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Two facets of geotextiles in coastal ecosystems: Anti- or profouling effects?

Roberta Varello[a], Markus A. Wetzel[b,c], Francesca Cima[a,*]

[a] Laboratory of Ascidian Biology, Department of Biology (DiBio), University of Padova, Via U. Bassi 58/B, 35131, Padova, Italy
[b] Department of Animal Ecology, German Federal Institute of Hydrology – BfG, Am Mainzer Tor 1, 56068, Koblenz, Germany
[c] Institute for Integrated Natural Sciences, University of Koblenz – Landau, Universitätsstrasse 1, 56070, Koblenz, Germany

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ABSTRACT

Nonwoven geotextile fabrics have physical, mechanical and hydraulic properties useful in coastal protection as an alternative to natural stone, slag, and concrete. In a 10-month experiment, the colonisation of macrofouling organisms on different substrata based on polypropylene (PP), polyester (PET) or high density polyethylene (HDPE) fibres was investigated in the Lagoon of Venice, Italy – an environment with temperate transitional waters with high biodiversity – and compared with the colonisation on wood as a reference substratum, because of its occurrence in artificial structures at the study location, until a stable stage was reached in the development of the macrofouling community. Geotextile fabrics showed implications for community development. They affected both ecological succession in different ways by disturbing biofouling settlement and growth (HDPE fabrics) or favouring species which become dominant (PP fabrics). For these two-faceted aspects that potentially cause different long-term impacts on the biodiversity of resident communities, the use of geotextile fabrics as antifouling or as profouling systems for restoration of degraded ecosystems is discussed. In all cases, the communities displayed unique properties, such as differences in the settlement of pioneer species, an initial disturbance to serpulid settlement, absence of barnacles, selection of dominant taxa (ascidians), and changes in the percentages of various taxa forming the community structure. Given the increasing interest in geotextile materials for employment in various marine developments and industries, these results could represent first lines of evidence to inform decision-making to minimise/modify biofouling, and/or predict the use of artificial substrata as habitats by marine organisms.

1. Introduction

Many marine algae and invertebrates depend on hard substrata for the settlement of their propagules and larvae. Both natural and artificial hard substrata are made of different materials. Natural hard substrata are not only represented by rocks, shingle and coral reef but also by shells, exoskeletons and teguments of other organisms. Artificial hard substrata include concrete, slag, steel piling, synthetic plastics, and wood, and offer relatively stable habitats but are often rare in natural areas compared with soft sediments (Taylor and Wilson, 2003). On the other hand, artificial substrata such as seawalls, steel and wood pilings, jetties, groynes, and pontoons are common habitats today along many coasts and estuaries of industrialised countries, where up to 60% of the shoreline is obstructed (Wetzel et al., 2014). Anthropogenic structures provide habitable spaces for many benthic organisms and can be colonised very rapidly, e.g., beginning from 1 to 2 weeks under favourable environmental conditions in the temperate zone (Scheer, 1945; Anderson and Underwood, 1994; Moreau et al., 2008), often causing severe damage to submerged structures (Connell, 2001; Atilla et al., 2003; Bulleri and Airoldi, 2005; Dobretsov et al., 2013). This phenomenon is of high economic interest because biofouling represents a large problem worldwide (Alberte et al., 1992; Holm, 2012). Biofouling on ships' hulls (Callow and Callow, 2002) and on surfaces of coastal structures, marine industries and hydrotechnical infrastructures is a major economic and technical problem with international efforts in the development of ocean engineering. Biofouling does not only increase static and hydrodynamic loading but also affects corrosion characteristics and impedes underwater inspection and maintenance (Callow and Edyvean, 1990; Flemming et al., 2009).

Geotextiles represent new synthetic materials that have been introduced into coastal environments to prevent shelf erosion and to protect artificial submerged structures. They are ultraviolet (UV)- and chemical-resistant and are widely used in civil and environmental engineering and construction projects, such as soil filtration (Palmeira et al., 1996), dyke

* Corresponding author. Department of Biology, University of Padova, Via Ugo Bassi 58/B, 35121 Padova, Italy.
E-mail address: francesca.cima@unipd.it (F. Cima).

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construction (Koffler et al., 2008), and the general prevention of erosion (Theisen, 1992). As an alternative material in aquatic engineering, geotextiles can replace natural stone, slag, or concrete materials. In some cases, such as protecting shores from erosion, large geotextile containers can be considered preferential solutions when traditional materials are not acceptable (Heerten et al., 2000a,b; Jackson et al., 2001; Restall et al., 2002; Tomlinson et al., 2003; Black and Mead, 2009). In particular, nonwoven geotextile fabrics have been increasingly used in coastal and marine engineering over the last decades (Lee and Douglas, 2012; Mitra, 2013; Oumeraci and Recio, 2017), representing in turn a potential settlement surface for species that naturally occur on hard substrata.

The surface structure of nonwoven geotextiles has a unique texture of polymers that is unlike any texture found on natural hard substrata as a result of their production process (Dassanayake and Oumeraci, 2012). They are made of long polypropylene (PP), polyester (PET), or high-density polyethylene (HDPE) fibres that are entangled or crimped in a fleece-like texture, which results in a highly irregular surface. The fibre geometry allows for efficient hydraulic and drainage performance, whereas the heavy mass of the fabric allows for a high level of toughness and damage resistance (Carneiro et al., 2018a). Because of their texture, these textiles could affect organism settlement and the biodiversity of the resident community in coastal ecosystems, preventing biofouling settlement or favouring species which could become dominant. Therefore, the impact on ecosystem biodiversity caused by geotextiles requires attention.

The aim of the present study was to investigate the differences in the ecological succession trends of the hard-substratum community in the southern basin of the Lagoon of Venice on four nonwoven geotextile fabrics based on PP, PET and HDPE. The selective effects of different polymer compositions and surface properties on both settlement and growth capability of fouling species were considered on the basis of significant change in biodiversity, substratum coverage and biocoenosis structure. The macrofouling communities that these textiles support have been compared with communities developing on wood. Natural hard substrata are not present in the Lagoon of Venice, but some artificial ones, like wooden piles (namely 'bricole'), have been 'naturalised' in this ecosystem by their being permanently immersed in the Lagoon waters over a longtime - in some cases, for centuries - and colonised by a complex benthic community which has been previously widely studied (Occhipinti-Ambrogi et al., 1988; Sacchi et al., 1998; Sconfietti et al., 2003; Corriero et al., 2007; Cima and Ballarin, 2013). Thus, wood has been chosen as an artificial-substratum reference for its prevalent presence in various artificial submerged structures throughout the Lagoon of Venice (Ceccato et al., 2013). Experiments were conducted on panels permanently submerged for ten months. The ecological succession was monitored monthly from biofilm formation to the reaching of a stable stage of the development of the community on the wooden panels (Scheer, 1945; Railkin, 2004; Wahl, 2009).

2. Materials and methods

2.1. Study site

The study site was a mobile wharf consisting of large plastic floats located in the southern basin of the Lagoon of Venice along the Sottomarina channel (Lat. 45° 14′ N, Long. 12° 17′ E), in a zone with low boat traffic representing a subtype of the euhaline, not confined microenvironment of the lagoon biome connected to the port inlet of Chioggia (Venice, Italy) (Fig. 1). The basin has a tidal range >50 cm and a depth <1.5 m. The plastic floats never contact with the bottom because the average height of the low waters is 30 cm. Temperature usually ranges between a minimum of 5.6 °C in February and a maximum of 29.9 °C in August. Salinity varies from 28.1 to 38.1 PSU depending on the rainfall trend (database of the Hydrobiological Station of Chioggia, https://chioggia.biologia.unipd.it/en/the-database/parameters-of-lagoon/). For the geographical location near the port inlet, the site is greatly exposed to water circulation and tides that increase the oxygenation. Dissolved oxygen concentrations usually range from 7.03 mg l^{-1} in August to 7.92 mg l^{-1} in February (Irato et al., 2007).

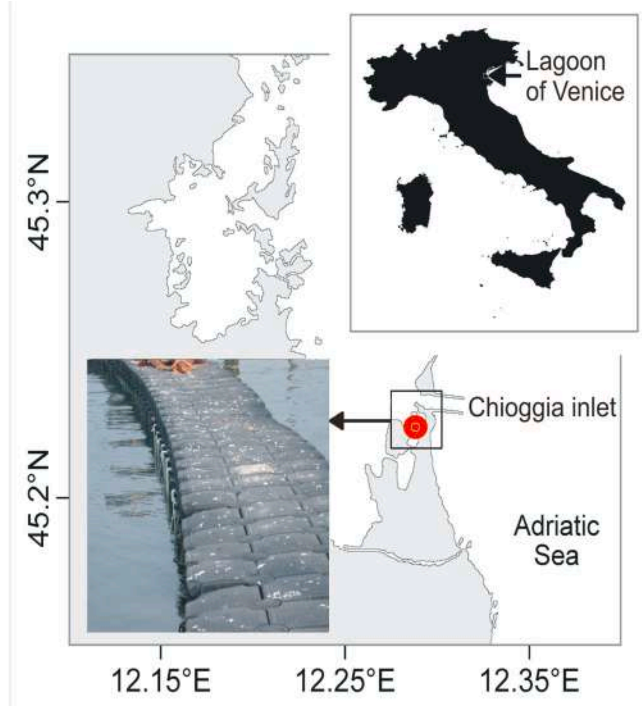

Fig. 1. Location of the mobile wharf (photo) in the experimental site close to the southern inlet (Chioggia) of the Lagoon of Venice, Italy.

