CHAPTER 9

Seafloor morphology and habitats of tidal channels in the Venice Lagoon, Italy tidal channel habitats

Fantina Madricardo[1], Giacomo Montereale-Gavazzi[2,3], Marco Sigovini[1], Aleksandra Kruss[1], Carlotta Toso[1,4] and Federica Foglini[5]

[1]ISMAR - Institute of Marine Sciences of the National Research Council of Italy, Venice, Italy [2]Operational Directorate Natural Environment, Royal Belgian Institute of Natural Sciences, Brussels, Belgium [3]Renard Centre of Marine Geology, Department of Geology and Soil Science, University of Ghent, Gent, Belgium [4]Department of Environmental Sciences, Informatics and Statistics (DAIS), Università Ca' Foscari Venezia, Campus Scientifico, Mestre, Italy [5]ISMAR - Institute of Marine Sciences of the National Research Council of Italy, Bologna, Italy

Abstract

Coastal lagoons are among the most vulnerable and economically important ecosystems on Earth and tidal channels are crucial for their functioning since they allow the exchange of water, sediments, nutrients, biota, and pollutants with the open sea. Despite their importance, there have been very few studies concerning their seafloor morphology and associated benthic habitats. Here we present the results of the high-resolution multibeam echosounder survey and ground truth sampling carried out in 2013 and in the following years to map in detail the main substrate characteristics. With unprecedented detail we highlight previously undocumented coastal wetland geomorphic features and benthic communities in coastal wetlands, describing their surrogacy. The substrate type and depth appear to influence the occurrence of distinct benthic biota. Overall, the tidal channel habitat described in our case study is in good condition and in a stable trend assessed with medium confidence.

Keywords: Tidal channels; benthic habitat mapping; extremely shallow water environment; Venice Lagoon

Introduction

The Lagoon of Venice (45°N, 12°E), located at the northern tip of the Adriatic Sea (Fig. 9.1A), is one of the largest coastal transitional ecosystems in the Mediterranean (about 550 km^2), stretching along the coast for 50 km. It has a mean width of 15 km and an average depth of 1.5 m (Molinaroli et al., 2007). The lagoon is characterized by strong

Seafloor Geomorphology as Benthic Habitat.
DOI: https://doi.org/10.1016/B978-0-12-814960-7.00009-9

