal plain between the lower stretches of the Brenta and Adige rivers, south of the Venice Lagoon (Italy) (Fig. 1).

This report includes the geomorphological characterization at the regional and local scale based on the summary of published scientific papers and cartographic products, related to the geology and geomorphology of the Italian site.

Some field validations were carried out through preliminary inspections and a first evaluation of the litho-stratigraphic log of sediment cores previously performed on the Italian study site (see the project document MoST-CNR 3.1-002).

A more detailed study was carried out on 5 new sediment cores taken within the MoST project: facies analyses allowed the geomorphologic and paleo-environmental reconstruction of the upper 20 m of subsoil of the pilot test area (see the project document MoST-CNR 3.2-004). Particular attention has been paid to the geomorphologic interpretation of the sandy high-permeable paleo-channel crossing the farmland in which a sub-irrigation system has been installed (see the project document MoST-CNR 4.2-007).

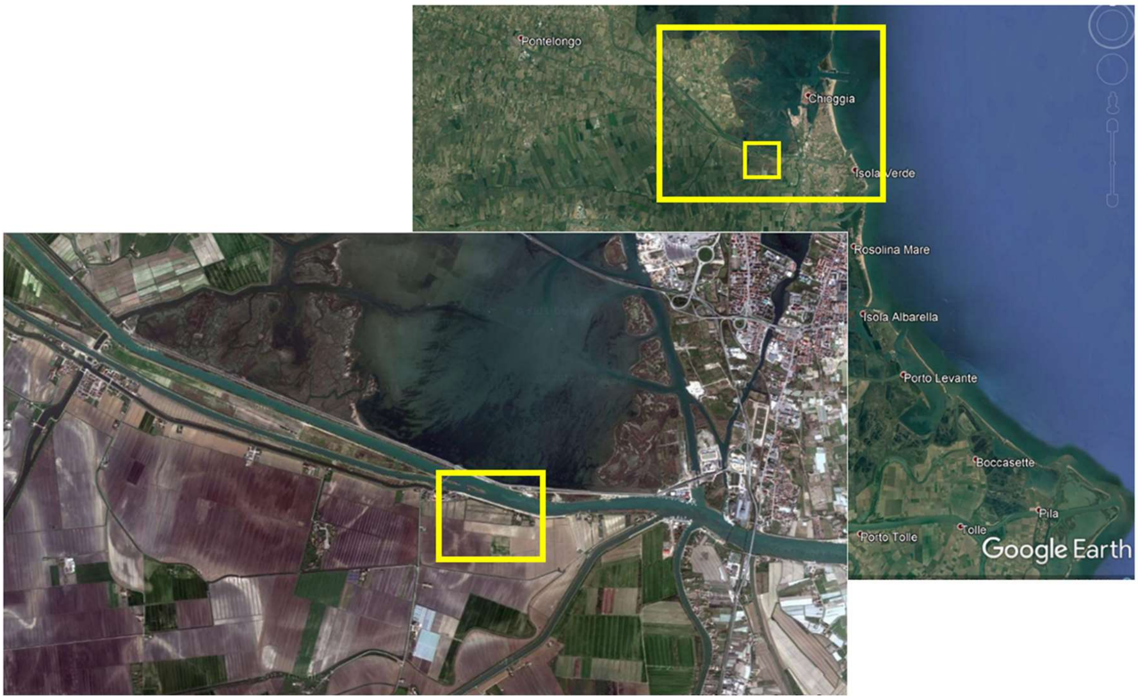

Fig. 1 - Location of the study area and the pilot test area

3. Geological framework

The sedimentary sequence down to 50 m depth is related to the Late Pleistocene and Holocene depositional events representing the uppermost part of the Venice Supersynthem (Tosi et al., 2007a,b). The deposits represent the transition from a fluvial to a tide-dominated depositional system triggered by sea-level changes (Fig. 2).

Late-Pleistocene deposits belong to continental depositional systems. Four different facies associations can be identified mainly related to fluvial environment:

a) fine-grained sediments associated with a low-energy floodplain environment and far from the main channel, where water stagnation forms swamps and freshwater marshes with vegetation development;

b) alternations of silt and fine micaceous sand with planar or ripple-cross laminations, often ordered in coarsening upward sequences, deposited in levees or crevasses and interlayered with floodplain deposits;

c) medium-coarse to fine sand with an erosive base, grading upwards to silt and clay, and ordered in fining upward successions related to channelized deposits of rivers crossing coastal lowlands;

d) paleosols with different degrees of maturity developed in the finest sediments of the fluvial system, testifying subaerial conditions.

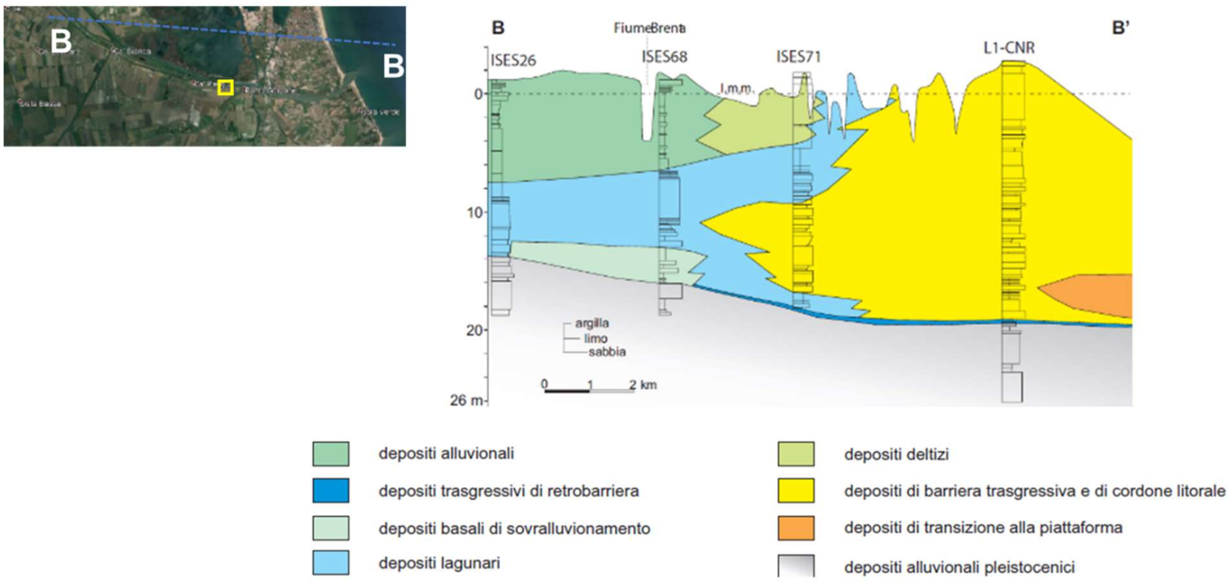

Fig. 2 – Setting of the Holocene depositional units.