2.2. Substrata

For this experiment, four different nonwoven geotextile fabrics furnished by Naue GmbH & Co. KG (Espelkamp-Fiestel, Germany) were used, represented by 'black HDPE', 'white PP & white PET', 'coloured (i. e., recycled) PP & PET', and 'white PP', showing different textures and engineering applications (Table 1). For their long-term abrasion resistance, recent special applications include i) rock revetments to prevent erosion to structures of coastal and estuarine defence from waves or currents and ii) sand container bags for visible and invisible shore protection and construction of artificial reefs, groynes, and breakwaters. For the morphological analysis of the fibres, small samplings (0.5 × 0.5 cm) of the geotextiles were observed and photographed under a Cambridge Stereoscan 260 scanning electron microscope (SEM) after critical point drying and gold scattering (Fig. 2).

Seasoned wood panels of larch (*Larix decidua*) were chosen as a reference substratum. Larch lumber is one of the best materials for naval, diving and hydraulic buildings, such as piles, bridges, wharves and pipelines, because it is water resistant and long lasting. It is heavy, compact, elastic and durable. It has high resistance to decay in water and was used, to a large extent, to build the foundations of the cities of Venice and Chioggia. Because of the presence of very marked parallel veins, the surface of larch wood is rough even when it has been smoothed, and the roughness increases with the duration in the water because of the action of both swell and organisms.

2.3. Experimental setup

Twenty experimental units were deployed in the study site, 16 of which with the four geotextiles considered in this study, represented by four replicates for each type, and 4 with larch wood as a reference

Table 1
Nonwoven monolayer geotextile fabrics employed in the present study.

Trade-name	Composition	Feature	Technical specifications	Applications
DEPOTEX R305	black HDPE	staple, needle-punched smooth fibres 30 μm in diameter	- highly UV-resistant - mass per unit area: 300 g m^{-2} - thickness: 2.7 mm - water permeability (VIH50): 5.5 $\times 10^{-2}$ m s^{-1}	protection of landfill geomembranes
SECUTEX GRK4C	white PP & white PET	staple, needle-punched, hot-calendared smooth fibres 30 μm in diameter	- mass per unit area: ≥250 g m^{-2} - thickness: 1.4 mm - VIH50: 5.5 $\times 10^{-2}$ m s^{-1}	road and dyke construction
SECUTEX R404	coloured PP & PET	mixture of recycled staple PP smooth fibres 30 μm in diameter, needle-punched and crimped fibres with PET fibres 40 μm in diameter and furrowed by longitudinal grooves	- mass per unit area: 400 g m^{-2} - thickness: 3.6 mm - VIH50: 7.5 $\times 10^{-2}$ m s^{-1}	sand-filled containers in barrier systems
SECUTEX R601	white PP	staple, needle-punched smooth fibres 30 μm in diameter	- mass per unit area: 600 g m^{-2} - thickness: 5 mm - VIH50: 3.0 $\times 10^{-2}$ m s^{-1}	drainage, separation and filtration

replicate-group. Each unit was formed of a single panel tied at a depth of 50 cm to a thick nylon rope. The latter was maintained vertically in the water column by a brick as ballast at the bottom end and was anchored to an eyehook on a mobile wharf at the top end. The wharf (Fig. 1) was a structure located 30 m from the docks, a site far from boat traffic and with limited hydrodynamics. For mobility, the wharf had panels that were always submerged following the tide fluctuations without contacting the bottom. Each unit was arranged randomly at 60 cm from each other. The wooden panels were 20 × 15 × 2.5 cm in size, with a 1-cm-diameter hole where the rope passed through. The panels of geotextiles, each forming a free surface of 20 × 15 cm with variable thicknesses, were supported by a frame of Plexiglas with a thickness of 0.5 cm and a 1-cm-diameter hole for the rope on its upper side. The close binding with the rope maintained the vertical orientation of the panels to limit rotation and exposition, which could influence fouling colonisation by shading or floating disturbance. Therefore, all panels had the same light-exposed colonisable area of 300 cm^2.

The units were constantly immersed from spring (April) to winter (January) as artificial substrata for settlement by fouling organisms. The ecological succession was monitored monthly on the light-exposed side of the panels. Photographs of the air-exposed panel surfaces were taken with a Nikon Coolpix 995 digital camera (Nikon Corporation, Tokyo, Japan). Samplings of small fouling organisms (0.5–10 mm in length) were collected from the panels and fixed in 5% formaldehyde in seawater for better species identification under a dissection binocular stereomicroscope Wild Heerbrugg with a 50x maximum magnification.

From the analysis of the photos, data were analysed according to previously developed methods and parameters for studying the macrofouling community of hard substrata in the lagoon ecosystem (Cima and Ballarin, 2008, 2013), which include tests for differences in both biodiversity indexes and rates of changes in biomass. In particular, the biotic data were expressed by means of four descriptors of biodiversity: i) *species richness*, i.e., the total species richness (total number of species) and mean species richness (average number of species ± standard deviation) by month present on all panels of the same type; ii) *biocoenosis structure*, i.e., the percentage of coverage for each taxon, namely the set of species belonging to the same taxonomic group, in respect of the total coverage of the whole community (100%) on panels of the same type of substratum; iii) *covering-abundance area*, i.e., a quantitative analysis (percent cover) of the settlement capacity of the various species on areas calculated in photos using the Infinity Analyze Application v. 5.0.0 software (Lumenera Co. 2002–2009); iv) *biomass*, expressed in g cm^{-2} of fresh weight (FW) of the living fouling organisms and determined by weighing the panels, after a rapid draining, with a portable electronic scale. All the operations on air-exposed panels occurred immediately and gently *in situ* to avoid withering, drying up and destroying collapse of biofoulers.

Data on the physical and chemical parameters of seawater, such as temperature, pH, and salinity (Supplementary Fig. S1), were collected monthly using a Cyber Scan XS PC 300 Waterproof Hand-held pH/Conductivity//Temperature Metre (Euthech Instruments Pte Ltd, Singapore, www.eutechinst.com). Conductivity values were subsequently converted to practical salinity unit values (PSU) in relation to the thermal properties of seawater (IOC et al., 2010).

2.4. Data analysis

Statistical analysis and figure compilation were performed using R software (version 3.1.2; R Core Team, 2014), and the level of significance was set at $p < 0.05$ for all statistical tests. The data on species richness and coverage area were analysed with analysis of variance (ANOVA) with a repeated measures design considering interactions among the predictors 'time' (month) and 'type of substratum'.

To investigate significant differences among the covering surfaces of each fouling species on the various substrata, the measures of the areas (cm^2) per month were compared using permutational multivariate analysis of variance (PERMANOVA plus; Anderson, 2001) considering one fixed factor, i.e., the type of substratum, and one random factor, i.e., the monitoring month. All analyses were carried out using 9999 permutations.

To test the hypothesis that the species composition of the community on different substrata was significantly different and changed over time, a Bray–Curtis similarity matrix (Kruskal and Wish, 1978) was calculated with presence/absence of species using raw data (untransformed). A hierarchical cluster analysis and the Similarity Profile Routine (SIMPROF; Clarke et al., 2008) were used to identify significant differences between species assemblages. Analysis of similarity percentages (SIMPER; Clarke, 1993) was used to rank the species that contributed most to the average Bray-Curtis dissimilarities between the communities identified by the SIMPROF procedure. Bray-Curtis, clustering, and SIMPROF calculations were performed with the 'simprof' function in the R package 'clustsig' (Whitaker and Christman, 2015), and the SIMPER procedure was performed using the 'simper' function from the R package 'vegan' (Oksanen et al., 2018). The results of these analyses were plotted in a classification dendrogram.

