

Article



Sabellaria alveolata versus Sabellaria spinulosa Reefs along the Italian Coasts: A New Methodological Proposal to Compare Different Growth Models

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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). **Abstract:** *Sabellaria* species are among the most important frame-builders in temperate, shallow marine areas. These polychaetes are suspension feeders able to build bioconstructions using sand and shell fragments cemented with a sticky mucous. Such feature makes these invertebrates "unusual bioconstructors", as they do not produce calcium carbonate. Sabellaridae reefs are widespread in the Mediterranean and along the Atlantic coast of Europe, but their sedimentological aspects are still poorly known. Over short time intervals, these bioconstructions can rapidly alternate between phases of growth, stasis and destruction during different seasons. In this paper, we compare reefs of two *Sabellaria* species (*S. alveolata*—Ostia, Roma and Tyrrhenian Sea; *S. spinulosa*—Torre Mileto, Foggia and Adriatic Sea) found at two different sites along the Italian coast. We describe the morphology of worm tubes at the macro- and microscale. Similarities and differences are discussed based on eco-biological features and physical environmental conditions. This work shows a measurement and observation scheme for this type of bioconstructions that has been verified at both the macro- and microscale and which was shown to be useful for defining evolutionary trends of sabellarian bioconstructions. The monitoring parameters were identified and verified over a long period.

Keywords: sabellarian bioconstructions; worm reef; sedimentology; sandy beaches

1. Introduction

Worm reefs are stable bioconstructions that are built by marine gregarious polychaetes able to form colonies very high densities at different depths [1,2]. Among frame-builder polychaetes, sabellariids form bioconstructions formed by adjacent and subparallel tubes, which are joined together with cement, sand grains and shells (whole or in fragments) using a glue secreted by the polychaetes [3–5]. As such, these bioconstructions have a crucial role in preventing coastal erosion by stabilizing the sediments involved [6]. The importance of these bioconstructions, although sometimes not long-lasting, is also linked to the high biodiversity of the associated fauna that contributes to defining a pattern similar to a community of hard, rather than soft, substrates [7].

Sabelliarian reefs can be found along the coasts of all oceans, although, according to the literature, they seem to be concentrated in temperate areas. *Sabellaria* reefs develop between 0 and 20 m of depth in intertidal or subtidal zones, depending on the species [8–15]. *Sabellaria alveolata* (Linnaeus 1767) and *Sabellaria spinulosa* (Leukhart 1849) are the most common species along the European coasts, locally building extensive reefs [5,8–10], such as in Mont Saint-Michel Bay, where it is possible to find the largest dimpled European

reef (approximately 60,000 individuals/m² [16,17]. In the Mediterranean, along the Italian coasts, *S. alveolata* forms mound-shaped reefs to large banks, while *S. spinulosa* generally forms smaller and isolated bioconstructions.

The presence of reefs, their development and temporal persistence are linked to many biotic (e.g., propagule pressure of *Sabellaria* planktonic larvae and their subsequent settlement) and abiotic factors (granulometry of the surrounding sediments, hydrodynamics and meteo–climatic regime). Propagules usually settle along the coastlines exposed to the proper action of tides, waves and currents. Indeed, a hydrodynamic regime must be sufficient to keep the sediment in suspension [18] but not tear off or erode the colony [19]. If temperature, salinity, nutrients, currents or other abiotic factors are optimal, the reef can have a constant growth [20]. After the first colony is established, it grows through particular mechanisms of recruitment in which adults induce the nearby rooting of larvae by producing organic glue similar to that used to form and cement tubes [9].

There are three main evolutionary stages of worm reefs: the phases of primary settlement, growth and erosion. *Sabellaria alveolata* and *S. spinulosa* reproduce throughout the year, with two principal reproductive peaks occurring in the spring and summer [18–21]. Attachment of larvae occurs in the presence of hard and stable substrates (both natural and artificial), but the colony can also grow on soft substrates [22]. A secondary settlement can arise during the growth phase and can help reef development. Growth begins when the tubes encrust the substrate, hence enlarging the colony horizontally [19]; after which, they also start growing perpendicularly to the seabed [23]. From the union of adjacent colonies, bioconstructions of different geometries and sizes are formed. These structures can become thick (>1 m) and wide (>2 km²; as in the case of the Mont Saint-Michel reef) platforms that can further evolve into real benches, whose shape and orientation vary according to the type of substrate and hydrodynamic regime [19], A classification of these structures was proposed by Griffin et al. [24] and was based on Gruet's morphological subdivision [8].

