VIE ET MILIEU - LIFE AND ENVIRONMENT, 2020, 70 (3-4): 137-148

CHANGES IN THE ECOLOGICAL STATUS AND NATURAL CAPITAL OF *POSIDONIA OCEANICA* MEADOWS DUE TO HUMAN PRESSURE AND EXTREME EVENTS

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SEAGRASS MEADOWS
EMERGY ANALYSIS
MARINE PROTECTED AREAS
DISTURBANCES
LIGURIA (ITALY)

ABSTRACT. – Littorals represent highly dynamic and complex systems which undergo changes imposed by several environmental factors and human-induced disturbances. Among coastal ecosystems, seagrass meadows represent a key habitat and, according to the European Water Framework Directive, the endemic Mediterranean *Posidonia oceanica* is considered as biological indicators thanks to their susceptibility to pressures and changes. In this work, four *P. oceanica* meadows in the Portofino Marine Protected Area (NW Mediterranean) are investigated to evaluate the potential effects of different disturbances (*i.e.*, anchoring and a severe sea storm) on them through the study of their conservation status (measured with the Conservation Index, CI) and their natural capital (NC). Results obtained for CI and NC are not always consistent: meadows with high conservation status often showed low NC values. A link between the ability of ecosystems to store NC and develop a complex functioning and the meadows conservation is evident only when ecosystems are subjected to strong disturbances like the sea storm that hit the Ligurian coast on October 2018. The two indices should thus be integrated in monitoring activities because they account for different and complementary aspects of the meadow status.

INTRODUCTION

Seagrasses support complex marine food webs and provide essential habitat for many coastal species, playing a critical role in the equilibrium of coastal ecosystems and human livelihoods (Short *et al.* 2011).

They are present in all coastal areas of the world, except for Antarctic shores, forming meadows that have important ecological functions. In fact, seagrass beds are highly productive ecosystems, provide habitat and nursery areas for a variety of invertebrates, fish and mammals (Francour 1997), and enhance water quality by stabilizing sediments, removing nutrients and concentrating and retaining toxic chemicals in their tissues (Lewis & Devereux 2009).

An iconic example of seagrass is represented by the endemic Mediterranean *Posidonia oceanica* (Linnaeus) Delile, whose meadows are able to protect the coast, buffering waves and currents (Terrados & Duarte 2000).

Posidonia oceanica meadows have been listed as priority natural habitat to be included in the Sites of Community Interest (SCIs), for which special plans of management and conservation must be designated (EEC 1992). Due to its wide distribution, long-life and susceptibility to changing environmental conditions, *P. oceanica* is considered a good biological indicator of water quality and health (Pergent-Martini *et al.* 2005), in accordance with the Annex V of the Water Framework Directive (WFD, 000/60/EC) (Foden & Brazier 2007).

Since the early 20th century, seagrasses have been experiencing a global crisis, as highlighted by decreasing coverage and associated biodiversity loss worldwide (Orth *et al.* 2006, Telesca *et al.* 2015, Thomson *et al.* 2015). Loss of meadows has been attributed to the combined effects of direct human activities (*i.e.*, habitat fragmentation, eutrophication, pollution, overfishing and biological invasions) and global climate change, both challenging their adaptability (Waycott *et al.* 2009).

An alarming decline of the *P. oceanica* meadows has been reported in the Mediterranean Sea and mainly in the north-western side of the basin (Ardizzone *et al.* 2006, Montefalcone *et al.* 2007a, Boudouresque *et al.* 2009, Montefalcone *et al.* 2010), where many meadows have already lost their original extension during last decades (Marbà *et al.* 1996, Bianchi & Morri 2000, Leriche *et al.* 2006, Montefalcone *et al.* 2007b, Burgos *et al.* 2017).

Disturbance is a key factor influencing the structure of ecological assemblages and evolution of species within ecosystems (Dornelas 2010, Ponge 2013). The degradation of habitats such as *P. oceanica* meadows means losing a series of ecosystem functions and services useful for the maintenance of the coastal marine system but also for human activities. There is an urgent need to quantify and estimate the ecological effects of natural and human disturbances to guide conservation efforts and the management of ecological resources.

This decline has been proved in response to human impacts that produce changes in water quality (Delgado *et al.* 1997, 1999, Dimech *et al.* 2000, Ruíz *et al.* 2001, Cancemi *et al.* 2003), mechanical erosion (Sánchez Lizaso *et al.* 1990, García Charton *et al.* 1993, Martín *et al.* 1997, Francour *et al.* 1999, Milazzo *et al.* 2002, 2004) or burial (Manzanera *et al.* 1998, Fernández Torquemada & Sánchez Lizaso 2005, González Correa *et al.* 2008), but also because meadows of *P. oceanica* are often affected by hasty environmental alterations resulting from natural phenomena. There is an urgent need to quantify and estimate the ecological effects of natural and human disturbances to guide conservation efforts and the management of ecological resources.