The top of the Pleistocene deposits is dated about 18,000 years BP, it corresponds to a regional unconformity, and it shows evident signs of pedogenesis.

The Holocene sequence shows the typical wedge-shaped architecture containing transgressive and highstand deposits. The transgressive sequence frequently shows a thin basal layer of lagoon/back-barrier deposits that gradually changes in over-flood facies towards the mainland. Upwards, the transgressive deposit starts to interfinger with lagoon, littoral and shelf deposits with heteropic relationships. The following units are related to the progradational system during the sea level highstand: generally they show heteropic facies from fluvio-deltaic to lagoonal deposits, gradually passing to littoral and shelf deposits (Tosi et al., 2007a,b).

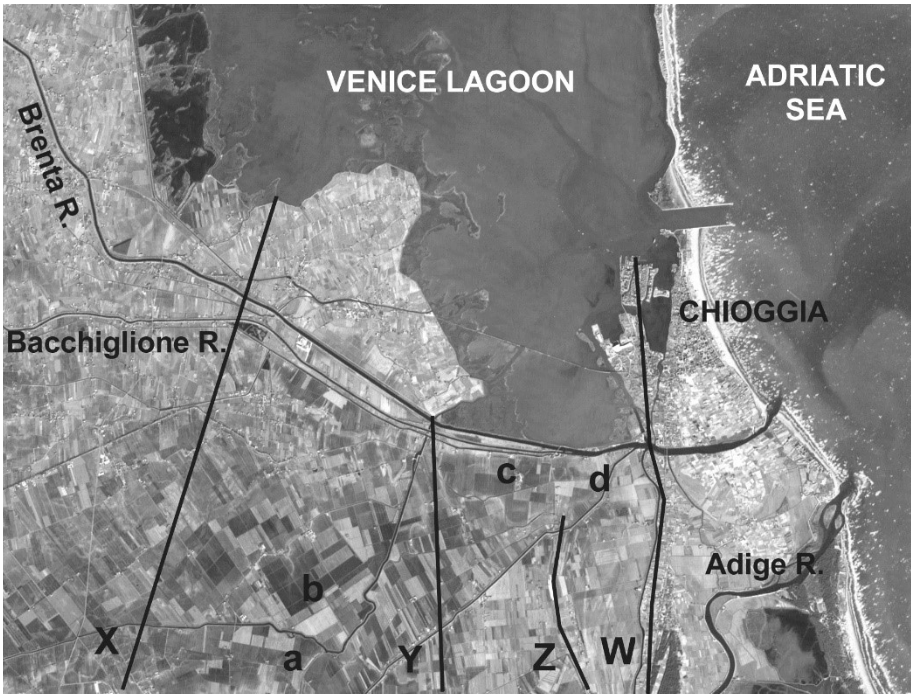

Fig. 3 – Satellite image of the study area. The coastline positions are highlighted (Favero & Serandrei Barbero, 1978; Bondesan et al., 2001): (X) 5–6000 years BP; (Y) 4500 years BP; (Z) 3000 years BP; (W) 2500 years BP.

Favero & Serandrei Barbero (1978) identified the innermost coastline position, reached during the Flandrian transgression (5–6000 years BP), in the north-western part of the study area, along the alignment X in Fig. 3. Here marine-lagoon deposits were buried by fluvial sediment inputs which caused a rapid eastward coastline progradation. Outcropping evidence of beach ridges are recognizable also 1–2 km east of the Zennare Basin, along the alignment Y in Fig. 3, which testify the position of the paleo coastline about 4500 years BP (Bondesan et al., 2001). During the last 4000 years, several fluvial depositional events of the Brenta, Bacchiglione, Adige and Po rivers filled up the back barrier lagoon and the surrounding swamps, with a consequent eastward coastal migration (Z, W in Fig. 3). The Holocene evolution of the coastlines was sketched by Tosi (1994) (Fig. 4).

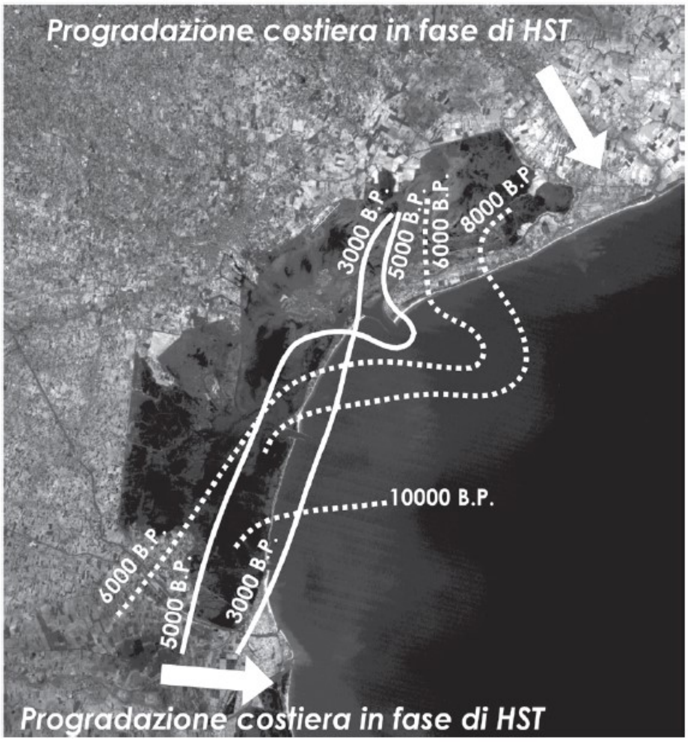

Fig. 4 – Schematic model of the Holocene evolution of the Venetian coast (Tosi, 1994). The arrows indicate the direction of advancement of the coastline caused by progradation of the rivers mouths during the sea level highstand.