When the colony has reached a considerable size, and in relation to the seasonality, the process of physical degradation can occur due to the rapid and destructive action of storm waves, tides and marine currents. Nevertheless, *Sabellaria* reefs appear to have great shear strength by opposing external mechanical stresses [25]. The presence of erosive/destructive phases can be related to climate changes; anthropogenic disturbances (such as trampling, water pollution or aquaculture activities) and the presence of specific organisms such as fish, crabs, mussels and oysters that can colonize and erode bioconstructions [9].

At the microscale, the general framework of the reef is defined by two main elementary structural units [15,26,27]: (1) the sands cemented directly by the worms (the tube area that is ordered in concentrical layers—t) and (2) the sands that remain trapped between a tube and the adjacent one (the intertube area with elements irregularly arranged—i). According to the literature, the tube has a known three-layered structure with different sizes and shapes of cemented grains [27–29]. The grains of sand, the inner layer of the tube, cemented directly by the worm are mainly elongated, flattened and oriented tangentially to the development of the tubes. All the observations carried out at the microscale start from the recognition of this basic pattern. Using a multiscale approach (from general to microscale), the present paper compares two different large-scale bioconstructions built by sabellarian polychaetes along the Italian coast. The first is an area with a bioconstructions of S. spinulosa near Torre Mileto along the Southern Adriatic Coast, described as the largest bioconstruction of S. spinulosa in the Mediterranean area of the Northern Gargano Coast. The second area, localized near Ostia in the Central Tyrrhenian Sea, is characterized by the presence of S. alveolata reefs. New data are here presented, discussed and compared with complementary and already described data [7,15,26,30], with the aim of: (i) analyzing the evolution in space and time of the reef. (ii) testing the reliability of technical procedures to describe the growth and destructive phases for a long period, (iii) defining a suitable classification for these types of structures and for the procedure proposed here, (iv) proposing procedural improvements adding simple and quantitative parameters and (v) developing seasonal growth models for the case studies observed here.

The final aim of this work is the comparison of growth models of the two most widespread and stable worm reefs in the Mediterranean Sea over a long period of continuous monitoring (about eight years) in order to discriminate general and specific features related to the interactions between sedimentological, biological and anthropic processes.

2. Study Area

The studied areas are localized in Central–Southern Italy, along the coasts of the Adriatic and Tyrrhenian Seas (Figure 1).



Figure 1. (a) *Sabellaria alveolata* (empty circles) and *Sabellaria spinulosa* (full circles) reefs along the Italian coast [31,32]. On the right, location of the sampling areas at (b) Torre Mileto and (c) Ostia. Four main observation transects are shown in white: one transect is parallel, and the other three are perpendicular to the coastline.

2.1. Torre Mileto Site

Sabellaria bioconstructions, found in the northern sector of the Gargano promontory, show well-developed formations between Torre Mileto (41°55′45.3″ N; 15°37′12.37″ E—Figure 1b) and Vieste (41°52′54.20″ N; 16°10′27.07″ E). Sabellaria spinulosa is found along the northern coasts of the promontory. In the westernmost sector (at the east of Torre Mileto), bioconstructions are continuous or isolated mounds. Towards Vieste, bioconstructions are becoming more frequent, although thinner [33]. Bioconstructions better developed and more extended were observed near Torre Mileto, along the rocky shore between Lesina and Varano Lakes. In 2019, the site was proposed as "Sites of Community Importance" to protect them. In this area, the highest storm waves are recorded during the winter, and previous works indicated prevailing storm waves from the NNW and a longshore current that runs eastward [15].

2.2. Ostia Site

The site is characterized by the presence of a *S. alveolata* reef. It is strongly affected by the presence of the Tiber River, which influences the coastal dynamics of the entire area (more than 40 km toward the northern and southern sectors from the delta). The beaches, currently found near the river mouth, are sandy (mainly with a quartz-feldspathic component) with dune sections that can locally reach 10–12 m in height [34]. Near the reef, there is the so-called "Canale dei Pescatori", an ancient natural emissary of the Ostia swamp, which extends for about 8 km towards the inland and is currently dammed and used as a port and an outflow route of reclamation canals [34]. The long beach of Ostia Lido is located between the river and "Canale dei Pescatori" (Figure 1c). It is influenced

by longitudinal transport towards the SE. The local tidal range is small (<0.5 m), and the closing depth of the beach profiles is -7 m approximately. During the last few decades, the entire area has been affected by intense erosive phenomena due to the sediment flow variation of the Tiber River and, from 1990, a submerged longitudinal barrier of 2.5 km in length, built as a coastal defense [35]. The main *S. alveolata* bioconstruction at Ostia originated on basalt blocks of the artificial barrier.