The hypothesis stating that the biomass development on different nonwoven geotextiles differs significantly depending on the type of surface was tested using a combination of statistical methods. First, we observed that the biomass development on the different substrata was differentiated into two sections: (i) the increase in biomass at the start of the experiment and (ii) a more or less static or decreasing phase, which occurred later in the year after the biomass development had reached its

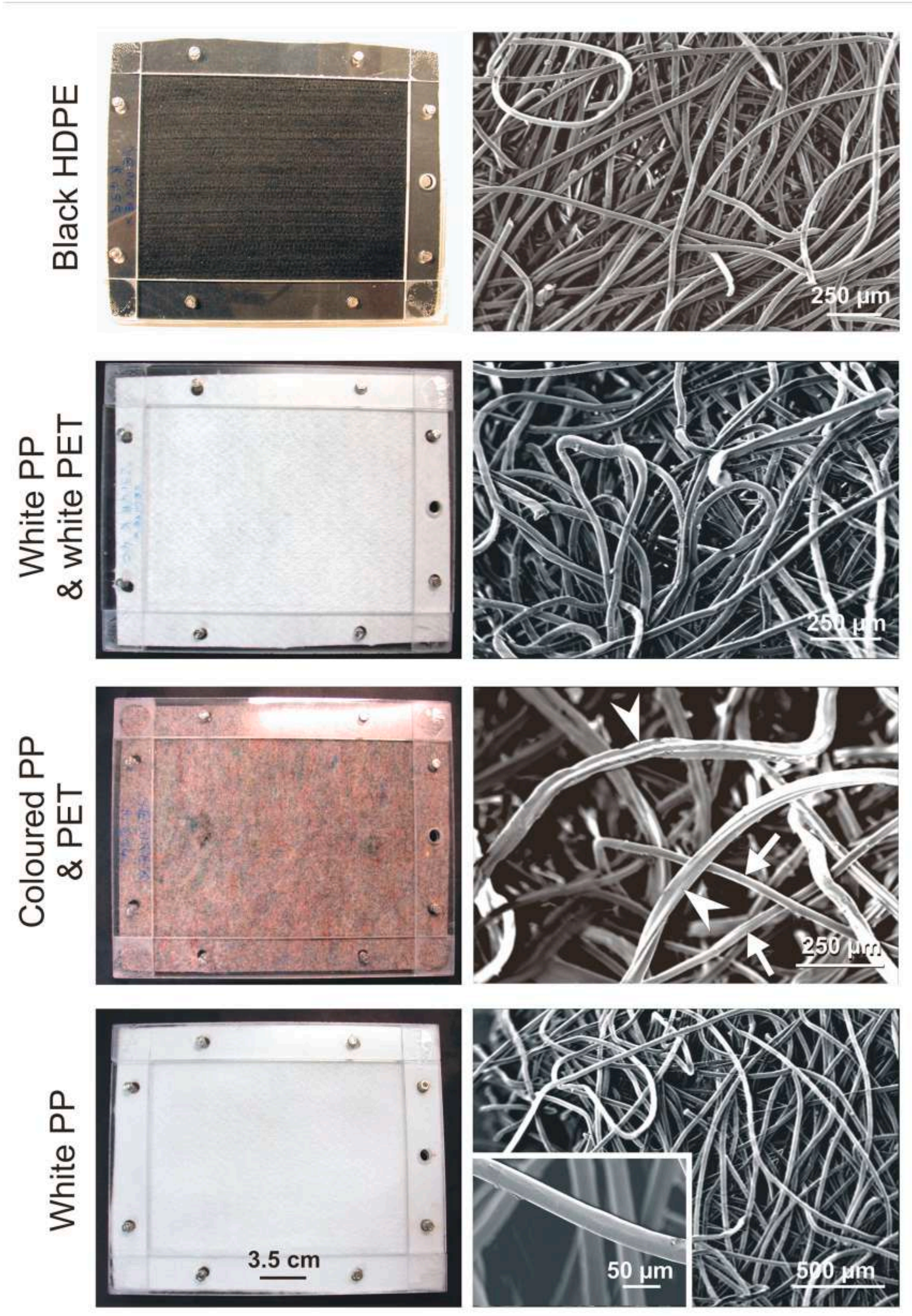

Fig. 2. Panels of geotextiles fixed inside a plexiglass frame (left) and detailed structure and microtopography of polymer fibres with SEM (right). Note that for the 'coloured PP & PET', two types of fibres formed the crimped felt, i.e., smooth PP fibres (arrows) and larger furrowed PET fibres (arrowheads).

peak (change point). The substratum-specific change points were identified using the method of Davies (2002). This method tests for a non-zero difference in slope parameters of a segmented relationship and is also suitable for small sample sizes. With this procedure, change-points were calculated as points where the linear regression coefficients shift from one stable regression relationship to a different one using the package 'segmented' (Muggeo, 2015). Data were expressed as means of FW with standard deviations. To allow identification of statistical differences between the change-points we used bootstrapping. In brief, from the biomass values collected on each substratum each month, the average value from four replicates was chosen and the change-point was calculated. This was repeated 100 times for each substratum, which resulted in a dataset of 100 randomly collected change-point values per substratum. These bootstrap generated values which were then used to test the hypothesis stating that different substrata showed a different change-point using one-way

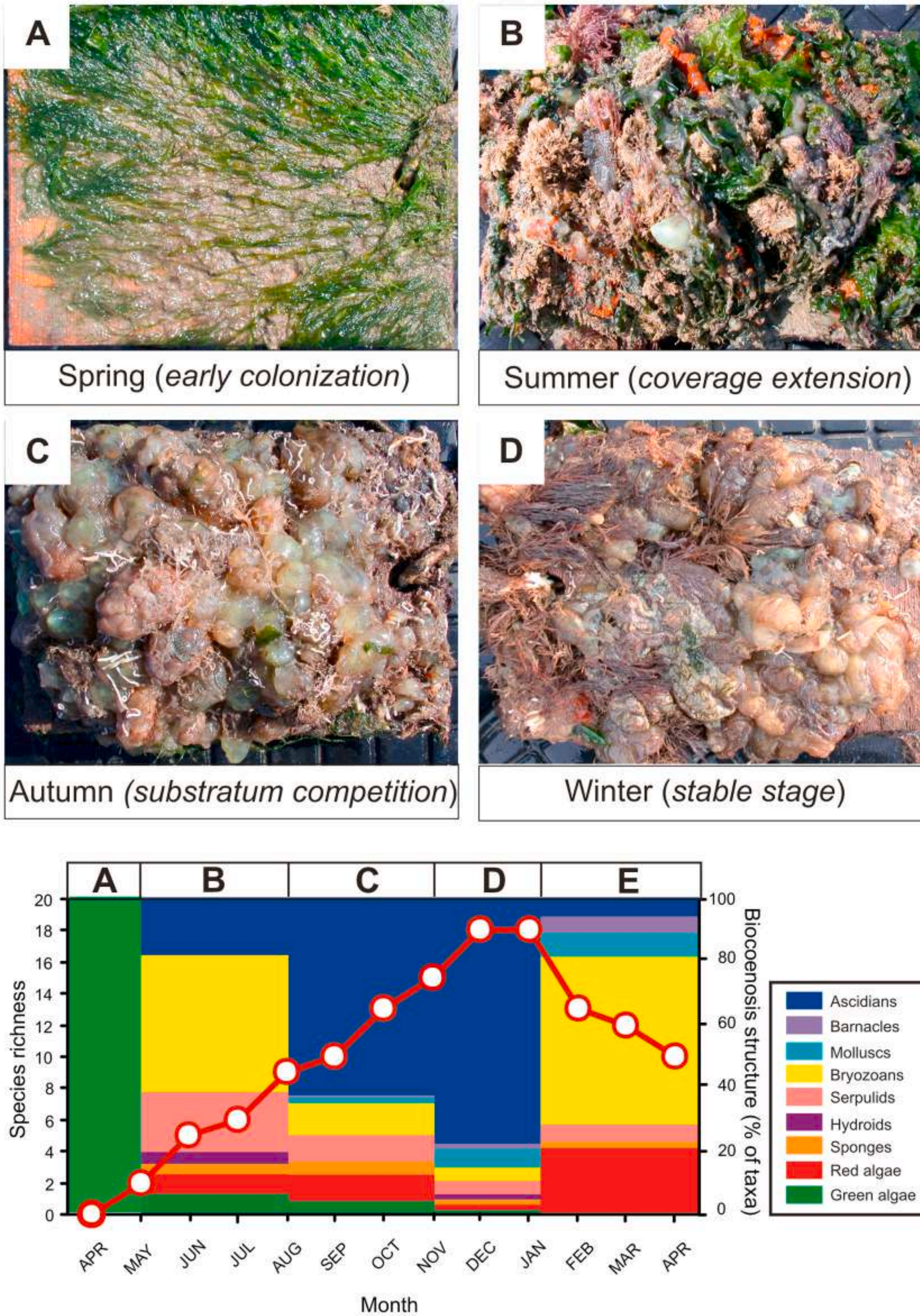

Fig. 3. Main seasonal phases (A–D) of ecological succession on selected wooden panels throughout the experimental immersion in the Lagoon of Venice. In the graph, example of typical trends of the biodiversity descriptors 'species richness' (solid line) and 'biocoenosis structure' (bar plots) during an 1-year experimental immersion (April 2005–April 2006), showing the phases (A–E) of ecological succession. After the reaching of a 2-month stable community between late autumn and winter called 'stable stage' formed of the maximum number of species belonging to dominant taxa (D), in late winter and early spring - when harsh winter conditions are established - a reduction in the number of species followed by a dismantling of the previous biocoenosis structure occur (E).

Analysis of Variance (ANOVA). The latter was carried out with month as random factor, followed by a Tukey Honest Significant Differences test (Tukey HSD) for post-hoc pairwise comparison.

3. Results

3.1. Changes in species richness and covering-abundance area

In the Lagoon of Venice, the ecological succession of the community on wooden panels (Fig. 3) occurred regularly with the same main phases over seasons observed in the previous monitoring campaigns on wooden and steel hard substrata (Cima and Ballarin, 2008, 2013): i) early settlement of pioneer organisms in spring (April–May), ii) progressive extent of macrofouling coverage in summer (June–August), iii) competition and establishment of dominant taxa in autumn (September–November), and iv) reaching of a stable stage in early winter (December–January). The latter is a prolonged stage characterised by the highest number of species forming a relatively stable community that temporarily survives under the mild climatic conditions of the area. When harsh winter conditions are progressively established (February–March), the community loses this stable structure because most previous dominant species die and, in the following spring, a new community settles and grows up over remnants and concretions. This indeed represents a manifestation of seasonal phenomena termed 'cyclical succession' due to the natural die-off of early colonists, as these species not only grow rapidly but also have short life spans (Shelford, 1930).