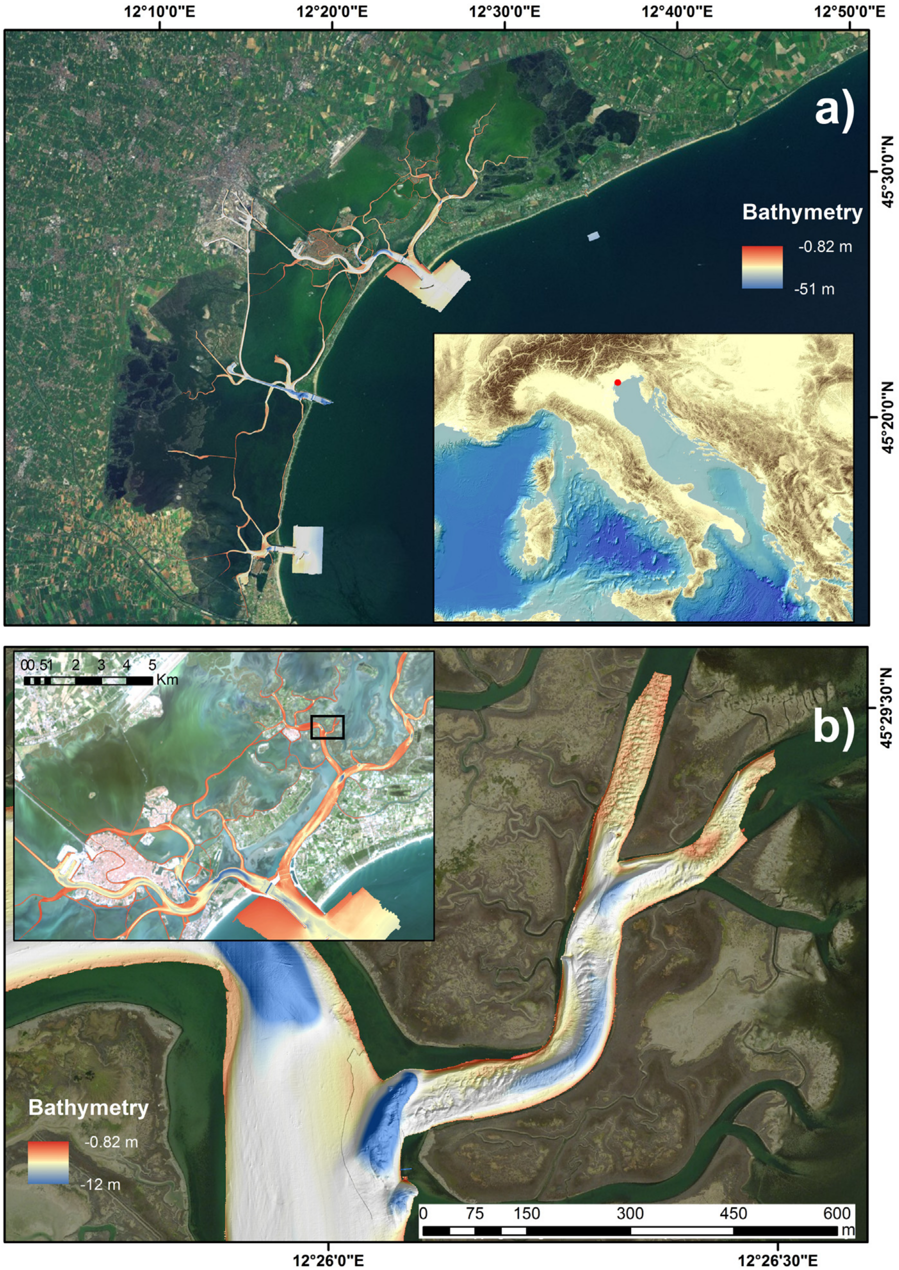

Figure 9.1
(A) The lagoon of Venice and the bathymetry obtained through the MBES survey carried out in 2013; (B) The northern lagoon and the natural channel of Scanello.

environmental gradients and a mosaic of landforms and habitats. Tidal channels occupy 15% of the lagoon surface, extending for an area of about 64 km^2. Their depth ranges from less than 1 m up to a maximum of 50 m.

The Venice Lagoon is a complex, heterogeneous, and highly dynamic system, subject for centuries to a number of anthropogenic drivers and pressures, including changes in its morphology and hydrodynamics, fishing activities, pollution, and nutrient loads (Solidoro et al., 2010, Madricardo et al., 2019). Both natural and anthropogenic stressors significantly affect the structure and functioning of the lagoon ecosystem at different scales, causing habitats degradation and loss. Some of the tidal channels are also subject to physical disturbance such as dredging to deepen or maintain navigable waterways. Other channels, including the case study presented in this paper, are less affected by direct human intervention. However, the effect of other indirect sources of impacts such as changes in hydrological, chemical, and biological parameters are harder to detect and quantify.

In 2013 the Institute of Marine Sciences (CNR−ISMAR), within the Flagship Project RITMARE (a National Research Program funded by the Italian Ministry of University and Research), carried out an extensive multibeam survey on the whole channel network (the detail of the survey and the link to the dataset can be found in Madricardo et al., 2017). A major target of the survey was to map the main seafloor geomorphic features and benthic habitats. Habitat mapping based on acoustic remote sensing methods has rarely been carried on extremely shallow coastal transitional systems such as lagoons (see e.g., Allen et al., 2005; Stolt et al., 2011). Prior to the 2013 survey the seafloor of the Venice Lagoon channels was relatively unexplored, both in terms of geomorphology and biota. Despite the fact that the benthic community was the subject of several quantitative studies in the past century, the only extensive sampling campaign on channel biocenosis was carried out in 1930−32 (Vatova, 1940). Later studies and monitoring efforts focused only on the mudflats communities, with the exception of a few studies of very limited spatial extent (e.g., Occhipinti Ambrogi and Gola, 2001). The high-resolution mapping of 2013 highlighted an unexpected richness in morphological features and biodiversity on the tidal channel seafloor.

Geomorphic features and habitats

The tidal channel geomorphic features can be separated in two classes: depositional (e.g., dunes, bars, and point bars) and erosive features (e.g., scours and pools). To exemplify the typical geomorphic features and benthic habitats of tidal channels, we selected a very shallow channel located in the northern part of the Venice Lagoon, Italy (Fig. 9.1B). The Scanello channel, a natural tidal channel, is part of a complex tidal system of tidal creeks and coastal salt marshes. Its depth ranges from 1 to 15 m and it follows a gentle downward slope from north to south. The channel represents a side branch of a main navigation channel. It extends into a salt marsh area and shows an erosion−deposition pattern characteristic of meandering tidal channels (Perrillo, 2009; Madricardo and Rizzetto, 2018).

A deep scour was found at the confluence with the main navigation channel (with values of the bathymetric position index (BPI) lower than −3) (Fig. 9.2), identified using Benthic Terrain Modeler toolbar within ArcGIS (Wright et al., 2005; Lundblad et al., 2006). The scour is steeper on the tributary channel side with the slope reaching values up to almost 70 degrees, whereas the seaward side of the scour has a gentler slope (up to 18 degrees). Confluence scours with similar asymmetry were found in most of the tidal channel confluences (Ferrarin et al., 2018).