4. Geomorphological characterization

The different depositional environments are responsible for the various lithologies and geological features outcropping on the ground surface. Sandy and silty soils characterize the remnants of ancient channels and beach ridges, whereas clayey silts, often rich in organic matter, fill the inter-distributary lowlands; bogs with peat layers occur in the reclaimed marshy areas.

Three main geomorphological features characterize the study area at regional scale: the littoral zone, the lagoon and its margin and the inland.

The Southern Venetian Plain is a very low-gradient (< 1‰) alluvial plain crossed by a network of alluvial ridges. Here, the rivers Adige and Po have occasionally intersected over the past four millennia, with an undefined boundary between the two sedimentary systems, resulting in a complex network of alluvial ridges belonging to ancient supraelevated channels belts (Piovan et al., 2012) (Fig. 5). In this area, natural fluvial processes interacted with anthropic control on rivers since the late

Middle Ages, when land reclamation began and rivers were embanked within artificial levees. Major river channels of the Po and the Adige have been straightened and also artificially diverted, starting from the 15th century. In particular, in order to prevent the northward progradation of the Po delta and the silting up of the Venice Lagoon, the final reach of the northernmost branch of the Po River was deactivated through the excavation of a new canal in 1604 (the so-called "Taglio di Porto Viro") (Bondesan et al., 2001).

The network of alluvial ridges created a "ridge and basin" geomorphological architecture with elevations ranging between 5 m above sea level at the top of the highest ridges and −3.5 m below mean sea level in the inter-ridge basins in the most distal part of the plain (Mozzi et al., 2018).

The coastal plain lies almost completely below the mean sea level (Fig. 6, Fig. 7), with the exception of the littoral zone, where old elevated beach ridges are preserved. This morphological setting is the results of anthropogenic activities (i.e. land subsidence due to hydraulic reclamation and the groundwater withdrawal) superposed to the geological evolution of the coastal plain over the Holocene.

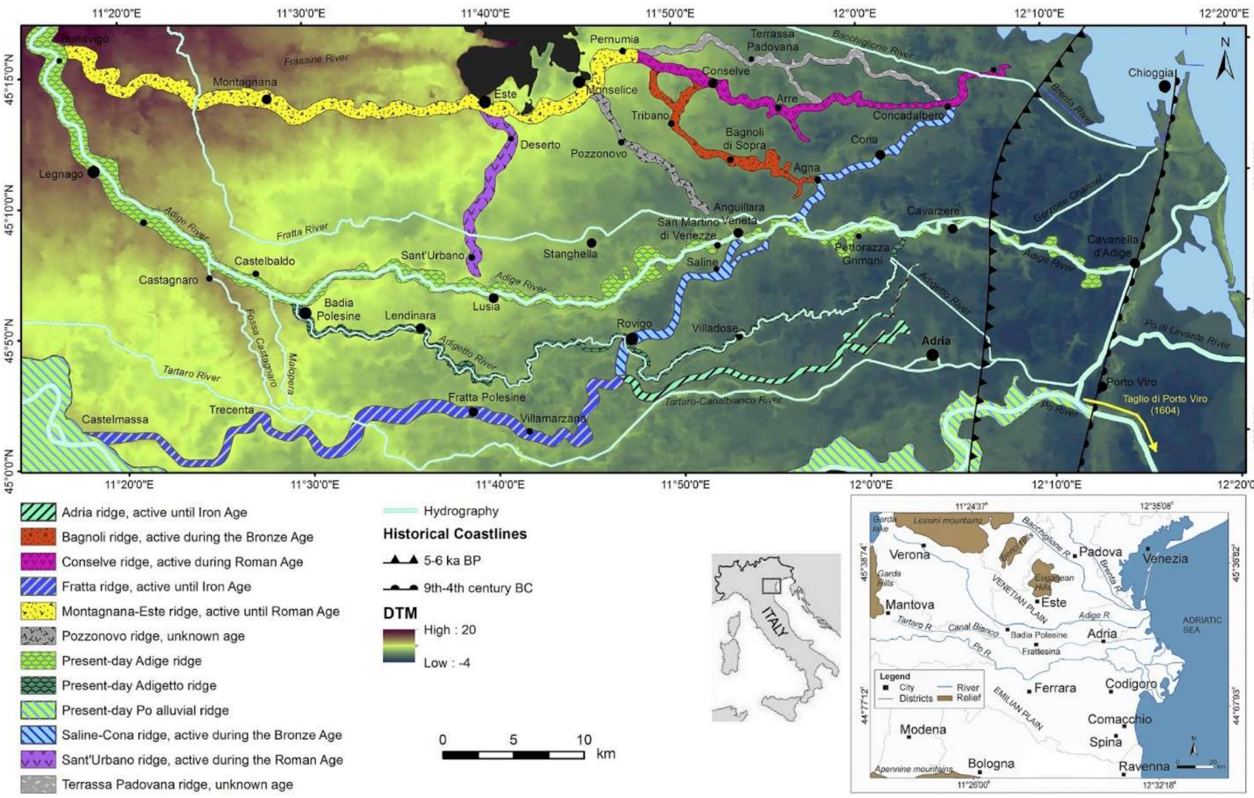

Fig. 5 - Geomorphological sketch of the Southern Venetian Plain (Mozzi et al., 2018).