The ANOVA analysis of change in species richness and coverage area on geotextiles by macrofouling (Table 2) revealed that significant differences in species richness only depended on month by month (i.e., seasonality), whereas the coverage area of biofouling depended significantly on both month and type of geotextile. In particular, at the end of the experimental period 'black HDPE' showed a significant decrease in the coverage area in comparison with both the other geotextiles and wooden panels (Supplementary Fig. 2S). The trends and fluctuations of species richness and covering-abundance area of each species on the various experimental substrata over the course of the experiment are reported in detail in Figs. 4 and 5, respectively. Total coverage dynamic on different substrata is described in Fig. 6. Results from these figures reveal that in spring, one month after immersion, all of the substrata were covered to a large degree with a biofilm - a fine mixture of inorganic sediment and organic substance entrapping microorganisms such as bacteria and microalgae - with the exception of the wooden substrata, the latter showing a higher coverage area (60%) of the green macroalga *Ulva intestinalis* Linnaeus, 1753 as a pioneer species. In the subsequent month, only ascidian species had largely colonised the geotextile substrata, represented by the solitary species *Ciona robusta* Hoshino & Tokioka, 1967 and *Ascidiella aspersa* (Müller, 1776) and the colonial species *Botryllus schlosseri* (Pallas, 1766). In summer, species richness showed very rapid growth on all of the substrata, from 1 to 3 species in May to 4 to 8 species in July. The red alga *Gracilariopsis longissima* Steentoft, Irvine & Farnham, 1995 first occurred on all of the substrata, and unlike the wooden panels, the geotextile panels did not display settlement of green algae during this period. The dominant animal species in the summer months were the solitary ascidians *A. aspersa*, *C. robusta*, and *Styela plicata* (Lesueur, 1823) and the colonial ascidians *Botrylloides leachii* (Savigny, 1816) and *B. schlosseri*. In particular, the solitary ascidians *A. aspersa* (coverage areas: 18.2% on wood, 87.4% on 'black HDPE') and *C. robusta* (coverage areas: 4% on 'black HDPE', 20% on 'coloured PP & PET') and the bryozoan *Bugulina stolonifera* (Ryland, 1960) (coverage areas: 7% on 'black HDPE', 15% on wood) appeared on all of the substrata. The latter two species remained, with changing coverage, throughout the experiment. Late in autumn and initial winter, new taxonomic groups were observed such as barnacles (*Balanus* sp.) only on all wood replicates, and molluscs (*Mytilus galloprovincialis*, *Ostrea edulis*, *Patella caerulea*) on all of the substrata. The number of species increased and the controls reached a stage of competition for the substratum preceding a stage of monopolisation of space by dominant species. The stable stage was completed on controls in December–January, with ascidians as the dominant species in the community and, in general, a constant increase in the number of species with the exception of the 'coloured PP & PET' and 'black HDPE' geotextiles. The latter also showed a decrease in coverage areas (35%) with respect to those of both the other geotextiles (70%) and wood (50%).

In general, among the approximately 24 species - 6 macroalgae and

Table 2
ANOVA on total species richness and coverage area of macrofouling. Statistically significant effects ($P < 0.05$) of the variables are indicated in bold.

Index	Source	df	SS	MS	F	P
Species richness	Month	8	100.8	12.6	8.972	**0.000**
	All substrates	4	16.7	4.2	1.174	0.336
	Geotextiles	3	16.6	5.5	1.520	0.227
	Month*Wood	8	128	16	2.97	0.072
	Month*Black HDPE	8	101.44	12.68	7.19	**0.006**
	Month*Wt.PP & Wt.PET	8	288.78	36.10	13.06	**0.000**
	Month*Col.PP & PET	8	239	29.87	25.31	**0.000**
	Month*White PP	8	155	19.38	45.00	**0.000**
	Wood*Black HDPE	1	16.05	16.05	1.336	0.264
	Wood*Wt.PP & Wt.PET	1	0.2	0.2	0.013	0.907
	Wood*Col.PP & PET	1	2	2	0.098	0.757
	Wood*White PP	1	5.5	5.5	0.439	0.517
	White PP*Wt.PP & Wt.PET	1	8	8	0.451	0.511
	White PP*Col.PP & PET	1	0.88	0.88	0.040	0.843
	White PP*Black HDPE	1	2.72	2.72	0.199	0.661
	Wt.PP & Wt.PET* Col.PP & PET	1	3.55	3.55	0.139	0.713
	Wt.PP & Wt. PET*Black HDPE	1	20.05	20.05	1.173	0.294
	Col.PP & PET*Black HDPE	1	6.72	6.72	0.315	0.582
Coverage area	Month	8	33,226	41,532	5.341	**0.000**
	All substrates	4	10,839	27,098	2.151	0.092
	Geotextiles	3	10,024	33,415	2.817	**0.044**
	Month*Wood	8	145,795	18,224	1.71	0.233
	Month*Black HDPE	8	467,458	58,432	5.16	**0.016**
	Month*Wt.PP & Wt.PET	8	426,709	53,338	29.21	**0.000**
	Month*Col.PP & PET	8	400,490	50,061	6.11	**0.010**
	Month*White PP	8	537,104	67,138	45.26	**0.000**
	Wood*Black HDPE	1	60,522	60,522	4.456	**0.040**
	Wood*Wt.PP & Wt.PET	1	14,463	14,463	0.105	0.749
	Wood*Col.PP & PET	1	43,569	43,569	0.352	0.561
	Wood*White PP	1	41,705	41,705	0.276	0.606
	White PP*Wt.PP & Wt.PET	1	105,288	105,288	0.79	0.386
	White PP*Col.PP & PET	1	170,529	170,529	1.429	0.249
	White PP*Black HDPE	1	964,683	964,683	7.344	**0.015**
	Wt.PP & Wt.PET* Col.PP & PET	1	7827	7827	0.073	0.789
	Wt.PP & Wt. PET*Black HDPE	1	432,570	432,570	3.669	0.073
	Col.PP & PET*Black HDPE	1	324,023	324,023	3.109	0.096

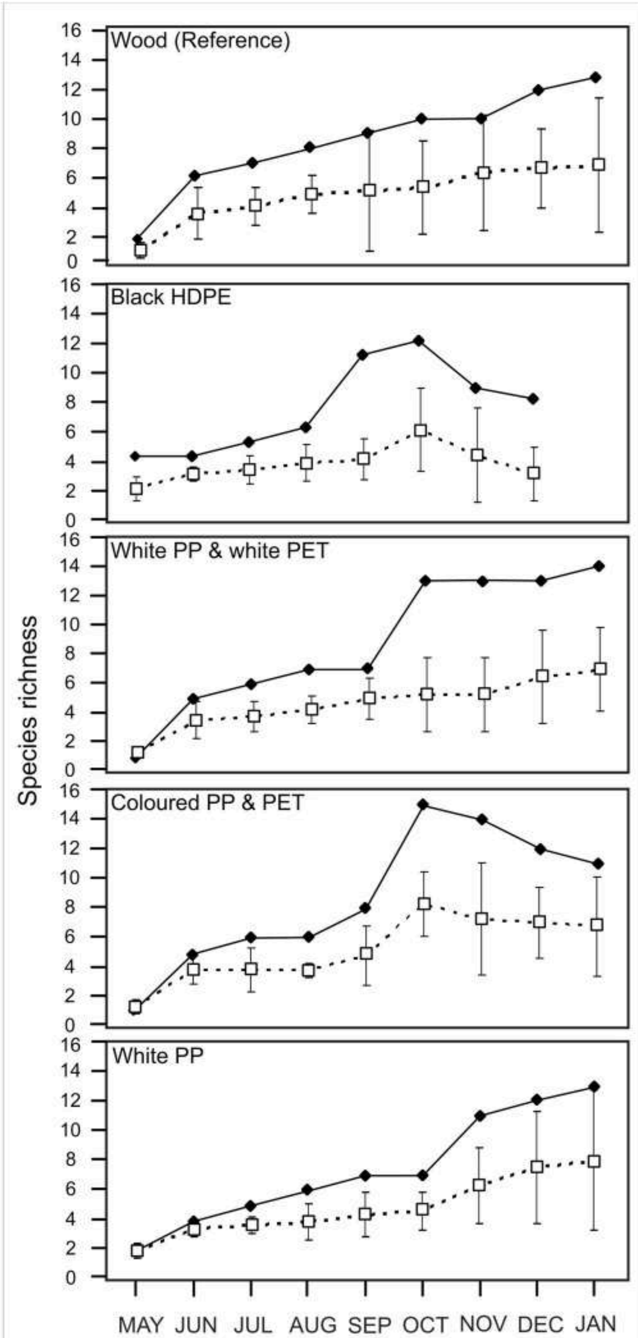

Fig. 4. Trend of the biodiversity descriptor 'species richness' as the total number of species (solid line) and mean number of species ± standard deviation (dashed line) found monthly on replicates (n = 4) of the five different substrata.