Ecosystem services have been defined as the benefits people obtain from ecosystems (Millennium Ecosystem Assessment 2005, TEEB 2010). In the last decades it became clear that ecosystem services provision completely depends upon ecosystems and their natural capital. As a consequence it is increasingly being emphasized that the measurement of the status of natural capital stocks, and not just the marginal valuation of flows of services and benefits, is vital to ensure that services can be provided in the future (HM Treasury 2018). Therefore, efficient management of natural resources and environmental assets requires adequate assessment of natural capital (Azad *et al.* 2020).

This study was carried out in the context of the Interreg GIREPAM (Integrated management of ecological networks through parks and marine areas) project for the Marine Protected Area (MPA) of Portofino (NW Mediterranean). The aim was to evaluate the effects of disturbances, such as anchoring and a severe sea storm on *P. oceanica* meadows.

Covering the seabed from the surface down to about 40 m depth, meadows of *P. oceanica* are often affected by direct mechanical damages caused by boat anchoring and mooring activities (Francour *et al.* 1999; Montefalcone *et al.* 2008). Boat anchoring can lead to seagrass meadow fragmentation and to formation of patches, thus modifying the seascape configuration (Meinesz & Lefèvre 1984, Kiparissis *et al.* 2011, Okudan *et al.* 2011). In fact, the impacts of anchoring systems on *P. oceanica* have been shown to impose huge stresses on the meadow, pulling up leaves and rhizomes (Walker *et al.* 1989, Hastings *et al.* 1995, Ceccherelli *et al.* 2007) and reducing shoot density and cover of the meadow (Francour *et al.* 1999). Notwithstanding, protection measures undertaken by the European Community for their conservation, *P. oceanica* meadows keep on being affected by this kind of impacts, which are hardly controlled within marine protected areas (La Manna *et al.* 2015).

Similarly, extreme storm events cause significant ecological shifts, and their occurrence is likely to increase due to climate change (IPCC, 2019) and it is considered a major environmental concern (Easterling *et al.* 2000, Harley *et al.* 2006). In fact, among natural factors, water movement, such as that associated with waves and currents, appears to be a main factor influencing the *P. oceanica* meadow structure at both within-meadow and seascape scales (Abadie *et al.* 2018).

Pace *et al.* (2017) showed that at shallow depth (6-11 m), high-energy wave climate leads to an increase of meadow patchiness and a decrease in architectural complexity. At greater depths also, even if negligible, currents derived from wave energy result in a decrease of meadow cover provoking the generation of patches of different bottom type (bare matte or sandy bottom) (Vacchi *et al.* 2010, Gobert *et al.* 2016, Abadie *et al.* 2017). Species often have a lower capacity to adapt to sudden events rather than to gradual changes (Wernberg *et al.* 2012, Smale & Wernberg 2013).

Two metrics were employed to assess effects of these two disturbances on *P. oceanica* meadows: the evaluation of conservation status through the application of Conservation Index (CI) (Moreno *et al.* 2001, Montefalcone 2009) and the Natural Capital (NC) evaluated through the emergy analysis (Odum 1988, 1996).

The CI was used to get information about meadows conservation status and their potential to recover.

Emergy analysis was applied to quantify the value and the changes in Natural Capital (NC) stock due to disturbances. NC is composed by all biophysical elements and it is an economic metaphor for the limited stocks of physical and biological resources (Costanza & Daly 1992). NC includes land, air, water, sea and ecosystems therein: a tight link exists between ecosystem services provision and NC since only if NC is preserved intact the supply of services in the future and at the actual level can be guaranteed (De Groot *et al.* 2012). Emergy analysis can be classified as a donor side approach since it accounts for the environmental effort, in terms of resources used, required to generate a certain product or service. For this purpose, emergy evaluates the convergence of matter and energy from several inputs to a system on a common basis: the equivalent solar energy required to maintain a process. The NC stocked within an ecosystem is then assessed as the environmental resources spent in space and time to create it (Vassallo *et al.* 2017).

The comparison between information obtained through CI and NC allowed making considerations about the ability of these two measures to record changes imposed by nature or humans.

MATERIALS AND METHODS

Study area: The MPA of Portofino (Liguria Region, NW Italy) hosts many tourist activities, especially during the summer period, that have the potential to damage coastal habitats. Nonetheless, some restrictions on tourist activities are imposed by the MPA. In particular, the MPA is divided into three zones: A, B and C, each with a different degree of accessibility. In the zone A (integral reserve) the system is fully preserved, being forbidden recreational and professional activities and permitted only rescue and scientific research activities. The zone B (general reserve) is characterized by wider constraints: recreational fishing is allowed (regulated) only to residents, scuba diving is allowed to diving centers and authorized individuals, while free bathing is allowed. The zone C (partial reserve), renowned for its large meadows of *P. oceanica*, has less restrictions allowing. Other activities are allowed, as underwater activity, recreational fishing, bathing, mooring and anchoring, considering limitations for the protection of the area. For management issues, the MPA is divided into 19 sectors moving from East to West as shown in Fig. 1.

Four *P. oceanica* meadows along the Portofino promontory have been investigated: Niasca (44°18'05.35"N; 9°12'44.98"E), Cervara (44°19'05.56"N; 9°12'43.74"E), Punta Pedale (44°19'12.92"N; 9°12'47.41"E) and San Rocco (44°20'01.07"N; 09°09'13.08"E) (Fig. 1). All meadows are within the zones C of the Portofino MPA.