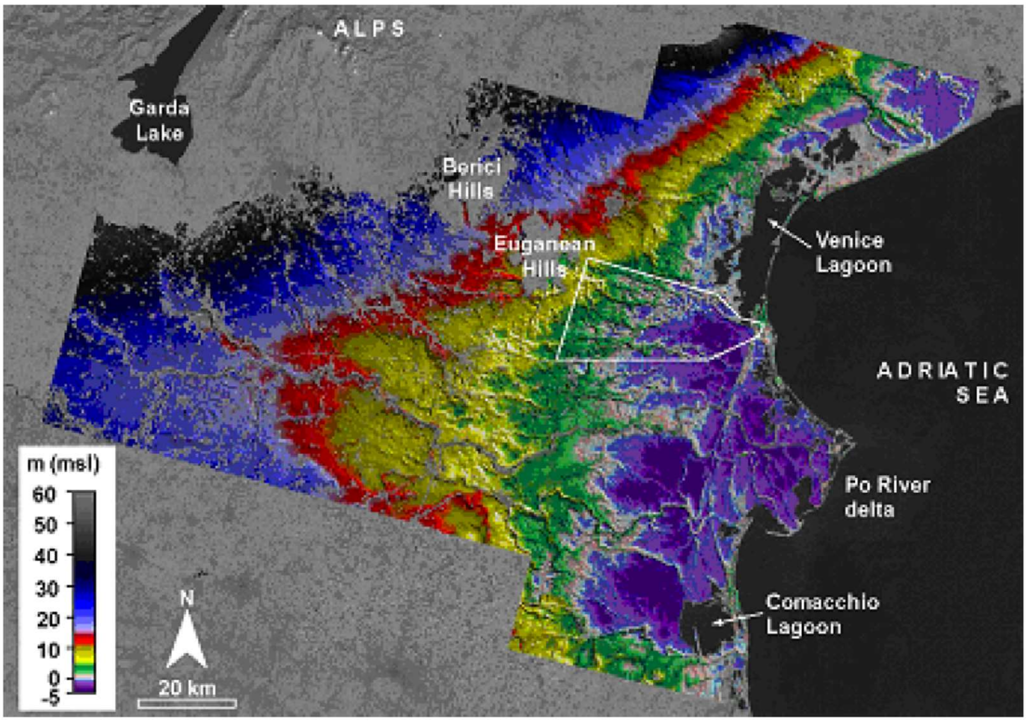

Fig. 6 - Digital elevation model (DEM) of south-eastern Venetian plain (Gasparetto et al., 2012).

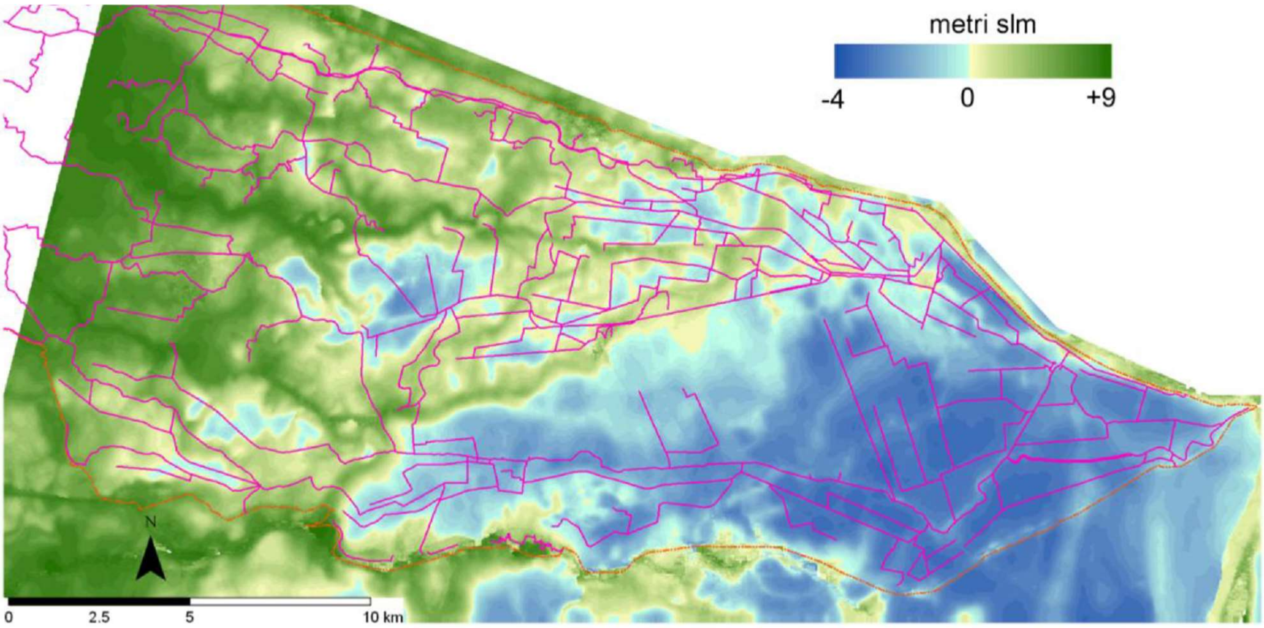

Fig. 7 - Digital elevation model (DEM) detail of the pilot test area and surrounding coastal plain.

At the beginning of the last century, most of these territories were completely reclaimed and now are mechanically drained by pumping stations to make agricultural activity possible. In addition, this area experienced high subsidence rates, resulting from the natural consolidation of the Holocene marine soft soils and the groundwater pumping occurred in the 1960s (Tosi et al., 2000).

A subsidence rate up to 2–4 cm $year^{-1}$ was determined for this area by comparing leveling surveys performed by the local water authorities, and the ground elevation of the 1983 Regional Topographic Map, and by the analysis of the macroscopic evidence of the area's settlement (Tosi et al., 2000). The high sinking rates are mainly due to the oxidation of soils rich in organic matter induced by the drainage and the intensive agricultural activity (Fornasiero et al., 2002), whereas natural sediment consolidation is only responsible for a secondary impact (2–3 mm $year^{-1}$) (Gambolati & Teatini, 1998; Tosi et al., 2000). Peaty soils are located in the lowest area, i.e. rapidly sinking, whereas sandy-silty deposits, representative of ancient fluvial ridges, are more stable.

In the study area, the littoral zone is a gently sloping sandy beach with a system of dune ridges, which have the same direction of the present coastline. This system results from the coastal advance that occurred during the last 2500 years (see Fig. 3). The present littoral shape is instead mainly due to human intervention, such as the diversion of the Brenta River mouth from the lagoon to the Adriatic Sea at the end of the 19th century, and the construction of the jetties at the Chioggia inlet between 1911 and 1930, which have strongly modified the coastal hydrodynamic and sediment transport regime. The Brenta-Bacchiglione River and the southern edge of the Venice Lagoon is the northern boundary of the inland sector. Most of the inland lies below the mean sea level, down to -4 m and is crossed by many ancient fluvial and lagoon channels and drainage canals, such as the old course of the "Canale Vecchio dei Cuori", which show the main flow direction towards the southern Venice Lagoon margin (Rizzetto et al., 2002). Paleo-beach ridges also occur in the coastal plain. The shaded relief map of the lagoon bottom superimposed on the satellite image, supported by seismic profiles, highlights the presence of ancient littoral ridges and Late Pleistocene and Holocene channelized sequences composed of sandy deposits linked with similar ones found in the farmlands (Fig. 8).