3. Materials and Methods

Quantitative data and qualitative observations were acquired to describe the structures of the bioconstructions at macro- and microscale. The macroscale data were acquired directly in the field. The following elements were described/measured for each site during each survey:

- distributional area of the main bioconstruction (calculated in m²). Five georeferenced points were used to establish the approximate reef extension and its eventual lateral displacement;
- fragmentation degree. Across five test square areas (3m × 3 m), located in the same zone as the five georeferenced points, we used a qualitative scale assigning: (i) a low fragmentation value (L) in the absence of interruptions, (ii) a moderate fragmentation value (M) if the discontinuities in the presence of recurring structure interruptions are equal to 30% of the entire test area and (iii) a high fragmentation value (H) in the presence of continuous structure interruptions higher than 50%;
- the roughness of the bioconstruction surface, evaluated in the central portions of the bioconstruction and in the same five test square areas (3 × 3 m). A high roughness value (H) was assigned in the presence of highly articulated surfaces, an average roughness value (M) for poorly articulated surfaces and a low roughness value (L) when smooth surfaces covered more than 50%;
- thickness, measured at five georeferenced points; the maximum thickness was measured in centimeters vertically by inserting a thin graduated iron rod into the bioconstruction.

At the microscale, the following parameters were measured (on a number of tubes between 70 and 150 for each season and for each site): (i) mean inner diameter of tubes composing the bioconstruction, defined as the arithmetic mean of average diameters in different seasons), (ii) variability coefficient, representing the ratio between the standard deviation and tubes on a square meter of surface, and (iii) the number of tubes/square meter.

The present paper reveals the results of 9 years (2012–2020) of monitoring by using the same procedures as in previous works. The surveys were performed over the last four weeks for each season, for a total of minimum four data for each season and site from 2012 to 2020 (Table 1). Choosing this timeframe allows us to monitor the effects of the entire season that is ending, the system mainly influenced by seasonal meteo–marine conditions. During all considered seasons, surveys were conducted to acquire photo and video materials and to measure the macroscale features of the bioconstruction along transects perpendicular to the coastline and parallel to the development of the bioconstructions in a bathymetric range between 1 and 5 m below the sea level. During the surveys, three sample replicates of reef fragments (minimum dimensions: $30 \times 30 \times 30 \text{ cm}^3$) were collected for each season. In particular, samples were collected at different depths (1 m, 2 m and 3 m) along the central and highest part of the bioconstruction to describe the temporal geometrical development in more detail. For each sample, tubes with live polychaetes were analyzed from the base to the top.

Season	Year	Site	Survey	Mapping	Sampling	Macrofeat. Measuring
Autumn	2012	Torre Mileto	х	х	х	х
Spring	2013	Torre Mileto	х	х	х	х
Winter	2013	Torre Mileto	х	х	х	х
Summer	2015	Torre Mileto	х	х	х	х
Autumn	2016	Torre Mileto	х	х	х	х
Spring	2017	Torre Mileto	х	х	х	х
Summer	2017	Torre Mileto	х	х	х	х
Autumn	2017	Torre Mileto	х	х	х	х
Spring	2018	Torre Mileto	х	х	х	х
Summer	2018	Torre Mileto	х	х	х	х
Autumn	2018	Torre Mileto	х	х		х
Winter	2018	Torre Mileto	х	х		
Spring	2019	Torre Mileto	х	х	х	х
Summer	2019	Torre Mileto	х	х	х	х
Autumn	2019	Torre Mileto	х	х	х	х
Winter	2019	Torre Mileto	х	х	х	х
Summer	2020	Torre Mileto	х	х	х	х
Winter	2020	Torre Mileto	х	х	х	Х
Autumn	2012	Ostia	х	х	x	Х
Autumn	2013	Ostia	х	х	х	х
Spring	2014	Ostia	х	х	х	x
Summer	2014	Ostia	х	х	х	х
Winter	2014	Ostia	х	х		
Spring	2017	Ostia	х	х	х	х
Spring	2018	Ostia	х	х	х	х
Summer	2018	Ostia	х	х	х	х
Autumn	2018	Ostia	х	х	х	х
Winter	2018	Ostia	х	х	х	х
Spring	2019	Ostia	х	х	х	х
Summer	2019	Ostia	х	х	х	х
Autumn	2019	Ostia	х	х	х	x
Winter	2019	Ostia	х	х	х	x
Summer	2020	Ostia	х	х	х	x
Winter	2020	Ostia	х	х		Х