18 invertebrates - considered, PERMANOVA data analysis (Supplementary Table S1) showed that for the ascidians *C. robusta* and *S. plicata*, the coverage depended significantly on both time (month) and type of substratum. For the ascidian *B. leachii* and the barnacles (*Balanus* sp.), the coverage depended significantly only on the substratum factor. For red algae (*Ceramium ciliatum* Ducluzeau, 1806; *G. longissima*), sponges (*Haliclona (Reniera) cinerea* (Grant, 1826)), serpulids (*Filograna* sp.), bryozoans (*Bugula neritina* (Linnaeus, 1758), *B. stolonifera*), and the ascidians *A. aspersa* and *Diplosoma listerianum* (Milne Edwards, 1841), the coverage depended significantly only on the time factor.

3.2. Changes in biocoenosis structure

For the description of the community, species were clustered in taxonomic groups, i.e., green algae (or chlorophyta), red algae (or rhodophyta), sponges (or porifera), hydroids (or hydrozoan cnidarians), serpulids (or serpulid polychaetes), bryozoans, molluscs, barnacles (or cirriped crustaceans), and ascidians (or benthic tunicates). In the various seasonal phases of ecological succession, the biocoenosis structure on the different substrata is expressed using stacked bars reporting the percentages of coverage of the taxonomic groups (Fig. 7). Promotion and inhibition of the settlement and growth of different species of fouling organisms was observed on the different substrata. On all of the geotextiles, the settlement of barnacles did not occur, and a delay in the settlement of serpulids was observed. 'Black HDPE' also inhibited the settlement of sponges and molluscs and disturbed that of the dominant ascidian *C. robusta*, which was less represented than on the other substrata. Conversely, 'white PP' favoured a brief (one month) settlement of hydroids, and both the mixed PP & PET geotextiles favoured the settlement of molluscs and ascidians.

The SIMPROF analysis indicated the presence of three clusters representing significantly different fouling communities (Fig. 8). The community from cluster A consisted of the samples from all of the substrata in May (spring), i.e., the pioneer assemblage of *U. intestinalis*, *B. schlosseri*, and *B. leachii*. Cluster B contained the samples from June to September (summer) from all of the substrata, including the community on 'white PP & white PET' from the month of November (autumn). Cluster C included the communities on all of the substrata from October to January (competition stage and stable stage), except for that on the 'white PP & white PET' substratum from November. These results showed that changes in community composition, based on the presence or absence of species, reflected seasonal changes involving the same taxonomic groups. The subsequent analysis of similarity percentages (Table 3) showed that the species contributing most to the differences between cluster A and cluster B were the bryozoan *B. stolonifera* and the ascidian *C. robusta*, each of which contributed 12.8% to the observed differences between the clusters. These species appeared in June on all of the substrata. The ascidians *A. aspersa* and *S. plicata* contributed to 11.5 and 8.3%, respectively, of the differences between these clusters. The differences between clusters B and C were mainly due to the bryozoan *B. stolonifera*, with a 4.5% contribution, and *A. aspersa*, with a 3.4% contribution to the observed differences.

3.3. Differences in biomass among substrata

By comparing the biomass values measured on all of the substrata, the wood substratum showed the highest biomass, with a mean value of 6.3 ± 0.51 g FW cm^{-2}, and the 'black HDPE' had the lowest value of 3.3 ± 0.11 g FW cm^{-2}.

Biomass increased on all of the substrata from the start of the experiment in April to the substratum-specific peaks (change points) (Fig. 9), and differences in the rates of biomass accumulation and decline, and the timing of peak biomass were evaluated. The community on the reference material (wooden panels) reached the biomass peak in October. As regards geotextiles, the biomass peak was reached the earliest (June) on the 'black HDPE' fabric, followed by the 'coloured PP & PET' and 'white PP' fabrics (July) and the 'white PP & white PET' fabric (August). With the exception of 'black HDPE', biomass stabilises over the last six months most likely for the extensive coverage of solitary ascidians on these panels (Fig. 5). Differences in the change points of biomass development were highly significant (F (4, 495) = 114.7, $p <$ 0.001), and the post hoc test indicated that significant differences were present among all of the change points, except for the comparison of biomass development between 'coloured PP & PET 'and 'white PP.'

In the initial growth phase, the increase in biomass was significant on all of the substrata and showed a similar pattern, except for one significant difference between the wooden substratum and the 'white PP'

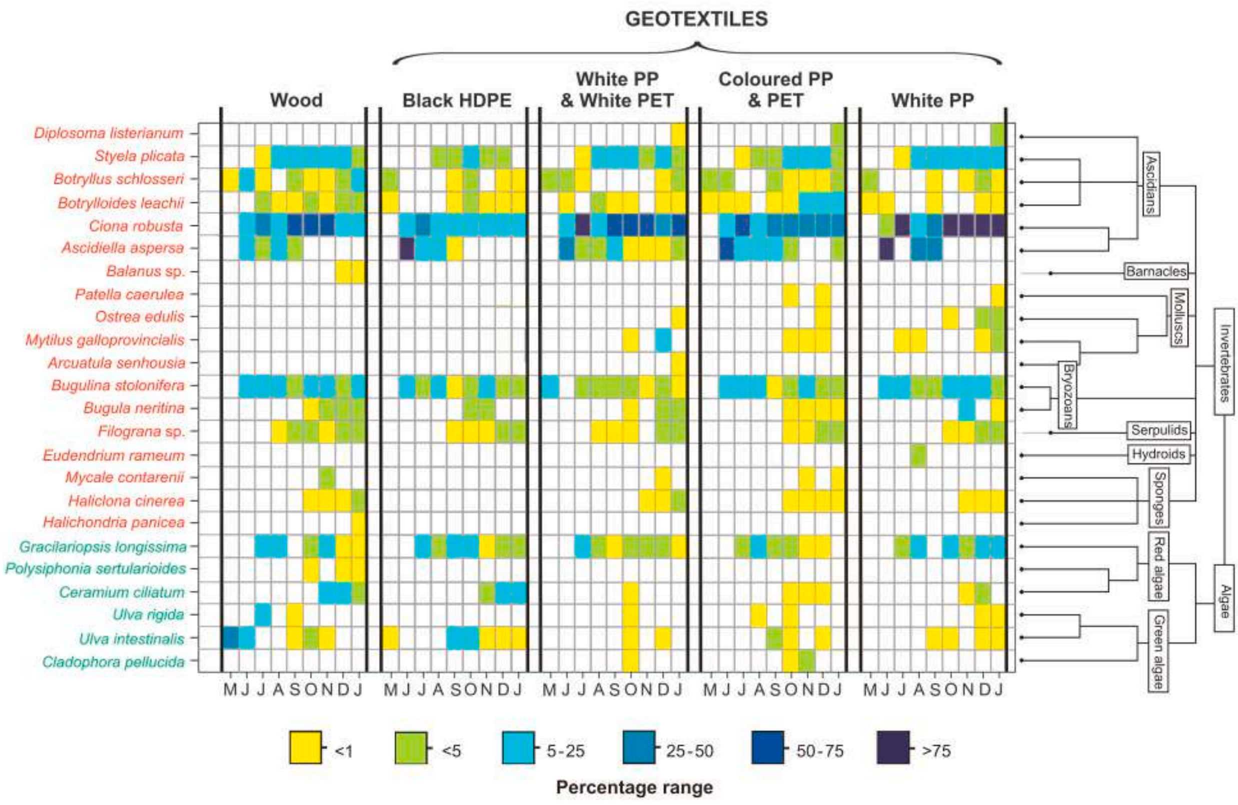

Fig. 5. Trend of the biodiversity descriptor 'covering-abundance area' as the total percent area of each species measured monthly using photos of replicates (n = 4) of the five different substrata. In the dendrogram of the similarities of the 24 species included in the analysis, species are clustered in taxonomic groups (right).

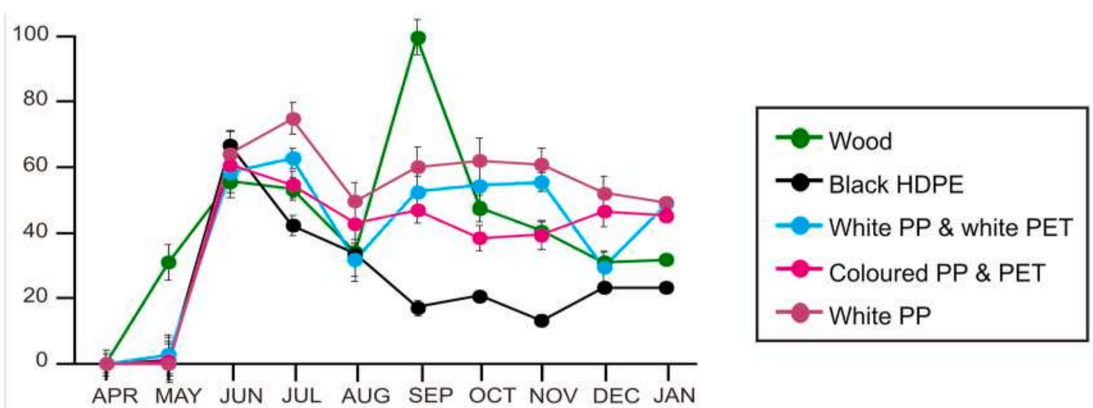

Fig. 6. Trend of total coverage dynamic monitored monthly as average ± standard deviation on replicates (n = 4) of the five different substrata.

fabric. After the biomass change point, only the wooden substratum and the 'black HDPE' fabric showed a significant decrease in biomass, whereas the other geotextile substrata showed only a small decrease in biomass, which was not significant.