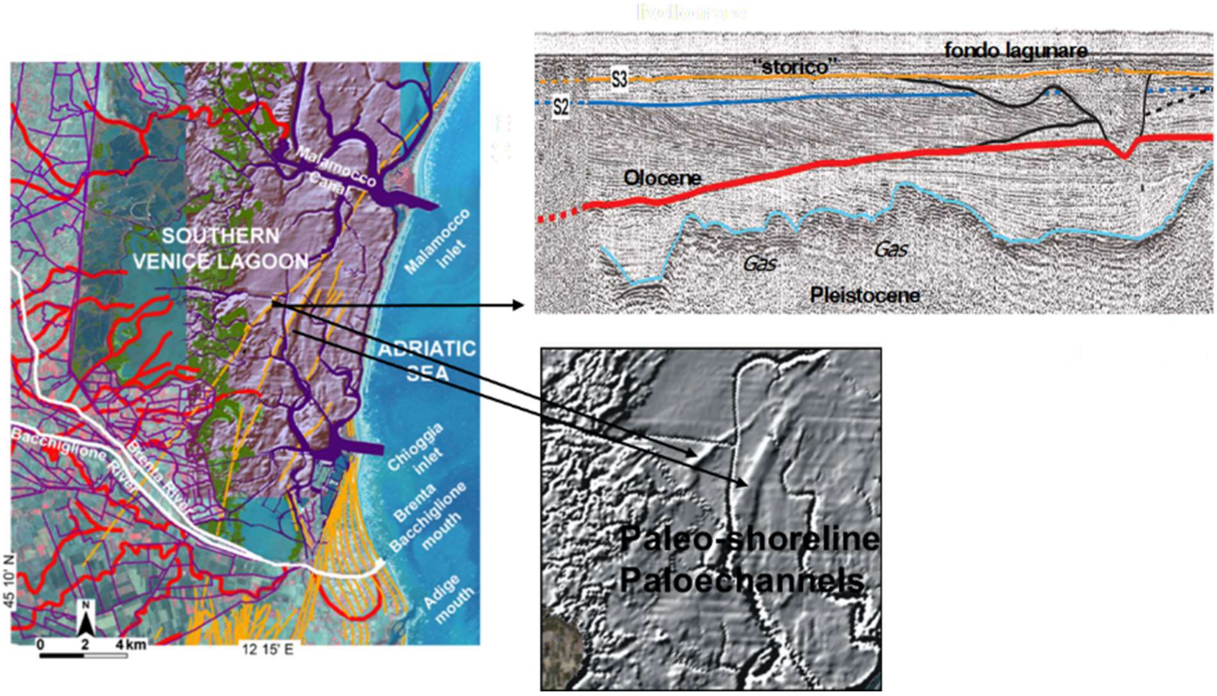

Fig. 8 - Buried and exposed geomorphological structures revealed by seismic survey, bathymetric data and remote sensing analysis: a) ASTER images and shaded relief images of the lagoon bottom morphology. Red lines: paleoriverbeds; orange lines: paleobeach ridges; dark violet and light violet areas: present lagoon channels and hydrographic network, respectively; green areas: salt marshes. White lines highlight the present courses of the Brenta and Bacchiglione rivers. b) Detail of geomorphological features identified by bathymetric data. d) Seismic profile acquired in lagoon shallows. Red line: Holocene – Pleistocene boundary.

Two of them, probably related to an ancient watercourse of the Adige River, cross the Zennare Basin (located west of the study area) with a SW–NE direction, whereas the ancient southernmost course of the Brenta and Bacchiglione River system (Favero & Serandrei Barbero, 1978) can be observed in the north-eastern sector (Fig. 8). The old course of the "Canale dei Cuori" is recognizable by the traces of its meanders, intersecting the new canal ("Canale Nuovo dei Cuori") built at the end of the 19th century. Finally, the meanders located close to the north-eastern boundary represent the northernmost ancient branch of the Po River.

Fig. 9 - Geomorphological features and main outflow routes south of Bacchiglione River (modified from Vitturi et al., 2011): 1) alluvial ridges of Adige and Po rivers; 2) province border; 3) main outflow routes; 4) ancient coastlines and delta systems. The red square indicates the location of the pilot test area (Fig. 10).

The study area, bounding the southern margin of the lagoon of Venice, is characterized by a wide areal variability of the soil deposits and the presence of several ancient sandy fluvial ridges and buried paleo-channels.

In particular, in the pilot test area, the sandy paleo-river beds cross the farmland with the main direction from inland towards the lagoon boundary, approximately from south-west to north-east.