Table 1. This table summarizes the phases of the field analysis carried out from 2012 to 2020.

All samples were treated with epoxy resin and then cut along the main tube growth axis to obtain slices that, once polished, were used to study the vertical development of the reef. After a detailed description, slices were used to acquire a high-resolution image using a scanner. The methodology used to acquire petrographical and granulometric data by image analysis on slices and thin sections has already been described in previous works [15,30]. High-resolution scans of thin sections allowed us to describe the worm reef framework at the microscale and in different seasons. Using ImageJ[©], the morphometric features were a total of about eighteen hundred tubes per species. Furthermore, about the same samples of annual and seasonal variations were analyzed. Tube width, mean diameter for each thin section, coefficient of variation and tube density were the main morphometric elements evaluated in the thin sections.

4. Results

4.1. Large-Scale Monitoring Results

The monitoring of worm reefs was focused on the assessment of four physical parameters: extension, fragmentation, roughness and maximum thickness. The variations of the mean values of the macroscale parameters during different seasons and years are shown in Figure 2.



Figure 2. Variations of the mean values of the macroscale parameters during different seasons and years. Diagram shows the variation trends of the parameters during different seasons, including extension; maximum thickness; fragmentation (using a qualitative scale: low fragmentation (L), moderate fragmentation (M) and high fragmentation (H)) and roughness (using a qualitative scale: high roughness (H), moderate roughness (M) and low roughness (L)). On the left is the main bioconstruction of *S. spinulosa* at Torre Mileto (**a**). On the right is the *S. alveolata* bioconstruction at Ostia (**b**).

The results indicate that the main *S. spinulosa* bioconstruction at Torre Mileto reached its greatest extent between the spring and summer (maximum measured value 5300 m^2). However, the extent decreased in the autumn (on average, about 4200 m^2) and was drastically reduced in the winter (maximum measured value 2300 m^2). The intensity of fragmentation was low during the spring, summer and autumn while high in the winter. The bioconstruction surfaces appeared very smooth in the winter while highly articulated in the other seasons. Values of the maximum thicknesses were comparable between the spring, summer and autumn (maximum measured value 0.75 cm) but significantly decreased in the winter (maximum measured value 0.25).

The main *S. alveolata* bioconstruction at Ostia reached its maximum extension in the autumn (maximum measured value 7200 m²) and decreased with the same intensity during all the other seasons (maximum measured value 4400 m²). Fragmentation of the bioconstruction decreased during the spring and summer and increased from the autumn to winter. The presence of smooth and eroded surfaces was less visible compared to the bioconstruction of Torre Mileto but showed a presence of more articulated areas between the autumn and winter. Finally, values of the maximum thicknesses were comparable during all the analyzed seasons, although slight variations were observed between the spring (maximum measured value 0.65 cm) and summer (minimum measured value 0.4 cm).

4.2. Meso- and Microscopic Monitoring Results

The mesoscale physical features associated with the growth of the reef of both species were analyzed using decimetric polished slabs. In particular, the slabs that were cut perpendicular to the base of the reef showed vertical development of the worm tubes (Figure 3). The growth of the reef was the result of both the vertical development of adjacent tubes and the continuous infill of intertube areas with sand. The upward-directed growth (see arrow in Figure 3) of the reef occurred along quasivertical directions, even if the actual angle seemed to slightly change over time (Figure 3). The slabs of the large-scale samples showed also an alternation of lighter and darker bands. Darker bands, connected to an abundance of organic matter, (green areas in Figure 3B) have a sharp top, while their base is more gradual. The sharp top of the darker sectors mainly corresponds to the interruption of worm tubes (red dotted line in Figure 3B) and to slight variations in the tube growth direction.