4. Discussion

The present study represents the first approach to long-term experimental monitoring, in an open-air natural laboratory rich in biodiversity such as the Lagoon of Venice, of the ecological succession of fouling communities on different nonwoven geotextile fabrics with various engineering applications, including prevention of shore and artefact erosion. These geotextiles showed to interfere with the settlement and growth of various macrofouling organisms, and potentially could cause changes in the composition, extension and structure of the hard-substratum natural community in the long term. Benthic communities found on artificial materials may differ from those found on natural substrata in many ways (Guerra-García, 2004; Marzinelli et al., 2009; Andersson et al., 2009). Differences occurred within both the taxonomic groups and the individual amounts, supporting a potential selective effect of the various substrata (Glasby, 1999), which could be added to differences in exposure time and different hydrodynamic conditions (Burt et al., 2009). The recruitment of benthic species colonising submerged hard substrata and the consequent type of community depend, to a large extent, on the microrelief and microtopography of the surface itself (Berntsson et al., 2000; de Nys and Steinberg, 2002). For example, rough substrata can support a completely different benthic community than smooth surfaces (Johnson, 1994; Commito and Rusignuolo, 2000).

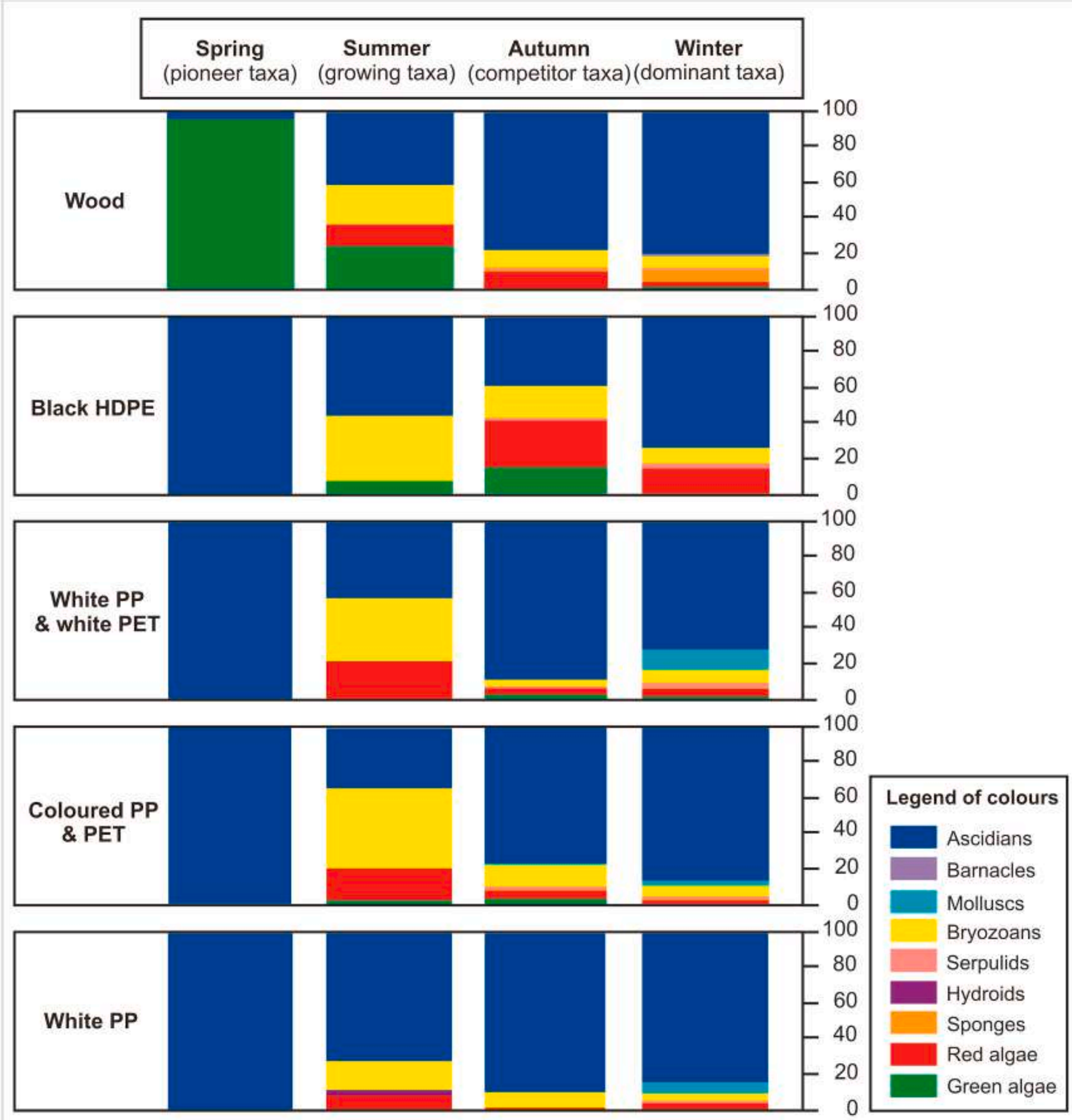

Fig. 7. Changes in 'biocoenosis structure' during the main phases of ecological succession on the various substrata. Percent value of coverage of each taxonomic group expressed as the total from the pool of four replicates.

The species communities found on geotextile fabrics were usually substantially different from those on natural reefs (Edwards, 2003), and considerable differences were observed between the fouling communities on woven and nonwoven substrata (Jackson et al., 2007; Wetzel et al., 2011). Jackson et al. (2005) also observed that barnacles made up approximately 90% of the coverage on woven textiles and that nonwoven textiles were mainly covered by red algae (>90%); thus, the geotextile type can influence the type of fouling community.

Our monitoring and analysis of the 10-month community growth revealed selective effects of nonwoven geotextile fabrics on species richness, covering-abundance area, biocoenosis structure, and biomass development with different potential impacts on the biodiversity of the resident community. The results support that nonwoven geotextile fibres can change biofouling settlement in a selective manner and, in some cases, favour species that increase rapidly in terms of number of individuals and strongly compete for the substratum, becoming dominant.

From the point of view of potential applications in biofouling prevention, geotextiles could represent a new tool as an 'antifouling system' alternative to the dangerous biocide mixtures employed worldwide in antifouling paints. The latter have the potential to disrupt aquatic communities by releasing pollutants with deleterious effects on non-target organisms (Ranke and Jastorff, 2000; Cima and Ballarin, 2008; Manzo et al., 2014). Therefore, in the last decades the research of new eco-friendly systems to prevent fouling settlement on artificial structures has become a primary requirement for the safeguarding of the coastal ecosystems. As regards the biomass trend and the structure/change of the community, all nonwoven geotextiles employed in the present study reduced fouling to some extent compared with wood. An order of effectiveness for the geotextiles in disturbing fouling growth can be established as follows: 'black HDPE' > 'coloured PP and PET' > 'white PP and white PET' > 'white PP'. The inhibitory activity of geotextiles is principally mechanical since the fuzzy surfaces of the geotextiles prevent larval and propagule settlement with continuous micromovements of the polymer fibres (Wetzel et al., 2011). This mechanism of action is not comparable with the real 'antifouling action' of biocide-based paints because it leads to a selection of species on the basis of a balance between the preference of the substratum and the disturbing action of the geotextile components. With respect to wood, geotextiles in general prevent the settlement of green algae as first colonists, initially block the settlement of serpulids and totally inhibit that of barnacles (all), green