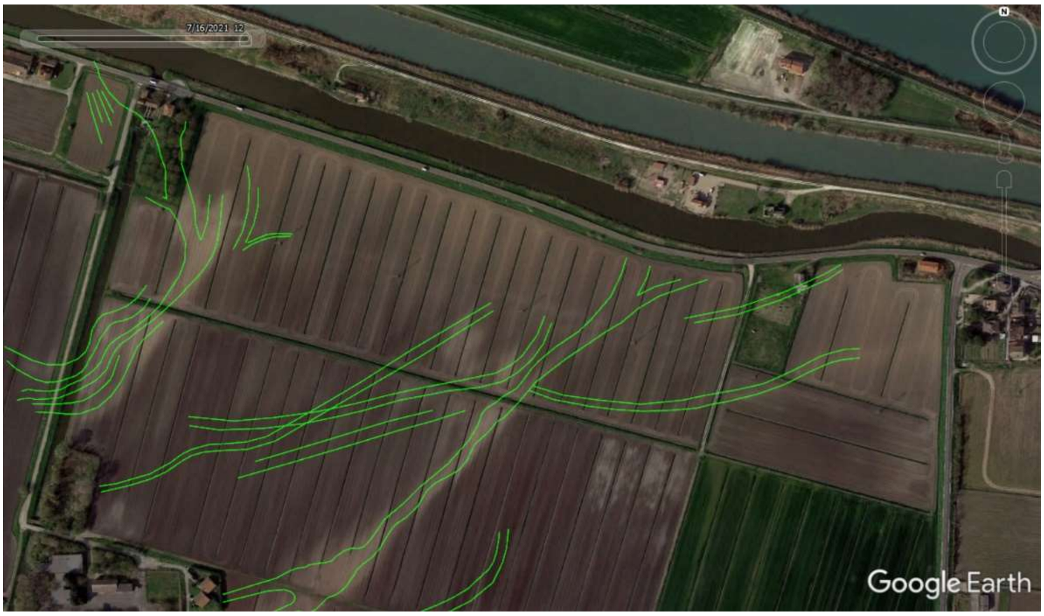

Fig. 10 – The Pilot Test area reporting the location of the buried paleo-channels

5. Surficial sub-soil stratigraphy of the pilot-test area

The excavation work for the positioning of the drainage pipe, allowed us to observe the soil profile along the trench down to about 1.5-1.7 m depth. The location of the trench is shown in Fig. 11. A stratigraphic section (reported in Fig. 12), showing the lithological characterization of the subsoil, is described in the following paragraph.

Fig. 11 – Localization of the trench in the Italian pilot test site. Yellow lines highlight the presence of sandy geomorphological bodies.

Four different intervals have been identified, namely: Layer A, B, C, and D.

- Layer A consists of a brown agricultural sandy-silty soil with roots, showing a mean thickness of 0.50 m.
- Layer B consists of dark brown peat, with a thickness ranging from 0 to 0.20 m showing a lenticular pattern.
- Layer C is made up of medium-fine yellow sand, with mottling and traces of oxidation, roots and organic remains. Layer C shows a variable thickness ranging between 0.20 and 0.40 m.
- Layer D consists of medium-fine well-sorted micaceous sand, with marine mollusk shells (Glycymeris, Turritella, Chamelea, Gibbula), grey in color. This layer is found at the bottom of the trench, from a depth of 0.70 – 0.90 m to 1.5 m.

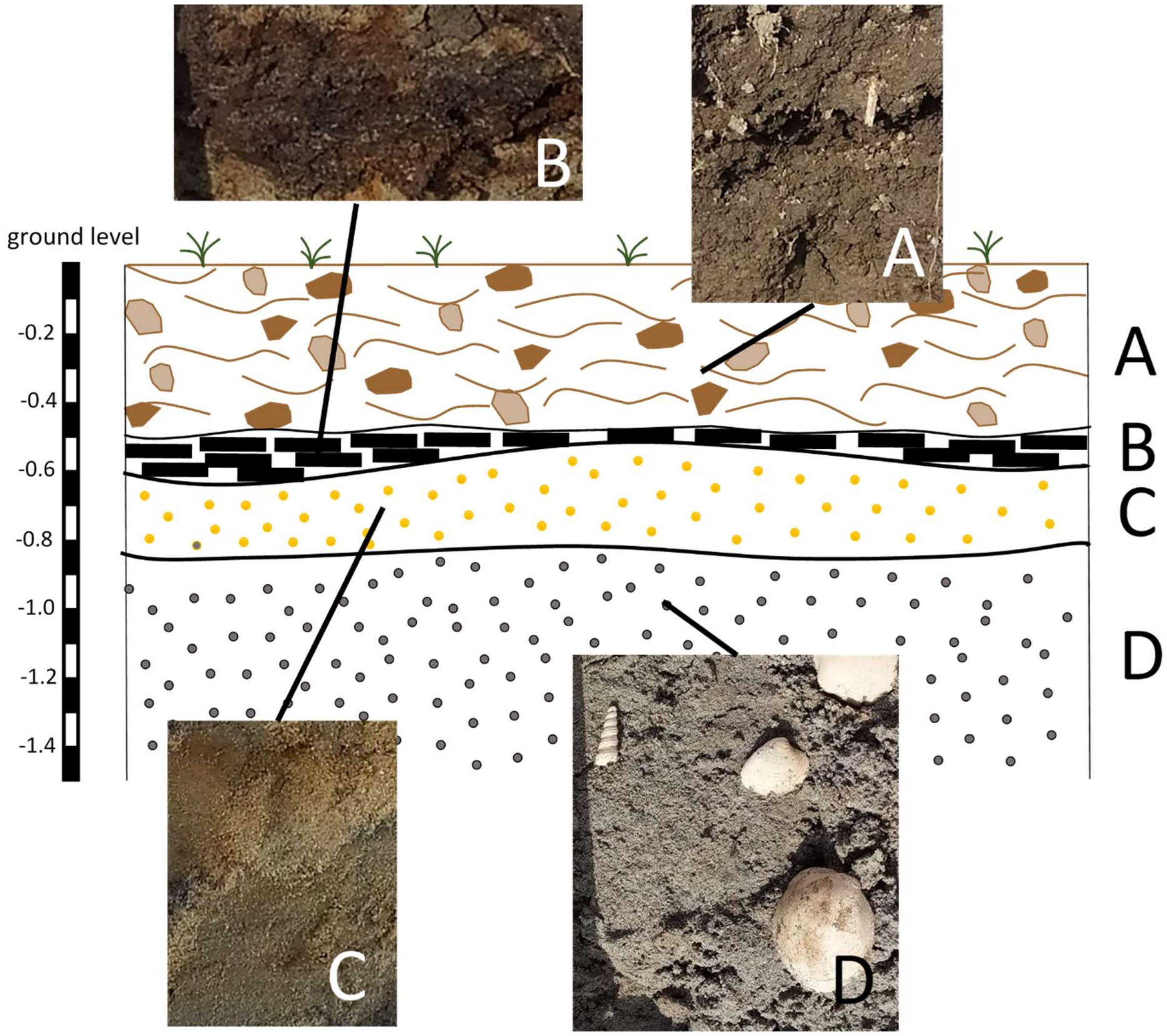

Fig. 12 – Sketch of subsoil of the first 1.5 meters.