Figure 3. Mesoscopic analysis on slab cuts along the growth direction (GD, white harrow in the lower left corner) of the Torre Mileto reef. (**A**) Note the presence of irregular alternance of the lighter and darker intervals and the slight changes in the angle of the growth direction. (**B**) The darker parts are highlighted in green. Note that their irregular and sharp tops (red dotted lines) correspond to some tube interruptions.

At the microscale, we were able to detail stages of the vertical development of the worm reef with the petrographic observations in the thin section (Figure 4). In particular, Figure 5 shows the substantial variations of the main morphometric features measured in the fragments of reef sampled in Torre Mileto (*S. spinulosa*) and Ostia (*S. alveolata*): the average values obtained for each season in the mean of eight years diameter and the cohefficient of variation of the tube width and tube density as the average values were compared.

Regarding the *S. spinulosa* bioconstruction, intermediate values of the tube diameters were observed during the winter (about 1800 mµ). In the following months, however, this value gradually decreased until reaching its minimum in the summer (about 1200 mµ) and then increasing again. The variability of the measured diameters was low from the winter to summer (about 0.27) but increased during the autumn (0.41). Finally, the average tube frequency per m² rapidly increased from the winter (about 55,000 tubes/m²) to autumn (about 165,000 tubes/m²).

The microstructure of Ostia's bioconstruction showed some variation compared to Torre Mileto. The highest mean diameter value was measured in the summer (about 1900 mµ), which then slowly decreased in the autumn (about 1100 mµ) and during subsequent seasons. The variability of the tube sizes was high in the autumn and winter (about 0.80) and slowly decreased in the following seasons until reaching its lowest values in the summer (about 0.20). The average tube frequency in m² increased slowly from the winter (about 40,000 tubes/m²) to autumn (about 155,000 tubes/m²).

For both species, wormless tubes filled with sediment were observed during the winter (about 7-12% of the total tubes) and were almost absent during other seasons.

Finally, the analyzed microscopic reef framework in the thin section confirmed two main sectors: the tube and intertube. The tube was built using grains of variable dimensions by the function of age (see References [15,30]). The intertube area (which was comprised of adjacent tubes) was filled with sand with textural parameters that fairly differed from the grains of the tube. Generally, intertube sands are coarser-grained and less sorted than tube sands.



Figure 4. Digitized thin sections for the image analysis. On the left, an example of the four-season sections of the Torre Mileto site. On the right, an example of the four-seasons sections of the Ostia site. The lumina of the tubes are highlighted in blue and the sediment trapped in the bioconstruction in yellow.

a	S. spinulosa bioconstruction (Torre Mileto site)			b	b <i>S. alveolata</i> bioconstruction (Ostia site)				
2000		Mean	inner r of tube		2000		Mear	n inner	
1500		unumete			1500		diamete		
mμ ()					mµ 0		-		
1		Coeffic	ient of		1		Coeffic	ient of	
		varia	variability			!	:		
0.5									
0		1			0				
200'000		N° of t	ube/m ²	• •	200'000	1 7	N° of t	ube/m ²	
400'000					100'000	1			
100 000				1	100 000				
0					0				
	Winter	Spring	Summer	Autumn	W	linter	Spring	Summer	Autumn

Figure 5. The variations in the mean value of the microscale parameters during different seasons and years (9). The diagram shows the variation trends of the parameters of the mean diameter of the tubes, the coefficient of variability and the number of tubes per m^2 of the bioconstruction during the different seasons. On the left, the main bioconstruction in *S. spinulosa* in Torre Mileto (**a**), and on the right, the one in *S. alveolata* at Ostia (**b**).

5. Discussion

5.1. A Stage-Based Model for the Temporal/Spatial Evolution of the Worm Reefs

The general macroscale features of the bioconstruction at Torre Mileto were highly variable over the seasons. A dramatic decrease in the extension and thickness of this bioconstruction has always occurred in the winter, while these parameters gradually increased from the spring. During the winter, the bioconstruction always appeared strongly fragmented and with smooth surfaces.

At Ostia, the distributional area and thicknesses of bioconstruction had comparable values throughout the year. Roughness, however, was subject to a drastic decline during the spring and summer. Fragmentation decreased slowly, starting from the winter and continuing until the following autumn.