Entering the channel there is a short straight section of about 200 m, where repetitive large-scale flow transverse bedforms are observed (indicated in Fig. 9.2A with the classes 2D dunes and 3D dunes; Ashley, 1990). Overall in the lagoon tidal channels there are dune fields with crest-to-crest spacing or wavelengths ranging from a few meters to more than a hundred meters at the lagoon inlets (Ferrarin et al., 2018; Fogarin et al., submitted). These are either two-dimensional (2D) or three-dimensional (3D) depending on the tidal current speed and the seafloor sediment grain size (Ashley, 1990; Madricardo and Rizzetto, 2018). The channel then bends to the North for about 300 m, where it bifurcates into two smaller branches flowing into an extremely shallow (<1 m) tidal flat. The tidal channel meanders and displays the development of point bars at the inner bends and pools at the outer bends, a pattern strongly resembling that observed in fluvial channels (Tambroni et al., 2017). The channel point bar and pool were mapped (identified by the BPI classes (0, −1) and (−3, −1), respectively). After the bend, following the north direction, there is a field of ripple-like structures and a small scour to the western limit of the channel, well highlighted by higher values of slope (Fig. 9.2). At the channel bifurcation there is another confluence scour and a tidal point bar on the eastern branch of the channel. After the bifurcation the channel branches are characterized by the relative highest ruggedness, quantified with the Vector Ruggedness Measure (VRM) as between 3×10^{-3} and 10^{-2}. However, the VRM isotropic distribution suggests the presence of biogenic features (Ferrini and Flood, 2006). The remainder of the of the channel is quite smooth (VRM ruggedness between 10^{-5} and 3×10^{-3}), with the exception of the dune-like fields in the main branch of the channel (VRM ruggedness between 10^{-5} and 1.5×10^{-3}).

The channel is characterized by strong tidal currents, that can reach speeds of 0.6 m s^{-1}, and by high water exchange, even during neap tides. Tidal currents, particularly during ebb tides, generate high turbidity. The suspended material, which includes organic matter, supports many species of benthic suspension feeders, including bivalves, sponges, sedentary polychaetes, tunicates, and bryozoans.