In order to collect more stratigraphic data on the surficial subsoil of the Test area, five more sedimentary cores were recovered using an Eijkelkamp hand auger, through a gouge sampler with a length of 1 m and a diameter of 30 mm. The cores were collected at the southern margin of the Test Site: GH06 next to the terminal part of the sub-irrigation system, GH01, GH02, GH03 and GH05 in the agricultural field just south of the one interested by the test (Fig. 13). All the cores, up to 1.5 m depth, were collected within the sand body interpreted as a paleo-channel, except GH01 core which was taken just outside this surficial sand body. The cores were successively cut longitudinally, photographed and described (Fig. 14). Sedimentological analyses were carried out on the study cores following the basic principles of facies analyses: sediment grain size and color, presence of sedimentary structures, bioturbation and occurrence of plant and/or shell remains were taken into account.

Fig. 13 – Location of the surficial sedimentary cores

- GH01: 0-0,10 m: brownish silt (agricultural soil); 0,1-0,5 m: silty clay passing upward to peaty clay; 0,5-1,20 m: fine to medium fine well sorted grey sand with rare vegetal remains; 1,20-1,25 m: peat layer; 1,25-1,40 m: grey sandstone with shell fragments.
- GH02: 0-0,30 m: fine sand (agricultural soil); 0,30-0,60 m: fine to medium/fine yellow sand with mottling and traces of oxidation and vegetal remains; 0,60-1 m: fine to medium/fine well sorted grey sand.
- GH03: 0-0,5 m: fine sand (agricultural soil) peaty at the base; 0,5-0,7 m: fine to medium/fine yellow sand with mottling and traces of oxidation; 0,7-1 m: fine to medium/fine well sorted grey sand.
- GH05: 0-0,4 m: peaty fine sand (agricultural soil); 0,4-0,9 m: fine to medium/fine yellow sand with mottling and traces of oxidation and vegetal remains; 0,9-1,0 5m: fine to medium/fine well sorted grey sand, with vegetal and peaty remains; 1,15-1,20 m: peat layer; 1,20-1,50 m: grey sandstone with shell fragments.
- GH05 bis (collected at the bottom of a ditch): 1-1,25 m: grey well sorted sandstone; 1,25-1,40 m: alternating peat layers and fine sand with vegetal remains.
- GH06 (collected at the bottom of a ditch): 1,25-1,45 m: grey sand with shell fragments, abundant at the base of the layer; 1,45-1,50 m: peat layer; 1,50-1,55 m: grey sand with shell fragments.

Fig. 14 - Sedimentary cores collected in the surficial sub-soil

Both stratigraphic reconstructions, resulting from the direct observation on the subsoil and from the recovery of the 5 surficial stratigraphic cores, respectively, record the transition between marine to continental paleo-environment, suggested by the superposition of 4 facies (from the bottom to the top):

- well sorted grey sand with shells and shells fragments,
- peat or peaty clay layers (locally),
- grey to yellow sand with vegetal remains,
- agricultural soil.

6. Stratigraphy of the upper 20 m of the sub-soil in the pilot test area

The litho-stratigraphic record of two representative sediment cores is shown in Fig. 15. The two cores (S1 and S3) were selected from the five ones previously drilled in the Pilot area (S1, S2, S3, S4 and S5).

Core S3, from the soil surface to a depth of about 9 m, has a fairly homogeneous lithology made up of medium-fine sand with bioclasts. From -9 to -20.00, the core consists of clayey and silty sediments. At the top of core S1 down to a depth of 1.4 m, peat and silty clay are found; between -1.4 m to -9.30 m the core consists of medium-fine sand with bioclasts; at the bottom of the core, between -9.30 and -18.25 m, silty and clayey sediments and micaceous, fine silty sand are found.

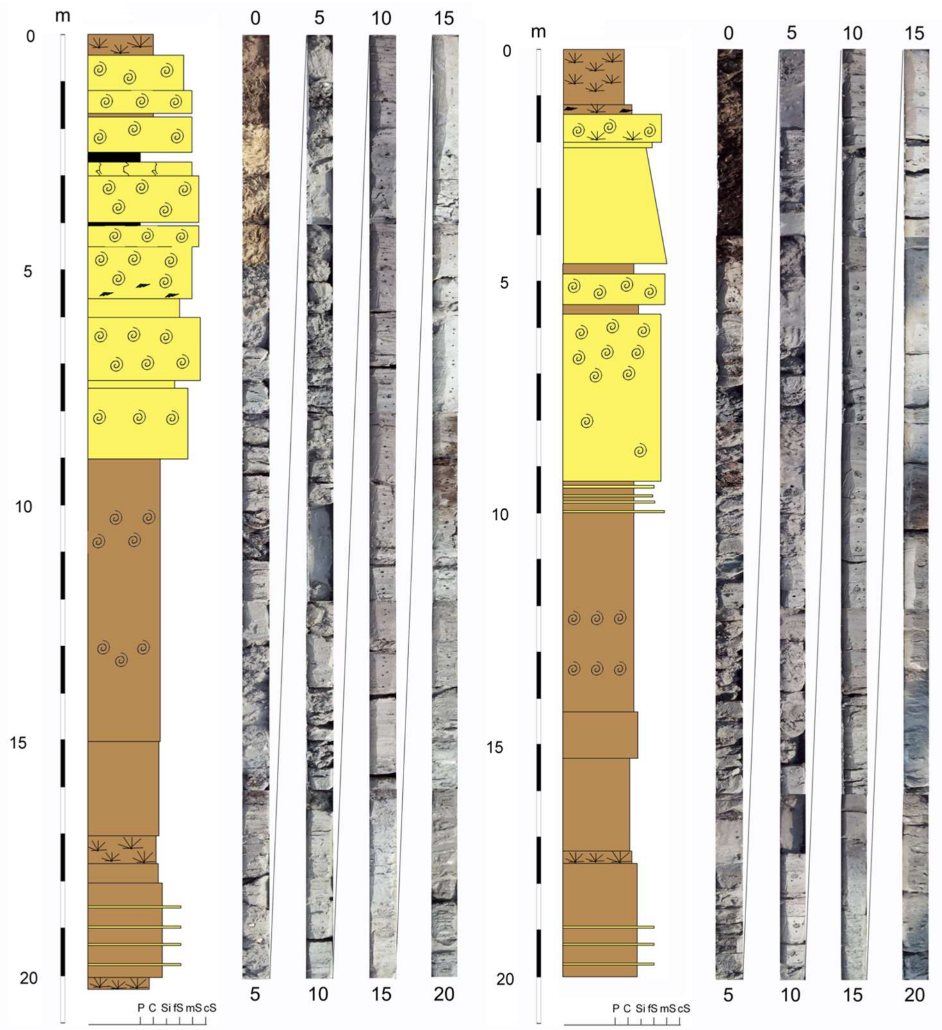

Fig. 15 - Litho-stratigraphic log of S3 and S1 sediment cores drilled in the study area.