Field activities: Surveys have been done during summer months, and particularly in 2005, 2011, 2017, 2018, but also after the severe sea storm of 29 October 2018. In each site, two divers moved along a transect perpendicular to the coast, collecting data from the lower to the upper limit of the meadow. The two operators independently estimated the percentage cover of living *P. oceanica* (on sand and on rock), dead matte and mosaic of *P. oceanica* and dead matte (henceforth mosaic) along each transect and recorded the linear occupancy (in meters) of each descriptor.

Conservation index: To evaluate the conservation status and the degree of alteration that the *P. oceanica* meadows have undergone, the Conservation Index (CI) was calculated (Moreno

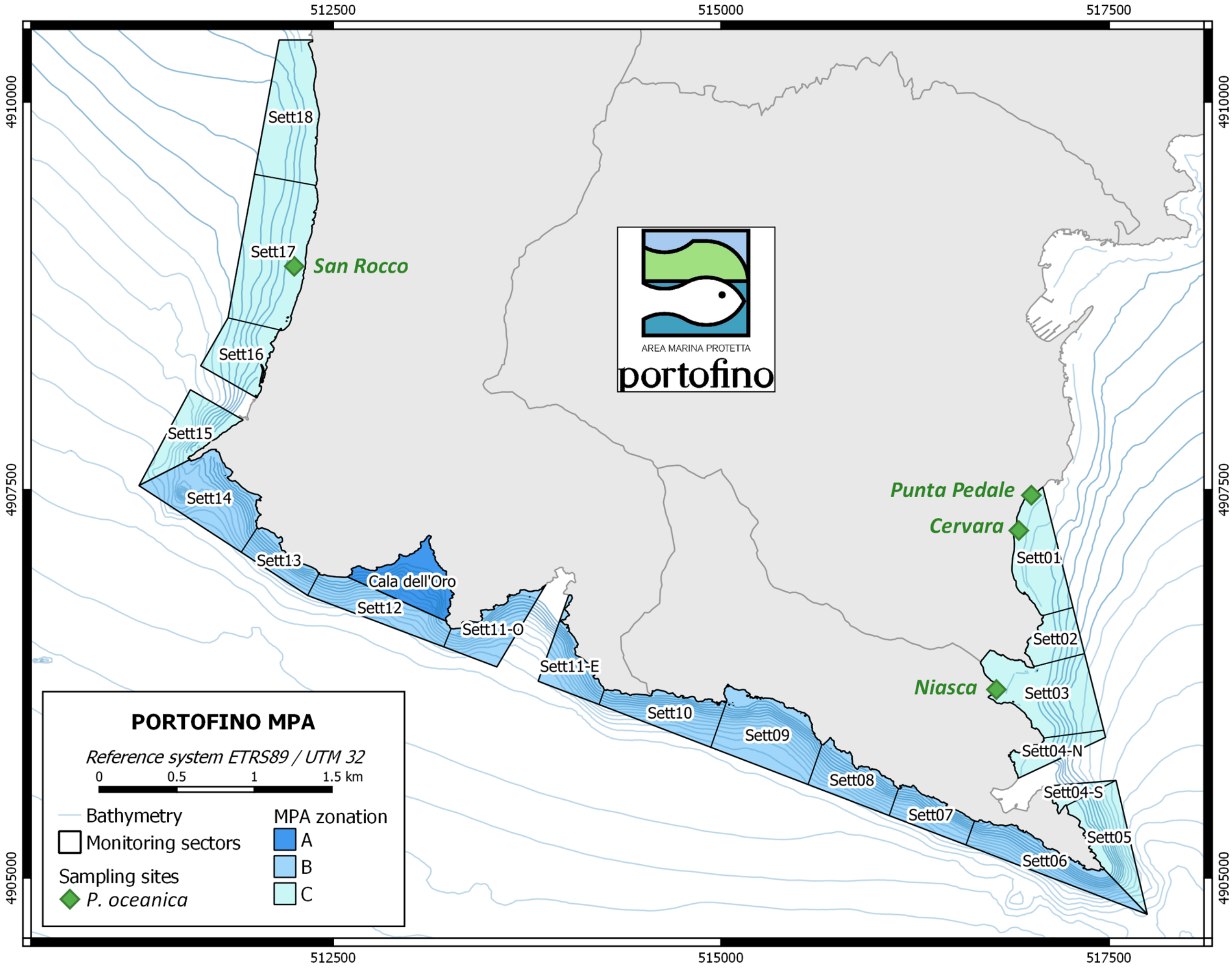

Fig. 1. – The Marine Protected Area of Portofino (Italy), with the four meadows investigated: San Rocco, Niasca, Cervara, and Punta Pedale.

et al. 2001) basing on the following formula:

$$CI = P / (P + D)$$

where P is the percentage cover of living *P. oceanica* (on sand, on rock and living part of mosaic), D is the percentage cover of dead matte determined for each transect.