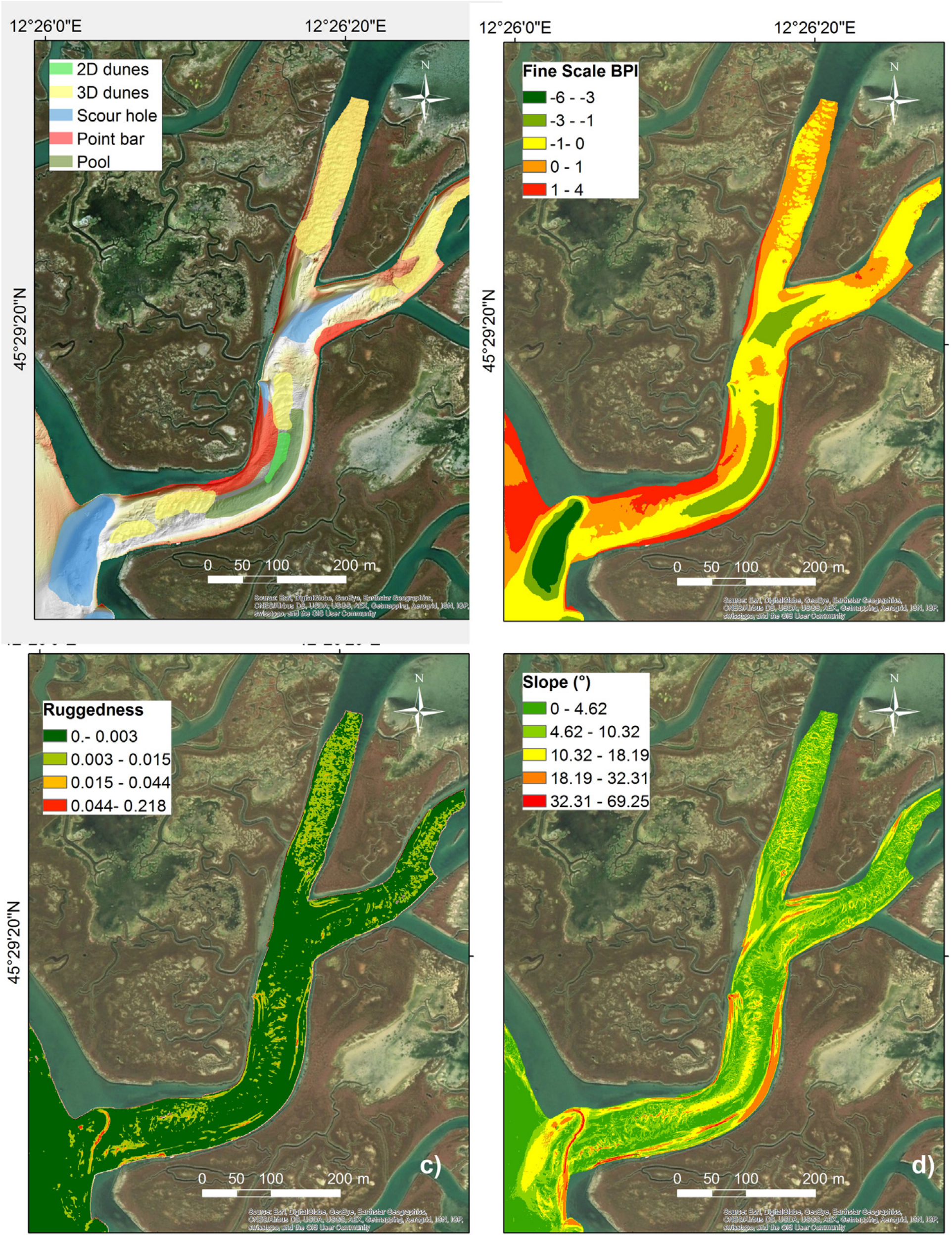

Figure 9.2

(A) Geomorphic features of a tidal channel; (B) fine BPI values; (C) ruggedness; and (D) slope values for the study area.

Biological communities

Bathymetry and backscatter (BS) data were collected during November 2013 with a Kongsberg EM2040 Dual-Compact Multibeam Echo-Sounder (MBES) obtaining extremely high-resolution DEMs and BS rasters (0.05- and 0.20-m grids). Along with acoustic data, sediment samples were collected with a Van Veen grab (7 L) and pictures and video transects of the seafloor were taken with an underwater camera. The sample locations were selected to comprise and characterize all the textural patterns identified from the BS imagery.

BS patterns can be attributed to different seafloor features, including cover, sediment hardness, and textures. We tested different methods to classify the BS rasters, and, in Fig. 9.3, we show the results obtained with the Jenks' optimization clustering within the ArcGIS platform with five classes. Given a certain number of classes, this method reduces

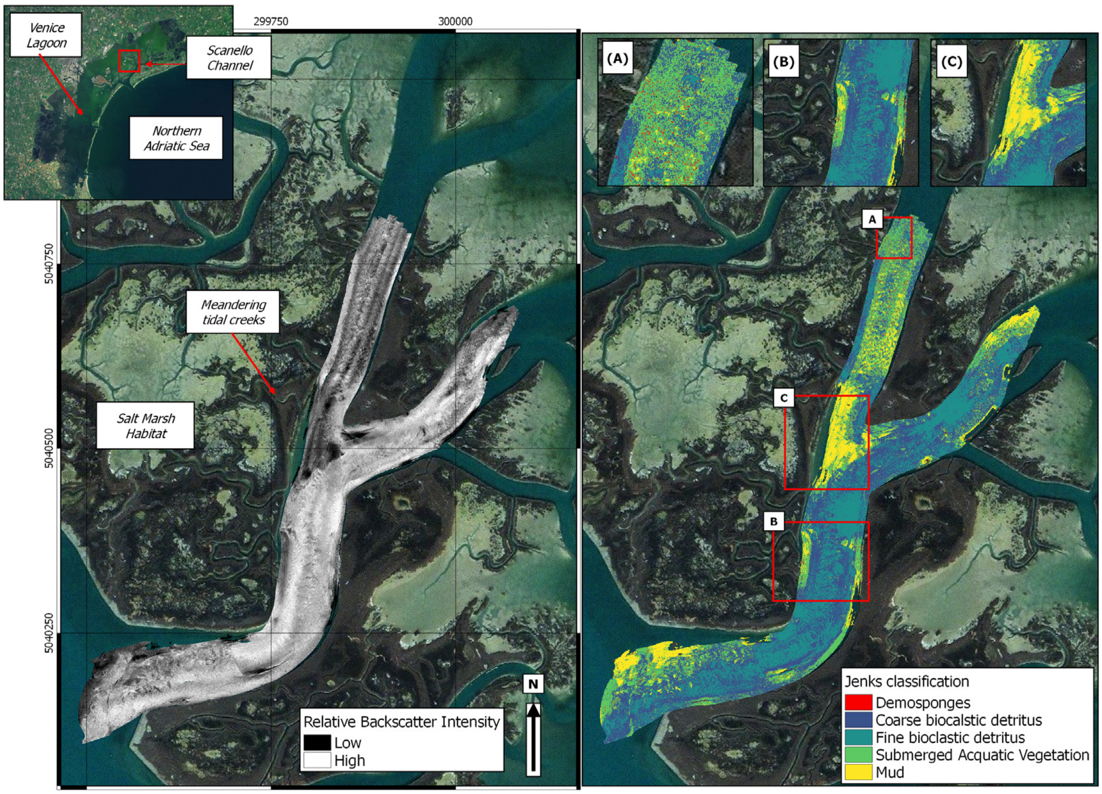

Figure 9.3
(left): BS mosaic of the study area with horizontal resolution of 0.05 m; (right): classified mosaic using an heuristic unsupervised clustering algorithm (Jenk's Optimization) (Montereale Gavazzi et al., 2016).

the variance within classes and maximizes the variance between classes (Jenks, 1967). To find the optimal number of BS classes, we applied the Jenks algorithm varying the number of classes from two to six with the R Package ClassInt (Bivand et al., 2009). For each segmentation deriving from a different choice in the number of classes, we computed the Goodness of Variance Fit index finding that five classes gave the best fit (see Montereale-Gavazzi et al., 2016 for a detailed description of methods and data types).