At the microscale, the measured parameters were closely related to the characteristics of the two different species. The general microstructure appeared the same as described by Lisco et al. [15]. It was characterized by an area in which the grains are directly cemented by the worm and an area interposed between adjacent tubes, filled by loose sediments. Furthermore, the precise granulometric range characterizes the microstructure in both species for the two different sectors (tube and intertube areas). Finally, the structures are usually made of flattened, elongated and porous granules. The average diameters of *S. spinulosa* were always small during the summer and then increased from the autumn until the winter, when the parameter recorded its highest values. The estimated number of tubes per m^2 and the variability coefficient demonstrated a similar trend. Indeed, they gradually increased from the beginning to the end of the year. The microscale parameters of *S. alveolata* demonstrated inverse trends compared to *S. spinulosa*. These trends were cyclical over seasons and were verified during the entire study period.

Nine-year monitoring, along with the analysis of the samples, allowed the elaboration of evolution models at different observational scales. All observations were combined to demonstrate the existence of seasonal alternations in the growth and degenerative phases. However, these phases may have different intensities depending on the conditions of the associated benthic community, succession of exceptional weather events and anthropogenic action (both fishing and trampling). Furthermore, an analysis of the microstructure along the vertical sections revealed the presence of surfaces that originated after erosional events, and the underlying brownish interval could represent degenerative phases. At the macroscale, the degenerative phase was characterized by: (i) a reduction of the surface area occupied by the main bioconstruction, (ii) increased fragmentation, (iii) the presence of leveled upper surfaces and (iv) low thicknesses. At the mesoscale, the degenerative or stasis phases seemed to be associated with the occurrence of darker intervals, where the were are interrupted and the growth seemed to restart with different directions. At the microscale, the degenerative phases were recognizable by (i) the presence of large diameter tubes, (ii) low variability of their size, (iii) low total number and (iv) a high number of tubes filled with sand.

The growth phase can be recognized by field measurements of: (i) an increase in the surface area occupied by the main bioconstruction, (ii) a relative increase in the bioconstruction continuity, (iii) the presence of highly articulated upper surfaces and (iv) an increase of the bioconstruction thicknesses. On decimeter-thick slabs, growth intervals are marked by lighter sectors and the continuous vertical development of worm tubes. At the microscale, the reef growth phase showed: (i) a slight decrease in the maximum tube diameter, (ii) a great variability of the tube sizes, (iii) a high total number of tubes and (iv) the absence of tubes filled with sand.

Using the results coming from the analysis carried out on two different worm reefs, we are able to trace the evolution of the Ostia (*Sabellaria alveolata* reef) and Torre Mileto (*Sabellaria spinulosa* reef) sites by discussing their significant differences in terms of the seasonal occurrences of the growth and decline phases. In fact, although the structures are very similar in both sites, their evolutionary stages are essentially opposite during the year,



apparently recording the same processes but during different seasons. The evolutionary model in Figure 6 summarizes these differences at different observational scales.

Figure 6. The evolutionary models of Sabellarian reefs. On the left, the sketch of the *S. spinulosa* bioconstruction of Torre Mileto (at the top during the summer and spring seasons, the growth phase; below, during the autumn and winter seasons, the degenerative phase). On the right, the sketch of the *S. alveolata* bioconstruction of Ostia (at the top during the summer and spring seasons, the degenerative phase; below, during the autumn and winter seasons, the growth phase). Each phase is represented at the macroscale and in a sketch of the arrangement of the voids at the microscale.

The *Sabellaria spinulosa* reef of Torre Mileto records intense periods of growth and decline. In the winter, the reef is deeply eroded by the action of storm waves, and the adjacent foreshore environments contain abundant aggregates of worm tubes. Younger organisms are not able to clink on the reef, and only adult worms survive to this degenerative phase.

At this stage, the abundance of tubes filled by sand probably preserve the reef by complete erosion. During the summer, the reef area is not subject to severe storm waves events. New and old generations of worms coexist and support the growth of the reef, which can reach relevant rates (tens of cm in 3 months). The anthropic action is not relevant even in the summer, since the reef area is not frequented by beach bathers.

The *Sabellaria alveolata* reef of Ostia seemed generally stable during the monitoring period, recording slight stasis or degenerative phases only during the summer. In this season, Ostia Beach is subject to an impressive human pressure related with the bathing season and direct trampling actions also on the artificial barrier. The reef fragments that eventually reach the foreshore are suddenly destroyed by deep cleaning operations that are ordinary in public and private bathing beaches. The engraftment of new generations on the pre-existing bioconstruction is not favored. During the winter, the actions of storm waves do not deeply influence the growth, since the presence of the artificial barrier mitigates their effects.