The index ranges between 0 (maximum state of alteration or minimum state of conservation, where only dead matte is present), and 1 (maximum state of conservation, where no dead matte is present).

Natural capital through time: NC had been already assessed by emergy analysis (Brown & Ulgiati 1999, Odum & Odum 2000, Pulselli *et al.* 2011, Franzese *et al.* 2015, Vassallo *et al.* 2017, Paoli *et al.* 2018). Emergy is a thermodynamic method (Odum 1983, 1996) able to analyze the overall functioning of a system and to ascribe a value to it.

In particular, emergy converts the effort made by the environment (measured as resources, space and time invested) to produce biomass stock (donor side approach) into a monetary value. The value calculated with emergy corresponds to the amount of natural resources (*e.g.*, nutrients, rain) used (directly and indirectly) to build up and maintain the biomass of all the organisms within the habitat (Vassallo *et al.* 2017).

These resources are then represented in a single unit of measurement (solar emergy joules – sej) and later expressed in monetary terms (emergy-Euros – em€) using an appropriate conversion factor. The emergy baseline 15.20E+24 sej (Brown & Ulgiati 2010) was used to calculate emergy in this study. Here the 9.60E+11 sej/€ ratio is employed (Pereira *et al.* 2013).

Solar energy is used up, directly and indirectly, in transformations chains happening in the biosphere: this energy is a measure of the work done to provide a flow or a service and of the investment made by nature and can be considered a proxy of NC value as production cost (Odum 1996, 2000, Odum & Odum 2000, Pulselli *et al.* 2011).

In this work, the surface that the studied descriptors (*P. oceanica* on rock, *P. oceanica* on sand, mosaic, dead matte) covered in 2005 was calculated from the map of Ligurian marine habitats classified by Diviacco & Coppo (2006). The surfaces of descriptors in years 2011, 2017 and 2018 were calculated from field activities data. In particular, the percentages of *P. oceanica* on sand, on rock, mosaic and dead matte were calculated as the ratio between the length of each descriptor and the length of the entire transect. The percentages variation obtained for a specific time frame (*e.g.*, 2005-2011) were applied to the 2005 cartographic surface to obtain the extent of descriptors in each year. NC values per unit of surface of the descriptors were accounted in previous studies (Vassallo *et al.* 2017, Paoli *et al.* 2018). Multiplying the calculated surfaces by biophysical values in emergy terms (sej m^{-2}) and monetary terms^{-2}, the overall values were evaluated to detect the changes of NC in the analyzed period of time, looking for effects due to different restriction/protection actions or caused by the severe storm.

In addition, in each site and year, the variation in the total value of NC was calculated, thus taking into account all the descriptors (*P. oceanica* on rock, *P. oceanica* on sand, mosaic and dead matte).

Anchoring pressure: This study was carried out in the zones C of the Portofino MPA where anchoring was allowed in the considered period (2005-2018). During the summer of each year, a monitoring of boats presence in zones C of the MPA was carried out on an annual basis. In order to easily identify and count boats and to make comparisons over the years, the number of small and medium sized boats was counted for each sector in which the Portofino MPA is divided for monitoring purposes (Venturini *et al.* 2016).

The damage of anchoring was evaluated as removed surface of *P. oceanica* on sand and mosaic, excluding *P. oceanica* on rock that is not suitable for anchorage. The calculation of these surfaces was based on the number of shoots removed by a single anchor considering previous studies (Francour *et al.* 1999, Milazzo *et al.* 2002, 2004, Lloret *et al.* 2008). The quantity of shoots removed was converted in the corresponding degraded surface and multiplied by the corresponding number of anchorages in the considered sector.

The effect of anchoring on the meadows was evaluated assessing the NC in three sectors of the MPA: sector 17 (San Rocco), sector 3 (Niasca) and sector 1 (Cervara e Punta Pedale) (Fig. 1).

The values obtained through this calculation represent the amount of NC subtracted from the overall values estimated as described in the previous paragraph.

To obtain the percentages of surface and NC removed by the impact of anchoring the following formula was used:

$$P = La_{(i-j)} / O_i \qquad (1)$$

where:

P = percentage of surface or NC loss;

$La_{(i-j)}$ = loss of surface or NC due to anchorages from the year i to the year j;

O_i = overall surface or NC in the year i.

Sea storm pressure: The sea storm of 29 October 2018, that hit the Ligurian coast, could be considered the cause of important damages on marine habitats. During this event gale, torrential rainfalls and extremely rough sea caused catastrophic consequences on the anthropic coastal structures, particularly along the coastal area surrounding the Portofino Promontory (Betti *et al.* 2020). For example, the parapet surrounding the Portofino cape lighthouse, placed 30 m over the sea level, was widely destroyed and the littoral road from S. Margherita Ligure to Portofino (SP227) completely collapsed for about 200 m. This storm, with SE winds exceeding 130 km/h and generating 10 m high waves, changed the coast morphology, due to the fall out of large rocky boulders.

At the purpose of evaluating storm effects on the four investigated *P. oceanica* meadows in Portofino MPA, two sampling campaigns, before and after the sea storm, were carried out through the application of CI and NC evaluation.