By comparing the classified BS and the ground truth samples collected, different substrate types were recognized in the channel (Fig. 9.3) ranging from coarse silt to very fine sand and coarse shell debris. Complex biogenic structures covered a large part of the channel seafloor developing on hard substrata: oyster beds encrusted and cemented by other bioconstructors such as tubicolous polychaetes and colonized by habitat-forming species such as sponges and bryozoans. Brown and red algae also covered a large extent of the tidal channel. These communities are characterized by relatively high structural complexity, diversity, and biomass.

The combination of satellite imagery and classified BS images of the study area revealed patches of bare muddy bottom on the channel seabed (thematic yellow class), which occur as a result of the sediment transported by small meandering tidal creeks from the inner salt marsh toward the tidal channel banks (Fig. 9.3 right). The photograph in Fig. 9.4A shows the Scanello channel close to the Burano Island and the adjacent salt marsh during a time of blooming for the *Limonium*, a characteristic plant of tidal salt marshes. Fig. 9.4B shows the channel bank close to the salt marsh and Fig. 9.4C illustrates a meandering tidal creek dissecting the salt marsh during low tide. The tidal creeks create a small scour at the junction with the studied tidal channel and deposition (a sort of "ebb-delta") on the seaward side of the channel (toward the main channel to the south) (see also Fig. 9.2A).

The five identified classes related to the main tidal channel substrate features and habitat-forming biota (with global classification accuracy of 0.71 and kappa coefficient of 0.63) can be identified as:

- "Sponges": massive (with diameters up to more than 1 m^2), cushion-shaped demosponges with associated canopy of red and brown macroalgae on oyster beds of the nonindigenous species *Crassostrea gigas* (visible in *red* in Fig. 9.3 right panel, zoom A and Fig. 9.4F).
- "Coarse bioclastic detritus": patches of coarse and dense shell detritus (mostly whole or fragmented bivalve shells) with some degree of cementation, intensely colonized by both infauna and epifauna, mostly suspension- and filter-feeders, such as Sabellidae and Terebellidae polychaetes, anemones, and ascidians (Fig. 9.4D).
- "Fine bioclastic detritus": patches of fine and sparse shell detritus (mostly the gastropod *Bittium* sp.) with abundant filter-feeding infauna, such as Sabellidae polychaetes.