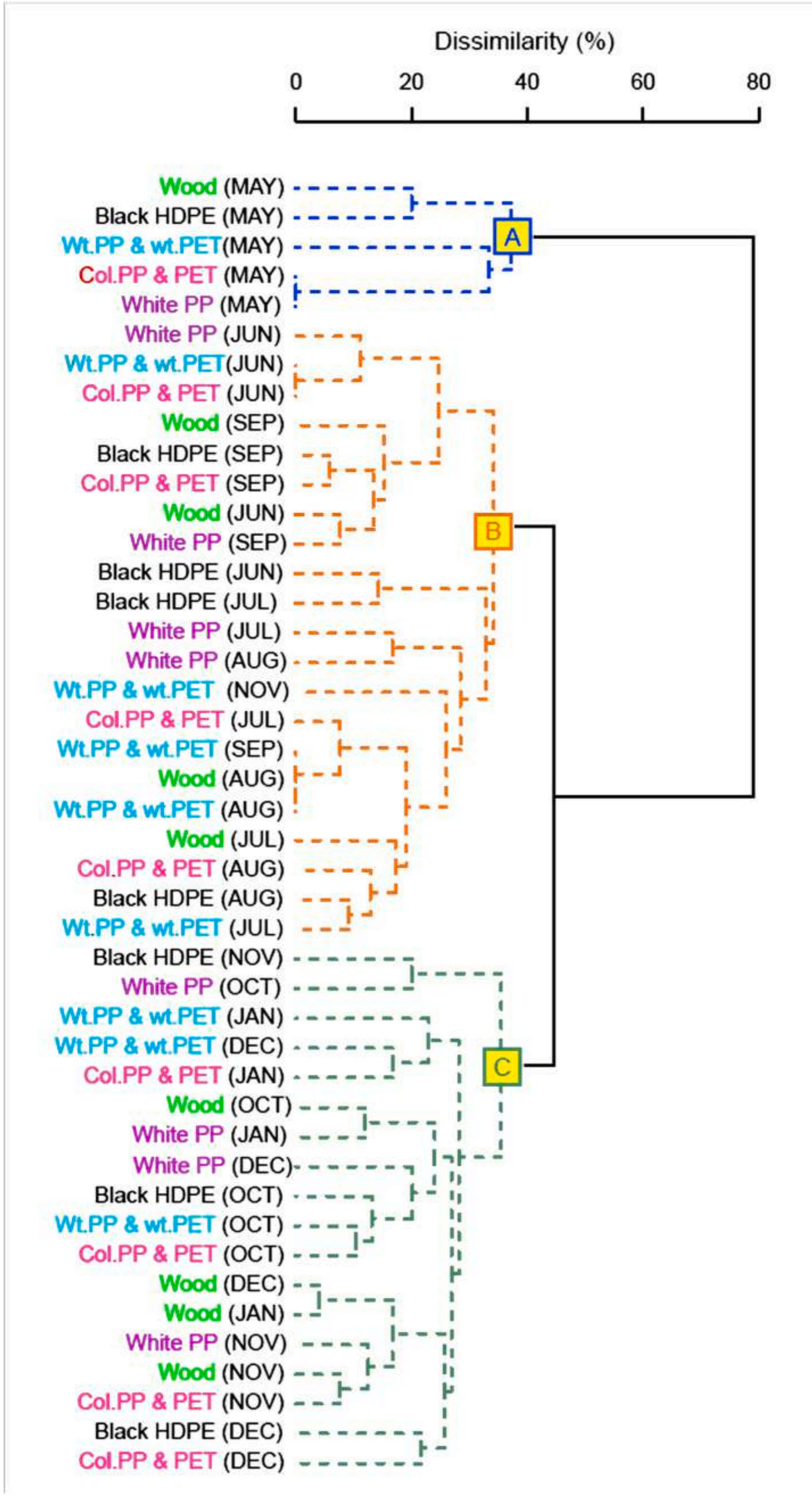

Fig. 8. Cluster analysis using Bray-Curtis dissimilarity values of presence/absence data. Significantly different clusters (A to C) were identified using SIMPROF procedure. For the species that contributed the most to the differences between clusters (SIMPER analysis), see Table 3.

Table 3
SIMPER analysis results showing the contribution (%) of the species responsible for the differences observed between the three clusters identified in the SIMPROF procedure (see Fig. 8). Only the topmost six values that contributed to the differences are shown.

Species	A – B	A – C	B – C
Red algae			
Gracilariopsis longissima	0.8	6.9	8.1
Serpulids			
Filograna sp.		7.4	
Bryozoans			
Bugula neritina		5.8	
Bugulina stolonifera	12.8	7.4	12.8
Ascidians			
Ascidiella aspersa	11.5		11.5
Ciona robusta	12.8	7.4	12.8
Botryllus schlosseri	0.7		7.9
Styela plicata	8.3	7.4	8.3

Cluster A: spring pioneer assemblage; cluster B: summer assemblage; cluster C: autumn and winter assemblages.

algae ('white PP' and 'black HDPE'), sponges and molluscs ('black HDPE'). This order most likely results from the differences in the material properties. Different species have different surface quality requirements. In particular, early colonists are very sensitive to the physico-chemical properties of the substratum (Wahl, 1989). The effects due to polymer composition, colour, texture, microtopography and tangle of fibres together with their thickness and capacity to move passively under various hydrodynamic conditions are worth considering in future studies. Initial recruitment was apparently not substratum specific because significant differences in the presence or absence of pioneer species were not observed between different substrata, with the exception of *U. intestinalis* on wood panels, and because the first biomass development on all of the substrata followed a similar pattern. This was likely due to the initial conditions of ecological succession that were shared by all of the substratum types, depending on the nutrient availability and the trend of blooms and dispersal of typical pioneer species, which were the eurythermal species of early spring in the Lagoon of Venice (Sconfietti and Marino, 1989; Libralato et al., 2002). However, the differences in biomass were particularly pronounced after the peak was reached. The substratum material was the most important factor and explained 57% of the biomass differences after the substratum-specific change point was exceeded. On the HDPE geotextile, the coverage of bacterial biofilm was abundant throughout the monitoring period, supporting the facts that the macrofouling biomass was particularly low and the panel surface never appeared fully covered. The polymer composition of this material might be responsible for the differences observed with respect to the other geotextiles employed. The influence of the chemical nature of substratum materials on the properties of fouling communities is well known (Pawlik, 1992; Bergey, 2008), and HDPE compounds in particular have been successfully used to prepare bioactive surfaces that can reduce biofouling (Yu et al., 2011). Ascidian larvae significantly prefer more hydrophobic substrates to hydrophilic ones (Sensui and Hirose, 2020; Hirose and Sensui, 2021). HDPE shows weak wettability as an effect of its hydrophobic character but, as a difference with the other geotextiles, has a low adhesion property due to the lack of a functional group (Conceição et al., 2019). 'Black HDPE' geotextiles might be suitable for fouling reduction measures on human-made structures, thereby enhancing their maintainability and decreasing maintenance costs. However, before employing this geotextile in coastal ecosystems with this purpose the underlying mechanism of action in fouling reduction should be better understood together with duration of the effects on the fouling growth in multi-year studies.

From the point of view of potential applications, geotextiles could find new employment as 'profouling systems' for habitat and microhabitat enhancement. Together with shore protection, they could play a key role in restoration of degraded and fragmented ecosystems by supplying alternative substrata which favour species settlement. In terms of substratum selection, bivalve molluscs settled on PP and PET geotextiles. This was in agreement with a previous study of oyster larval settlements on various plastic materials, where PP represented a good substratum that was also superior to other plastics, such as PVC (Taylor

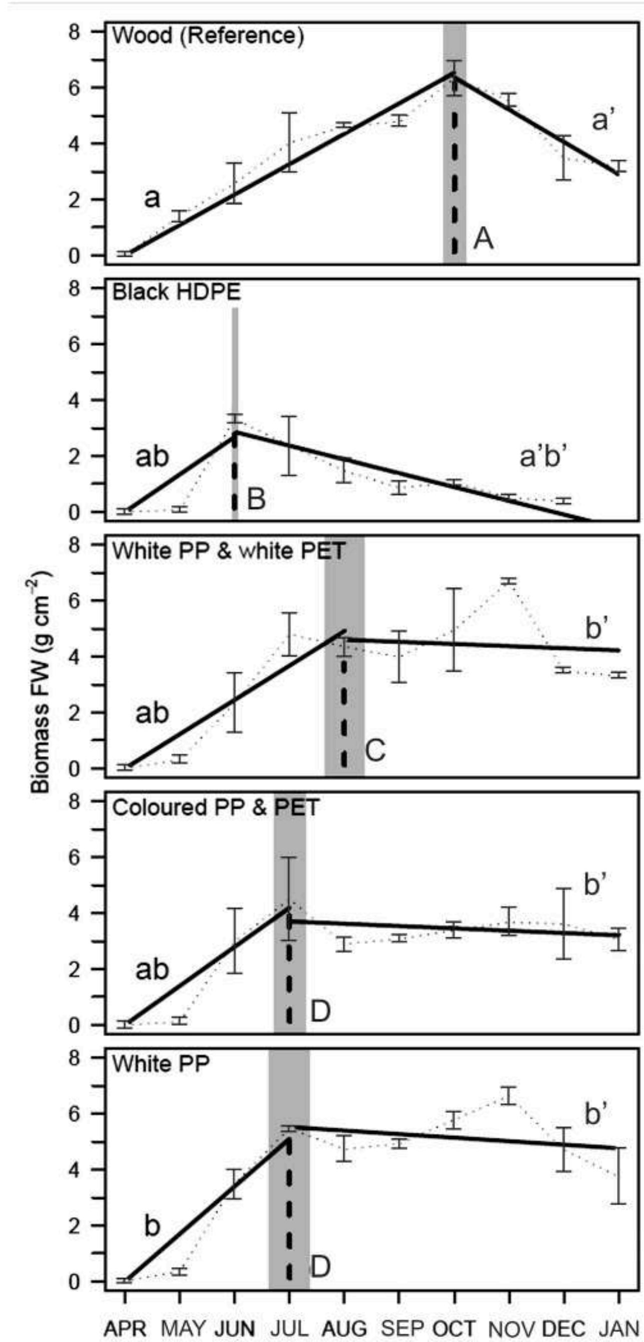

Fig. 9. Differences in biomass development monitored monthly on the five different substrata. The mean of four replicates with standard deviations is shown throughout the dotted line. The calculated change points, i.e., the substratum-specific peak of biomass expressed in g cm^{-2} of fresh weight (FW) is indicated by the dashed lines, and their corresponding confidence intervals are indicated by the grey areas. Different letters indicate significant differences for the pairwise comparison of the slopes before the change points (a to b, left), the position of the change points (A to D, middle), and the slopes after the change points (a' to b', right) among the five substrata.

et al., 1998). Tunicates found the ‘white PP’ geotextile to be particularly suitable for their settlement. In particular, the most favoured species was the dominant tunicate *C. robusta*, which is typical of the Lagoon of Venice (Brunetti et al., 2015), where it was first described by Lazzaro Spallanzani in the 18th century (Gibin, 1997). It is now considered among the most damaging of invasive species in the world by the effect of natural spread of the larvae and of human-related transportation of larvae through bilge waters and adults on boat keels (Shenkar et al., 2018). Also the didemnid ascidian *D. listerianum*, although not invasive in the Lagoon of Venice, appear to settle and grow easily on geotextiles according to the previous failed approaches to eradicate the invasive *Didemnum vexillum* based on geotextile fabrics to protect artificial structures in harbours and mussel farms of New Zealand (Coutts and Forrest, 2007). Therefore, it must be considered that a long-term and extensive use of geotextiles worldwide could negatively affect local biodiversity and develop on artificial substrates such as plastic, a high selection of invasive species by acting as a collector for larvae (Pinochet et al., 2020).