Finally, by comparing the difference between the NC values (as the sum of all descriptors) before and after the storm and the

Table I. – Linear occupancy (in meters) and cover (in %) of the meadow descriptors (PR: *Posidonia oceanica* on rock, PS: *P. oceanica* on sand, MOS: mosaic of *P. oceanica* and dead matte, DM: dead matte) and CI values in the four meadows investigated in each sampling period. * data obtained after the severe sea storm of October 2018.

Sites	Years	Transect length (m)	PR (m)	PS (m)	MOS (m)	DM (m)	PR (%)	PS (%)	MOS (%)	DM (%)	CI
San Rocco	2005	205	45	100	40	20	21.95	48.78	19.51	9.76	0.81
	2011	230	10	150	15	55	4.35	65.22	6.52	23.91	0.66
	2018	280	41	145	64	30	14.64	51.79	22.86	10.71	0.69
	2018*	290	20	140	90	40	6.90	48.28	31.03	13.79	0.66
Niasca	2005	40	0	30	5	5	0.00	75.00	12.50	12.50	0.61
	2018	32	0	10	2	0	0.00	83.33	16.67	0.00	0.77
	2018*	30	0	20	0	10	0.00	66.67	0.00	33.33	0.61
Cervara	2005	185	80	40	20	40	43.24	21.62	10.81	21.62	0.57
	2011	140	75	20	35	10	53.57	14.29	25.00	7.14	0.75
	2018	159	95	23	8	33	59.75	14.47	5.03	20.75	0.68
	2018*	235	10	0	110	115	4.26	0.00	46.81	48.94	0.47
Punta Pedale	2005	265	20	55	65	75	7.55	20.75	24.53	28.30	0.44
	2017	260	20	80	30	110	7.69	30.77	11.54	42.31	0.39
	2018*	240	0	0	80	160	0.00	0.00	33.33	66.67	0.27

initial value, it was possible to assess which sites were the most damaged due to the heavy event and the corresponding percentage of loss.

RESULTS

Conservation index

The conservation status of the four meadows showed high spatial and temporal variability (Table I).

In San Rocco the *P. oceanica* meadow showed a worsening of the conservation status between 2005 and 2011, which stabilized in the following years, also after the sea storm of October 2018.

The Niasca meadow showed a little improvement in the conservation from 2005 to 2018. Following the storm the status declined and returned to the condition detected in 2005.

Also the Cervara meadow underwent an improvement of values from 2005 to 2011, then a decline in 2018 and a sharp worsening after the sea storm.

Finally, Punta Pedale meadow maintained a low conservation status through time, with a further decrease after the sea storm.

Results reported a general CI decrease in all sites after the sea storm, which varies between 3 % (San Rocco) to 31 % (Cervara and Punta Pedale).

Natural capital through time

The NC values were calculated from information obtained from cartography and transects data. Value per unit area are reported in Table II, expressed in biophysical and monetary units (sej and em€). NC values showed different trends through time in the four sites. The percentage of variation between sampling years is shown in Fig. 2.

From 2005 to 2011, the meadow in San Rocco had a decrease in the NC value for *P. oceanica* on rock and mosaic of about 17.6 % and 12.9 %, respectively. These values recovered in 2018, partly for *P. oceanica* on rock and completely for mosaic. Concerning *P. oceanica* on sand, a 16.4 % increase in its NC value was recorded between 2005 and 2011. However, since 2011 inconstant losses were assessed over time.

The *P. oceanica* meadow in Niasca develops only on sand. Between 2005 and 2018 the NC value increased by 8.3 % for *P. oceanica* on sand and 4.2 % for mosaic, while the storm caused a NC loss for both descriptors (16.7 %) and a significant increase of dead matte (33.3 %).

NC of *P. oceanica* on rock in Cervara increased by 10.3 % from 2005 to 2011 and further by 6.2 % from 2011 to 2018. Instead, *P. oceanica* on sand decreased from 2005 to 2011 (7.3 %), remaining then stable until 2018. Mosaic in Cervara had an increase in NC values between 2005 and 2011 and a decrease in 2018.

In Punta Pedale site the meadow showed a stable condition of NC values for *P. oceanica* on rock and an increase for *P. oceanica* on sand and dead matte in the period between 2005 and 2017. Instead NC value associated with mosaic, decreasing from 2005 to 2017, resulted increased in 2018.

Anchoring pressure

Starting from the dataset on boats monitoring provided by the MPA, the estimation of the impacts (expressed

Table II. – Values of natural capital expressed in surface (m²), emergy (seJ) and monetary equivalents (em€) in the four meadows investigated in each sampling period. PR: *Posidonia oceanica* on rock, PS: *P. oceanica* on sand, MOS: mosaic of *P. oceanica* and dead matte, DM: dead matte.