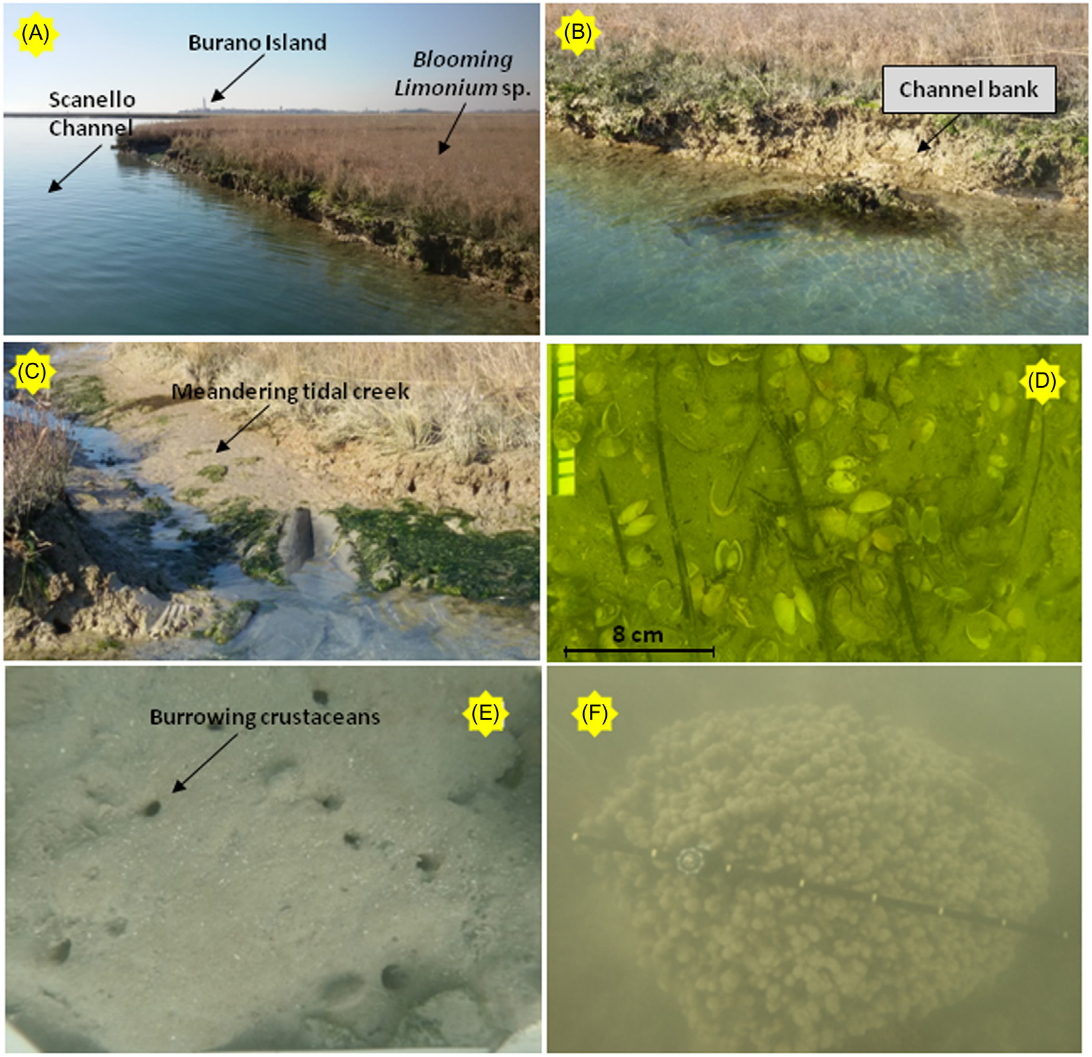

Figure 9.4
(A) Photo of the Scanello Channel and the adjacent salt-marsh in a time of *Limonium* blooming; (B) channel bank at the salt marsh edge; (C) meandering tidal creek dissecting the salt marsh photographed at low tide; (D) coarse bioclastic detritus; (E) silt deposits with burrows of *Upogebia* sp.; (F) a specimen of the sponge *Mycale contarenii* (graduated scale with 10-cm steps).

- "Submerged Aquatic Vegetation": the class includes macroalgae and algal turfs on fine sediments, as well as canopy-forming red and brown macroalgae on oyster beds and cemented coarse shell detritus; the physical proximity between sponges and algal canopy produces a relatively noisy classification of sponges in the pixel-based method applied, due to the similar signal intensities of these two spatially correlated features.
- "Bare muddy bottom": patches of bare mud and sandy mud with benthic diatom film and burrows of the thalassinid decapod *Upogebia* sp. (Fig. 9.4E)

Surrogacy

A hierarchical agglomerative cluster analysis was carried out with the open software environment R using the package *vegan* (Oksanen, 2011). The preliminary cluster analysis was performed on a data matrix produced from 17 photoquadrat samples collected by scuba diver and drop-frame in the study area (Fig. 9.5). From the quantitative analysis of photoquadrats, matrices of presence–absence and of percentage cover were produced.

These data include SAV and megazoobenthos (to the highest taxonomic resolution possible, including some organisms included in morphofunctional groups) as well as shell detritus cover. The data were expressed as percentage cover (in terms of ratio) and then transformed by square-root. Bray–Curtis dissimilarity measures and Group Average linkage method