Integrating the study of the surficial sub-soil, the sedimentological analyses of the cores S1-S5 and the sedimentological analyses of the new cores MoST1-MoST5 (taken in the frame of the present project), together with micropaleontological analyses (Doc MoST-CNR 3.2-004), the stratigraphy of the upper 20 m of the subsoil and the paleo-environmental and geomorphologic reconstruction have been deciphered.

In Fig. 17 is reported a stratigraphic section along the path of the sub-irrigation pipe and of the paleo-channel.

Fig. 16 – Location of the analyzed sedimentary cores (white square: S1-S5; yellow triangles MoST1-MoST5). The red and white lines represent the sub-irrigation pipe and the stratigraphic section showed in Fig. 17.

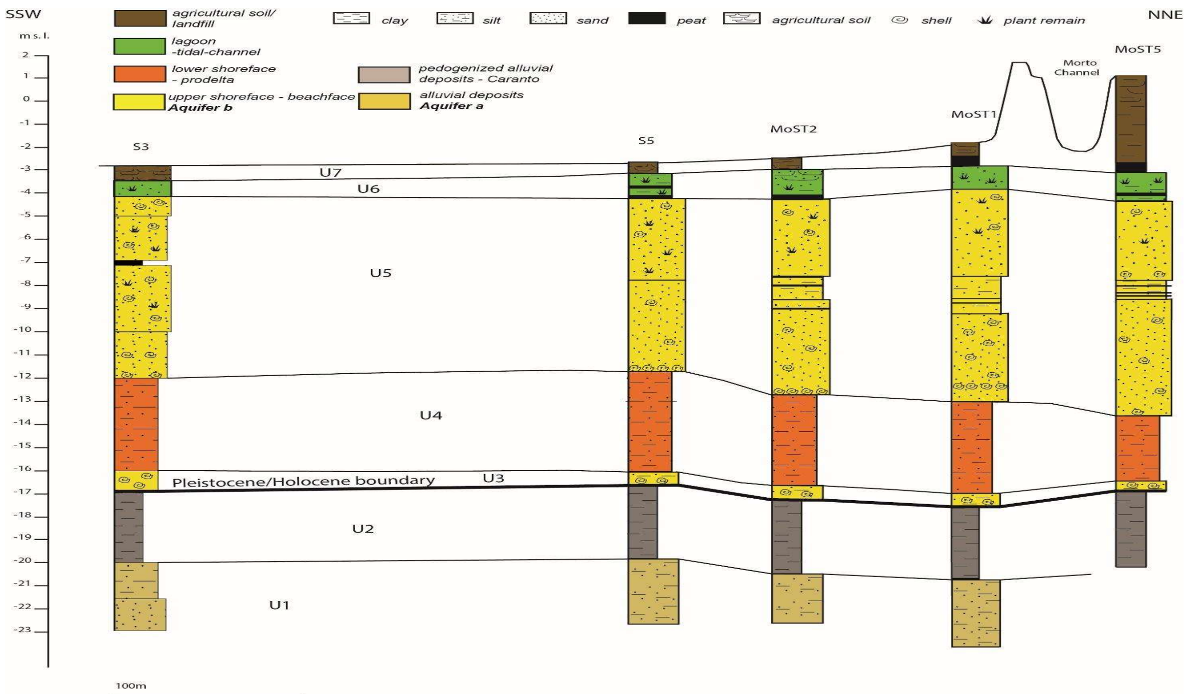

Fig. 17 – Stratigraphic section of the pilot test site, along the surficial sandy paleo-channel (the locations of the section, of the pipe and of the analyzed cores are shown in Fig. 15).

In the studied succession 7 informal stratigraphic units have been distinguished, each one corresponding to a different step in the paleo-environmental evolution of the area.

- Unit 1: Pleistocene alluvial sand and silt.
- Unit 2: Pleistocene alluvial clay and silt with mottling and carbonate nodules and other signs of pedogenesis. This level is referred to as the Caranto paleosoil (Donnici et al., 2011). The top of this unit marks the Pleistocene/Holocene boundary, and represents a stratigraphic hiatus.

Units from 3 to 7 record the Holocene transgressive-regressive cycle, in accordance with the regional stratigraphic reconstruction reported by many authors (e.g., Bonardi et al., 2006).

- Unit 3: back-barrier to barrier sandy deposits with abundant shells and shell fragments. The base of this unit is marked by an erosional surface interpreted as a ravinement surface, indicating the marine ingression.
- Unit 4: fine sand, silt and silty clay in alternation, presenting sub-horizontal lamination, interpreted as lower shoreface – prodelta deposits.
- Unit 5: fine to medium sand showing abundant shells and shell fragments, peat layers in the middle part and vegetal remains in the upper part. The lower portion of the unit is characterized by a higher sorting than the upper portion. This unit is interpreted to be deposited in an upper shoreface (beachface) environment, testifying the progressive progradation of sediments from land to sea. At the base of this unit, in the majority of the studied cores, a shell lag was found, possibly related to the maximum flooding surface (the innermost position reached by the sea).
- Unit 6: Sand to silty sand with vegetal remains, particularly abundant at the base. This unit corresponds to the surficial sandbody, and it is interpreted to be deposited in a lagoon environment (see the micropaleontological analyses in Doc MoST-CNR, 3.2-004), specifically within a tidal channel.
- Unit 7: agricultural soil

The described succession is well framed in the regional subsoil models already reconstructed in literature (Tosi et al., 2007; Tosi et al., 2009; Zecchin et al., 2008; Zecchin et al., 2009; Zecchin et al. 2011).

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