Sites	MPA sectors	Years	Surface (1E+02 m²)					Natural Capital (1E+15 seJ)					Natural Capital (1E+03 em€)				
			PR	PS	MOS	DM	Total	PR	PS	MOS	DM	Total	PR	PS	MOS	DM	Total
San Rocco	17	2005	49.00	124.94	61.54	0.00	235.48	301.45	767.52	215.94	0.00	1284.92	314.02	799.50	224.94	0.00	1,338.46
		2011	40.37	145.48	53.55	0.00	239.40	248.39	893.68	187.89	0.00	1329.96	258.74	930.92	195.72	0.00	1,385.37
		2018	44.53	125.94	62.30	0.00	232.76	273.96	773.64	218.58	0.00	1266.19	285.37	805.88	227.69	0.00	1,318.94
		2018*	41.08	121.52	67.39	0.00	229.99	252.74	746.49	236.46	0.00	1235.68	263.27	777.59	246.31	0.00	1,287.17
Niasca	3	2005	0.00	9.01	0.82	9.37	19.19	0.00	50.30	2.40	15.10	67.81	0.00	52.40	2.50	15.73	70.63
		2018	0.00	9.76	0.85	8.20	18.80	0.00	54.50	2.50	13.21	70.21	0.00	56.77	2.61	13.76	73.14
		2018*	0.00	8.13	0.71	10.93	19.77	0.00	45.41	2.09	17.62	65.12	0.00	47.31	2.17	18.35	67.83
Cervara	1	2005	5.80	56.34	4.69	27.77	94.60	32.43	314.74	13.80	44.76	405.73	33.78	327.85	14.37	46.63	422.63
		2011	6.39	52.21	5.36	23.75	87.71	35.78	291.65	15.76	38.28	381.47	37.27	303.80	16.41	39.87	397.36
		2018	6.79	52.30	4.29	26.98	90.36	37.99	292.17	12.61	43.49	386.26	39.58	304.34	13.13	45.30	402.36
		2018*	3.02	44.74	6.08	34.59	88.42	16.91	249.91	17.88	55.75	340.44	17.61	260.32	18.62	58.07	354.63
Punta Pedale	1	2005	5.80	56.34	4.69	27.77	94.60	32.43	314.74	13.80	44.76	405.73	33.78	327.85	14.37	46.63	422.63
		2017	5.80	61.98	4.08	31.66	103.53	32.48	346.26	12.01	51.03	441.77	33.83	360.68	12.51	53.16	460.18
		2018*	5.36	42.91	4.97	39.37	92.61	29.98	239.72	14.62	63.46	347.78	31.23	249.70	15.23	66.10	362.27

as shoots, surface and NC losses) due to anchorages on *P. oceanica* meadows, for the investigated period between 2005 and 2018, is shown in Table III. The ratio between the losses reported in Table III and the initial overall NC values of the period reported in Table II gives the percentages of removed NC.

Considering the formula 1 reported in materials and methods, from 2005 to 2018, the San Rocco meadow reported a loss of *P. oceanica* on sand of 911.5 m² ($La_{(i-j)}$) (Table III) that correspond to the 0.7 % (P) of the initial overall surface (O_i). Concerning mosaic, the loss is 478.4 m² that corresponds to 0.8 % of the initial overall surface. These damages are equal to a 0.7 % decrease in NC values in both descriptors, that amount, in monetary terms, to 5,304.3 em€ for *P. oceanica* on sand and 1,465.7 em€ for mosaic.

Anchoring monitoring was not carried out in Niasca, because it is an area where anchoring was banned since the establishment of the MPA.

On the other hand, the meadow in Cervara showed a small loss of NC for both descriptors. The decrease of surface was 0.1 % of the initial overall surface for both *P. oceanica* on sand and mosaic during the entire period from 2005 to 2018. As consequence of the impact due to anchoring in this site NC diminishes of 2,458.4 em€ for *P. oceanica* on sand and 144.5 em€ for mosaic.

In Punta Pedale the decrease of surface was lower than 1 % for both descriptors. This decrease corresponds to a NC loss of 2,228.8 em€ for *P. oceanica* on sand and 131.0 em€ for mosaic.

Sea storm pressure

After the severe sea storm of October 2018 the meadow at San Rocco suffered a 7.8 % loss of NC for *P. oceanica* on rock, 3.5 % for *P. oceanica* on sand and a 8.2 % increase in mosaic compared to data collected in the same year during the summer season (Fig. 3).

These percentages expressed a loss of 22,106.0 and 28,285.2 em€ for *P. oceanica* on rock and on sand, respectively, and an increase in mosaic of 18,618.9 em€.

Niasca meadow experienced a 16.7 % loss for both *P. oceanica* on sand and mosaic, which correspond to 9,461.2 and 434.8 em€.

The meadow in Cervara reported a high loss of NC for *P. oceanica* on rock (55.5 %) but also for *P. oceanica* on sand (14.5 %).

Losses were therefore 21,962.2 em€ for the former and 44,024.7 em€ for the latter. On the contrary, the mosaic showed a 41.8 % increase of the NC, which in monetary equivalents corresponds to 5,487.3 em€.

Similarly, at Punta Pedale the meadow showed a decrease in *P. oceanica* both on rock (7.7 %) and on sand (30.8 %), representing losses of 2,602.6 em€ and 110,979.2 em€, respectively.