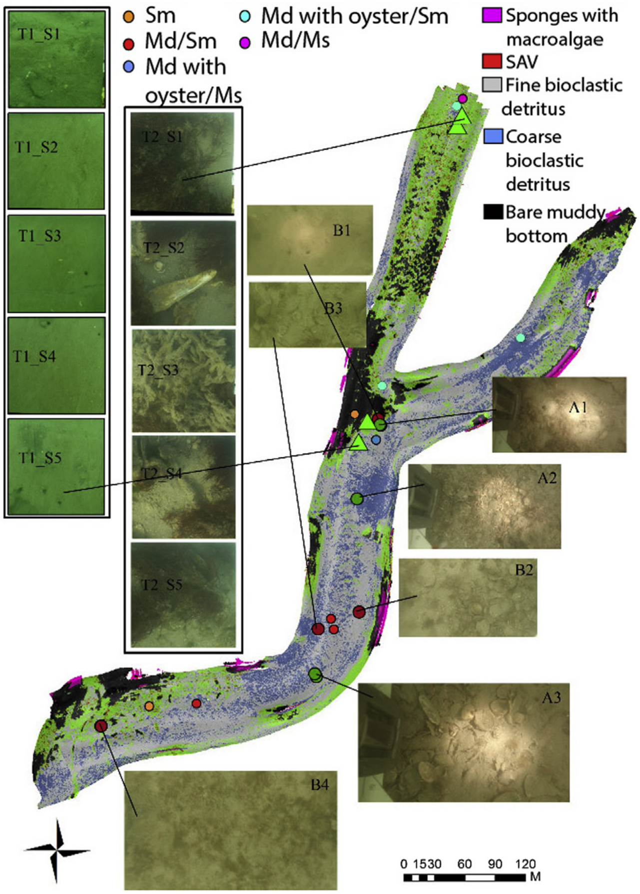

Figure 9.5

Map of segmented BS and photoquadrats shown with their corresponding geographic locations. The green triangles indicate the initial and final point of the video transects. *Sm*, Sandy mud; *D*, detritic; *Ms*, Muddy sand; *Md*, Mix detritic; *SV*, Submerged Aquatic Vegetation.

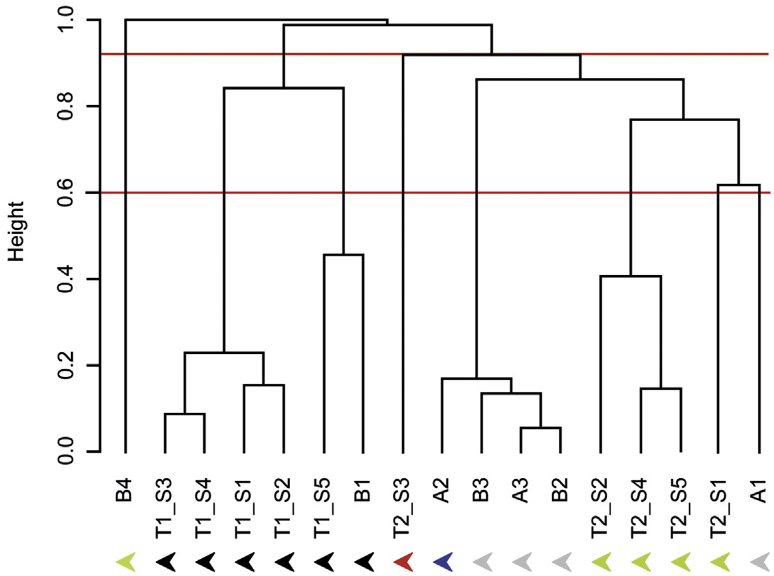

Figure 9.6

Bray–Curtis cluster dendrogram produced for the analysis of dissimilarity of photoquadrats. The colored arrow indicates the backscatter class sampled. Red lines indicate the cuts at dissimilarity level $H = 0.92$ and $H = 0.6$.

were used. The dendrogram (Fig. 9.6) was cut at two levels of dissimilarity (0.92 and 0.6) and relationships of clusters to BS classes were checked. At the highest dissimilarity level chosen, samples are grouped into two large clusters with the exception of samples B4 and T2_S3. At the lower dissimilarity level, four clusters can be identified, which correspond to specific BS classes. Sample B4 stands out as an outlier due to its unique characteristics (algal turf) but it however remains similar to transect T1, forming one cluster, due to the shared similarity in terms of relatively-bare ground and lack of shell detritus cover. Sample B1 shows similar physical and biological characteristics to transect T1, with which it clusters. T2 samples are also clustered with the exception of sample T2_S3 (which corresponds to a dead, massive sponge covering the whole sample's surface). The remaining isolated samples are very similar ($H = 0.18$) and correspond to shell detritus habitat.

This analysis confirms that habitats identified by BS classes are not only distinct in terms of substrate type but also in terms of the biological component. This is particularly true for SAV, bare mud, and sponges classes (classes 1, 4, and 5). The remaining two classes relating to bioclastic detritus show more similarity to each other than to the other habitats and are spatially correlated, reflecting bottom current forcing. The cluster analysis discriminated distinct types of communities. In terms of surrogacy, substrate type and depth (in particular at the intertidal range and in reference to light penetration and waves disturbance) appear to influence the occurrence of distinct benthic biota. In particular, the presence of a coarse detritus provides the structural complexity (i.e., hard substratum, crevices, and roughness), favoring the settlement of a rich biota. This includes bioencrusting species and other sessile organisms, such as the massive sponges (mostly distributed in the channel's northern bifurcation, with the largest individuals of *Mycale contarenii* being more than 1 m^2) (Fig. 9.4F).

Naturalness, condition, and trend

The habitat described in our case study is in good (5−6) condition and in a stable trend assessed with medium confidence.

References

Allen, Y.C., Wilson, C.A., Roberts, H.H., Supan, J., 2005. High resolution mapping and classification of oyster habitats in near shore Louisiana using sidescan sonar. Estuaries 28 (3), 435−446.

Ashley, G.M., 1990. Classification of large-scale subaqueous bedforms: a new look at an old problem-SEPM bedforms and bedding structures. J. Sediment. Petrol. 60, 160−172.

Bivand, R., Ono, H., Dunlap, R., 2009. classInt: Choose Univariate Class Intervals. R package version 0.1 − 14.