In conclusion, geotextiles act by selecting species, and modifying the biocoenosis composition with potential long-term impact on coastal ecosystems. They represent technical surfaces that are capable of exerting only a partial and temporary physical defence against the settlement of organisms and must not be considered as eco-friendlier barriers that are alternatives to antifouling paints in biofouling control. On the other hand, these materials provide - by paying close attention to fibre dislodgement, long-term fabric durability and abrasion resistance to avoid a potential contribution to plastic pollution in the marine environment (Dias et al., 2017; Carneiro et al., 2018b) - a good substratum for a wide range of benthic species (Jackson et al., 2004). In some conditions, they could enhance biodiversity and productivity at a local scale in depauperated areas and contribute to overall regional productivity (Edwards, 2003; Jackson et al., 2005). At present, artificial structures account for a great deal of the potential negative impacts of increasing connectivity, facilitating the spread of non-native species and contributing to biotic homogenisation. The ecological engineering of artificial habitats aims to test alternative materials and designs to encourage the colonisation of more diverse or more natural communities (Rinkevich, 2020). Consequently, the study of the influence of the substratum on the settlement of various organisms of the hard-substratum macrofouling community represents an essential tool to choose a geotextile for the most appropriate application in a variety of coastal marine ecosystems. Further efforts should be made to better clarify the effective role of the type of substratum on species selection by monitoring the macrofouling settlement capability on monthly-renewed nonwoven geotextile panels for limiting the interference of accumulation of high amounts of biofilm and sediment, which could progressively change the original characteristics of the fabric surface.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2021.105414.

Credit author statement

Varello Roberta: Original draft preparation. Visualization, Investigation. Wetzel Markus A: Software, Validation, Data curation, Formal analysis, Validation. Cima Francesca: Conceptualization, Methodology, Writing – review & editing.

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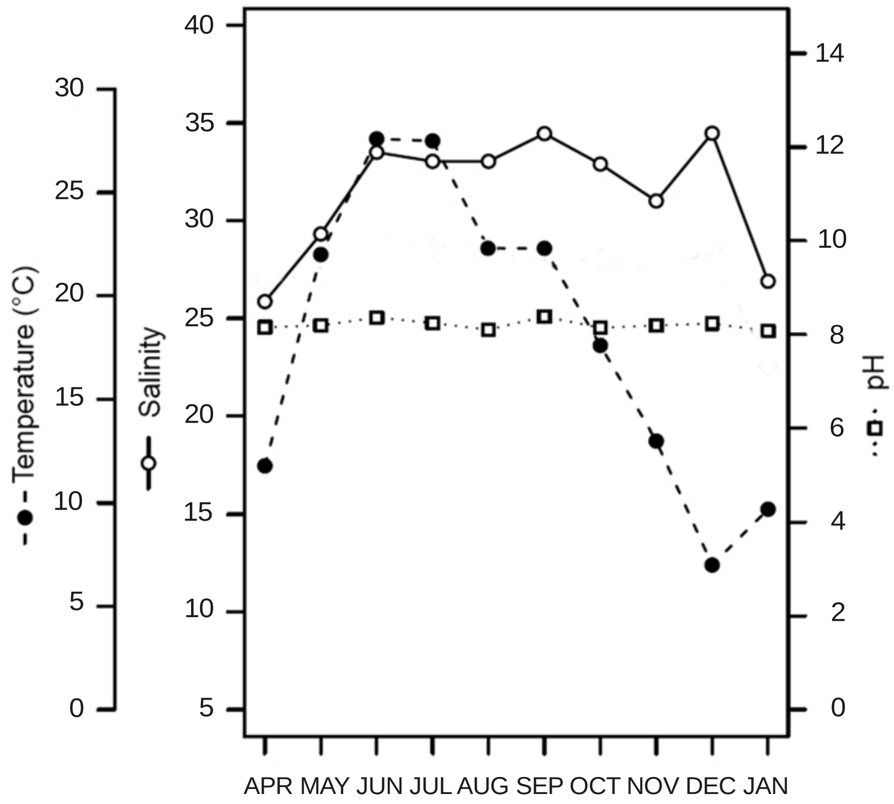

Supplementary Fig. S1. Monthly trends in water temperature, salinity, and pH, measured in the water column close to the study site over the course of the experiment.

Supplementary Fig. S2. Comparison between selected panels of Black HDPE (left) and White PP (right) at the end of the experimental period (i.e., December) in the Lagoon of Venice. Note the lower coverage of macrofouling represented by clusters of ascidians, bryozoans and red algae on Black HDPE in respect of the extensive coverage of ascidians on White PP. For details on fouling composition, see Figs 5 and 7.

Supplementary Table S1

PERMANOVA analysis results of species coverage. For each species, statistically significant effects ($P < 0.05$) of "month", "substrate", and "month*substrate interaction" are indicated in bold.

Species	Source	Pseudo-F	P
Cladophora pellucida	Month	1.370	0.242
	Substrate	0.725	0.580
	Month*substrate	3.622	1.304
Ulva intestinalis	Month	0.827	0.584
	Substrate	1.914	0.126
	Month*substrate	11.770	2.064
Ulva rigida	Month	0.987	0.461
	Substrate	0.980	0.428
	Month*substrate	5.098	2.045
Ceramium ciliatum	Month	2.300	**0.041**
	Substrate	1.714	0.165
	Month*substrate	9.133	2.438
Neosiphonia sertularioides	Month	0.928	0.505
	Substrate	1.697	0.169
	Month*substrate	25.969	3.209
Graciliopsis longissima	Month	2.528	**0.027**
	Substrate	0.763	0.555
	Month*substrate	1.735	0.161
Halichondria panicea	Month	1.000	0.452
	Substrate	1.000	0.418
	Month*substrate	9.008	3.406
Haliclona cinerea	Month	2.843	**0.014**
	Substrate	0.917	0.463
	Month*substrate	3.231	2.174
Mycale contarenii	Month	1.907	0.089
	Substrate	1.445	0.237
	Month*substrate	9.009	2.760
Eudendrium rameum	Month	1.000	0.452
	Substrate	1.000	0.418
	Month*substrate	10.567	2.966
Filograna sp.	Month	33.736	**0.000**
	Substrate	0.084	0,986
	Month*substrate	0.542	0.705

(Continues)

Bugula neritina	Month	2.808	**0.015**
	Substrate	0.559	0.693
	Month*substrate	2.940	3.199
Bugulina stolonifera	Month	3.343	**0.005**
	Substrate	0.840	0.508
	Month*substrate	1.315	0.280
Arcuatula senhousia	Month	1.000	0.452
	Substrate	1.000	0.418
	Month*substrate	7.349	2.986
Mytilus galloprovincialis	Month	1.164	0.346
	Substrate	0.940	0.450
	Month*substrate	4.881	2.665
Ostrea edulis	Month	0.904	0.523
	Substrate	0.808	0.527
	Month*substrate	5.536	2.394
Patella caerulea	Month	0.911	0.517
	Substrate	1.870	0.134
	Month*substrate	4.293	1.938
Balanus sp.	Month	0.875	0.546
	Substrate	2.285	**0.046**
	Month*substrate	1.543	0.482
Ascidiella aspersa	Month	16.645	**0.000**
	Substrate	0.475	0.753
	Month*substrate	1.613	0.189
Ciona robusta	Month	6.552	**0.000**
	Substrate	2.270	**0.048**
	Month*substrate	3.419	1.698
Botrylloides leachii	Month	0.710	0.680
	Substrate	3.063	**0.027**
	Month*substrate	24.129	3.292
Botryllus schlosseri	Month	1.199	0.326
	Substrate	0.967	0.436
	Month*substrate	3.557	1.419
Styela plicata	Month	2.173	**0.049**
	Substrate	1.181	0.333
	Month*substrate	2.991	**0.029**
Diplosoma listerianum	Month	3.283	**0.006**
	Substrate	0.686	0.605
	Month*substrate	5.281	1.954