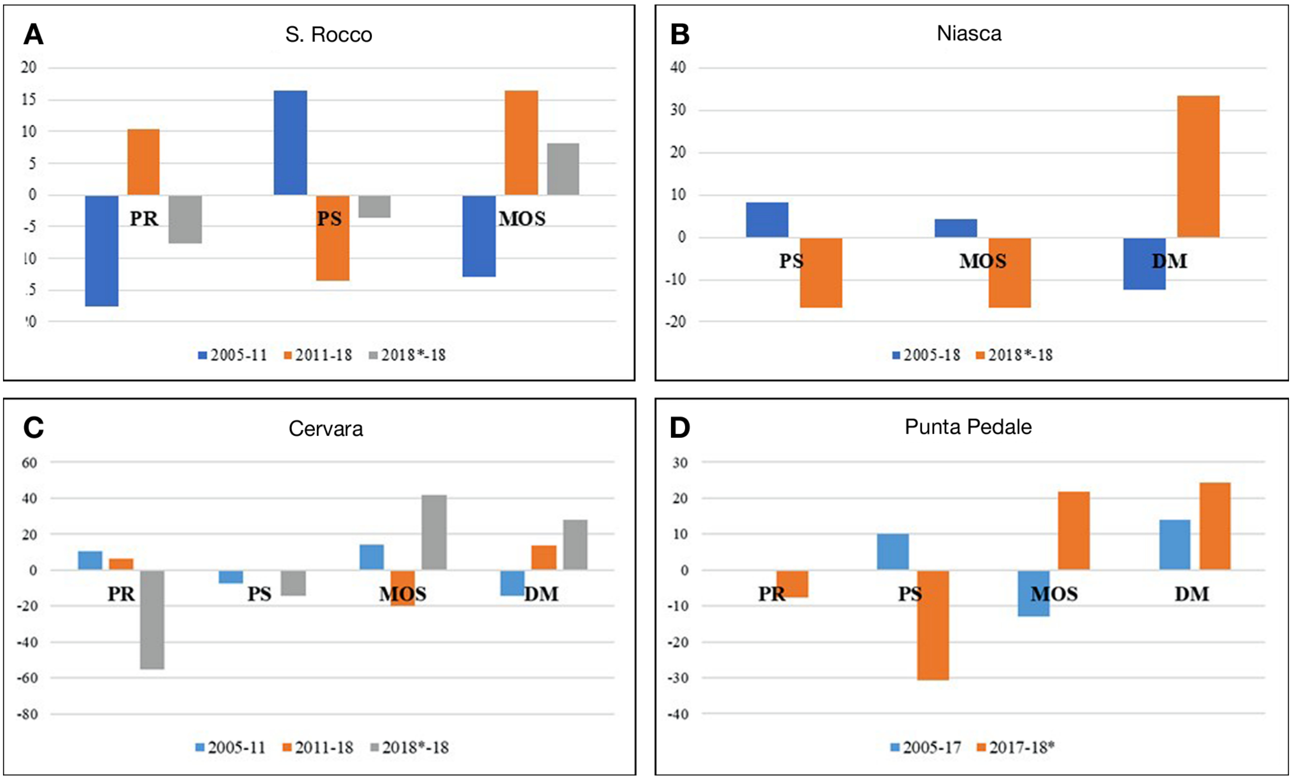

Fig. 2. – The percentage of NC variation between sampling years in each site. **A**: San Rocco; **B**: Niasca; **C**: Cervara; **D**: Punta Pedale.

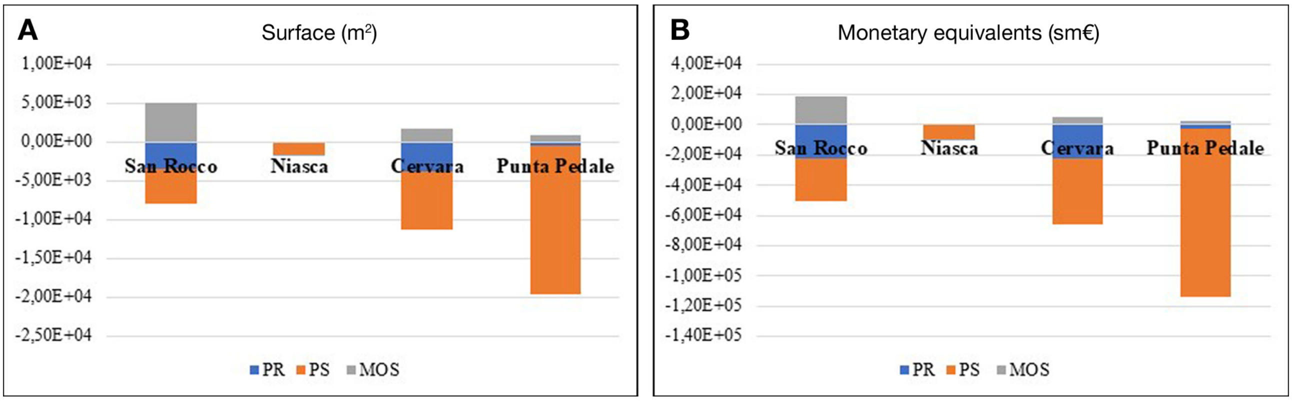

Fig. 3. – Changes in natural capital due to the sea storm of October 2018 expressed as (**A**) surface (m^2) and (**B**) monetary equivalents (em€) in the four meadows investigated in each sampling period.