Other environmental (physical, biological and human) parameters seem to be similar in both sites. The spawning and recruitment phases are generally present all-year-round but are more concentrated in the spring and summer, depending on the species and local conditions [21,22,36,37]; therefore, this does not represent a difference between the two sites. Only for a brief phase in Torre Mileto (2014), the presence of mussels significantly reduced the population of Torre Mileto worms, but generally, both species do not seem to have undergone degeneration phases linked to other species. Furthermore, we have no evidence of particular episodes of pollution, although the Ostia area undoubtedly suffers greater anthropogenic pressure. All data showed that the *Sabellaria* reef environment for both species seems to be dominated by a finite number of variables (physical, biological and anthropic processes) that can be evaluated with a detailed multiscale and multitemporal approach.

5.2. Towards an Integrated Approach for the Description of Growth/Degenerative Phases of Worm Reefs

Aiming at the creation of a final model that would take into account all the results achieved at the macro-, meso- and microscales, the present study suggests a new qualitative/quantitative classification of the "reef evolutionary stages" based on seasonal variations of the main volumetric and textural features of *Sabellaria* bioconstructions. This classification is composed of two terms:

- 1. all macroscale observations and data (it partially modifies the classification proposed by Griffin et al. [24] by adding several new parameters (Table 3);
- 2. microscale textural features (Table 2).

Table 2. Summary table of the microscale features proposed in this work.

Microscale Features	Description
E	Inner mean diameter of tubes composing bioconstruction. It is defined as the arithmetic mean of the average tube diameters in different seasons.
F	Coefficient of variation as a measure of the relative variability. It is defined as the ratio of the standard deviation of mean (average) tube values for one square meter of surface.
G	Number of tubes/square meter.
Н	Presence/absence of tubes filled with external random sediment.

Table 3. Summary table of the macroscale features proposed in this work.

Macroscale Features	Description
А	Variation in the overall distributional area of the main bioconstruction.
В	Fragmentation degree of the main bioconstruction. It is a qualitative measure carried out in the central portion of the bioconstruction based on three classes of relative lateral reef continuity: low fragmentation (L), moderate fragmentation (M) and high fragmentation (H) values.
С	Roughness of the bioconstruction surface. It is a qualitative measure carried out in the central portion of the bioconstruction and is based on three classes: high roughness (H), moderate roughness (M) and low roughness (L) values.
D	Thickness.

The combination of these two terms seems to adequately describe the evolutionary stages of *Sabellaria* reefs.

6. Concluding Remarks

Sabellaria bioconstructions show high seasonal variability in the main physical parameters. In a few days, large-scale reefs can be deeply modified or even destroyed by storm wave action, able to reduce them into small, isolated colonies occupying only hard substrate sectors. Bioconstructions can also rapidly regenerate and, in few months, can reach 50 cm

in height and colonize new substrates. Moreover, bioconstructions can suffer from gradual or sudden destruction phases due to the influence of various factors, including storms, competition with other organisms and anthropic pressures.

The evolutionary model of the Sabellarian reef is composed of two alternating phases: (a) a degenerative phase in which the bioconstruction is divided into numerous isolated colonies of varying sizes and (b) a growth phase in which the reef extends over large areas and colonizes sandy substrates; in this phase, the reef is laterally continuous, and its surface is strongly articulated. These phases can almost always be recognized, although they show small differences due to the specific characteristics of *S. alveolata* and *S. spinulosa* and slight variations of the bathymetric ranges in which these species occur.

Bioconstructions interplay with the physical dynamics of the beaches in different, specific ways and positively influence the natural nourishment of coastal areas. The cycles are linked to the phases of reproduction, the physical actions of storms and the anthropogenic impacts, and although developed at different times, their dynamics are very similar. Descriptions of the current evolution models of this bioconstruction type are necessary to understand the evolution of these fragile environments, fundamental for coastal dynamics.

The procedure model proposed represents a useful tool for monitoring these structures. Indeed, this work identified the monitoring parameters useful for classifying the state of preservation of *Sabellaria* bioconstruction. The microscopic analyses alone proved to be sufficient for this purpose, and if performed on bioconstructions with detectable extension and thickness during seasonal cycles, they could completely replace monitoring.

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