Ferrarin, C., Madricardo, F., Rizzetto, F., Mc Kiver, W., Bellafiore, D., Umgiesser, G., et al., 2018. Geomorphology of scour holes at tidal channel confluences. J. Geophys. Res.: Earth Surf. 123.

Ferrini, V.L., Flood, R.D., 2006. The effects of fine-scale surface roughness and grain size on 300 kHz multibeam backscatter intensity in sandy marine sedimentary environments. Mar. Geol. 228 (1), 153−172.

Fogarin, S., Madricardo, F., Zaggia, L., Sigovini, M., Montereale-Gavazzi, G., Kruss, A., et al., 2019. Tidal inlets in the Anthropocene: geomorphology and benthic habitats of the Chioggia inlet, Venice Lagoon (Italy). Earth Surf. Process. Landforms. Available from: https://doi.org/10.1002/esp.4642.

Jenks, G.F., 1967. The data model concept in statistical mapping. Int. Yearb. Cartogr. 7, 186−190.

Lundblad, E., Wright, D.J., Miller, J., Larkin, E.M., Rinehart, R., Battista, T., et al., 2006. A benthic terrain classification scheme for American Samoa. Mar. Geodesy 29 (2), 89−111.

Madricardo, F., Rizzetto, F., 2018. Shallow coastal landforms. In: Micallef, A., Krastel, S., Savini, A. (Eds.), Submarine Geomorphology. Springer International Publishing, Cham, pp. 161−183. Available from: https://doi.org/10.1007/978-3-319-57852-1_10.

Madricardo, F., Foglini, F., Campiani, E., Grande, V., Catenacci, E., Petrizzo, A., 2019. Assessing the human footprint on the sea-floor of coastal systems: the case of the Venice Lagoon, Italy. Scientific reports 9 (1), 6615. Available from: https://doi.org/10.1038/s41598-019-43027-7.

Madricardo, F., et al., 2017. High resolution multibeam and hydrodynamic datasets of tidal channels and inlets of the Lagoon of Venice. Sci. Data 4 (170121). Available from: https://doi.org/10.1038/sdata.2017.121.

Molinaroli, E., Guerzoni, S., Sarretta, A., Cucco, A., Umgiesser, G., 2007. Links between hydrology and sedimentology in the Lagoon of Venice, Italy. J. Mar. Syst. 68 (3), 303−317. Available from: https://doi.org/10.1016/j.jmarsys.2006.12.003.

Montereale Gavazzi, G., Madricardo, F., Janowski, L., Kruss, A., Blondel, P., Sigovini, M., et al., 2016. Evaluation of seabed mapping methods for fine-scale classification of extremely shallow benthic habitats-application to the Venice Lagoon, Italy. Estuarine, Coastal Shelf Sci. 45−60. Available from: https://doi.org/10.1016/j.ecss.2015.12.014.

Occhipinti Ambrogi, A., Gola, G., 2001. Macrozoobenthos di fondo incoerente in Laguna di Venezia: contributo alla conoscenza del bacino di Malamocco. Biol. Mar. Mediterr. 8 (1), 393−402.

Oksanen, J., 2011. Multivariate analysis of ecological communities in R: vegan tutorial. R package version, 1 (7).

Perillo, G.M.E., Wolanski, E., Cahoon, D.R., Brinson, M.M., 2009. Coastal Wetlands: An Integrated Ecosystem Approach. Elsevier, 941 pp.
Solidoro, C., Bandelj, V., Bernardi Aubry, F., Camatti, E., Ciavatta, S., Cossarini, G., et al., 2010. Response of Venice Lagoon eco system to natural and anthropogenic pressures over the last 50 years (ch. 19). In: Kennish, M.J., Paerl, H.W. (Eds.), Coastal Lagoons. Critical Habitats of Environmental Change. CRC Press.
Stolt, M., Bradley, M., Turenne, J., Payne, M., Scherer, E., Cicchetti, G., et al., 2011. Mapping shallow coastal ecosystems: a case study of a Rhode Island lagoon. J. Coast. Res. 27 (6A), 1−15.
Tambroni, N., Luchi, R., Seminara, G., 2017. Can tide dominance be inferred from the point bar pattern of tidal meandering channels? J. Geophys. Res.: Earth Surface 122 (2), 492−512.
Vatova, A., 1940. Le zoocenosi della Laguna veneta. Thalassia 3 (10), 1−28.
Wright, D.J., Lundblad, E.R., Larkin, E.M., Rinehart, R.W., Murphy, J., Cary-Kothera, L., et al., 2005. ArcGIS Benthic Terrain Modeler. Oregon State University, Corvallis, OR.

Further reading

Dalrymple, R.W., Rhodes, R.N., 1995. Estuarine dunes and bars. Geomorphol. Sedimentol. Estuaries 53, 359−422.