Table III. – Changes in natural capital due to anchoring expressed as shoots (no), surface (m^2), emergy (sej) and monetary equivalents (em€) in the four meadows investigated in each sampling period. PR: *Posidonia oceanica* on rock, PS: *P. oceanica* on sand, MOS: mosaic of *P. oceanica*

Sites	MPA sectors	Years	Shoot (1E+03 no)			Surface (m^2)			Natural Capital (1E+12 sej)			Natural Capital (em€)		
			PR	PS	MOS	PR	PS	MOS	PR	PS	MOS	PR	PS	MOS
San Rocco	17	2005-2011	ND	–17.3	–29.1	ND	–455.9	–231.6	ND	–363.8	–97.3	ND	–379.0	–101.4
		2011-2018	ND	–20.9	–31.0	ND	–455.7	–246.8	ND	–363.6	–103.7	ND	–378.8	–108.0
		2005-2018	***ND***	***–38.1***	***–60.0***	***ND***	***–911.5***	***–478.4***	***ND***	***–5092.1***	***–1407.1***	*ND*	***–5304.3***	***–1465.7***
Niasca	3	2005-2018	No anchoring zone											
Cervara	1	2005-2011	ND	–17.3	–1.8	ND	–24.9	–2.6	ND	–152.7	–9.0	ND	–159.0	–9.4
		2011-2018	ND	–20.9	–2.1	ND	–30.0	–3.1	ND	–184.5	–10.8	ND	–192.1	–11.3
		2005-2018	***ND***	***–38.1***	***–3.9***	***ND***	***–54.9***	***–5.6***	***ND***	***–2360.0***	***–138.7***	*ND*	***–2458.4***	***–144.5***
Punta Pedale	1	***2005-2017***	***ND***	***–34.6***	***–3.6***	***ND***	***–49.8***	***–5.1***	***ND***	***–2139.6***	***–125.8***	***ND***	***–2228.8***	***–131.0***

The increase of mosaic was instead 21.8 % compared to the period before the storm, corresponding to 2,725.6 em€.

Results reported a overall NC decrease in all sites after the sea storm which vary between 2 % (San Rocco) to 21 % (Punta Pedale).

DISCUSSION

Over the last three decades the interest in landscape ecology has grown and spread from land to marine ecosystems (Bell *et al*. 2006). In the marine realm, *P. oceanica* meadows are among systems analyzed to assess the conservation status of coastal areas (Montefalcone *et al*. 2013).

In Europe, the umbrella regulations for addressing the ecological quality of the coastal and marine systems are the Water Framework Directive (WFD, 2000/60/EC) for lakes, rivers, transitional and coastal waters and the Marine Strategy Framework Directive (MSFD, 2008/56/EC) for marine waters. To manage human pressures on marine environments, recent and worldwide-approved legislative instruments address the need to assess a system's condition (Borja & Dauer 2008). Both health status and natural capital assessment provide a system-wide analysis fulfilling to this requirement.

Therefore, in this work, human-induced and natural impacts that affect *P. oceanica* ecosystem conditions were investigated applying two methodologies based on the study of different properties: conservation status (using the Conservation Index) and the natural capital (using emergy analysis).

The case study of the Portofino MPA was examined because recently the *P. oceanica* meadows were affected by an overlap of several natural and anthropogenic disturbances. Among them, the impacts of boat anchoring and of a severe sea storm were analyzed to evaluate ecosystem changes.

Comparing MPA sectors, the impact of boats appeared 2.7 times greater in terms of NC in the western sector (*i.e*., San Rocco) than in the eastern one (*i.e*., Cervara and Punta Pedale) of the Portofino promontory. The southeast direction of the wind, which usually affects coasts of Portofino MPA, causes more turbulence on the eastern side. Therefore, boats tend to anchor in areas sheltered by the promontory on the western side, consequently reducing the impact due to anchoring on the east coast.

Only in eastern sector where anchoring is forbidden (*i.e*., Niasca) the positive effect due to the ban is recorded by a 8.3 % increase in NC value for living *P. oceanica* and a 12.5 % decrease for dead matte between 2005 and 2018, with a consequent improvement in meadows conservation status.

Table IV. – Comparison between trends obtained through the Natural Capital (NC) and the Conservation Index (CI). The symbol "+" indicates a situation of increase, the symbol "–" a situation of decrease. * data obtained after the sea storm of October 2018.

Sites	Years	NC	CI
San Rocco	2005-2011	+	–
	2011-2018	–	+
	2018-2018*	–	–
Niasca	2005-2018	+	+
	2018-2018*	–	–
Cervara	2005-2011	–	+
	2011-2018	+	–
	2018-2018*	–	–
Punta Pedale	2005-2017	+	–
	2017-2018*	–	–

On the contrary, the loss of NC due to the severe sea storm of October 2018 was 12.7 % greater in the eastern side of the promontory than in the western side.

The CI confirmed this evaluation, showing a major decrease of status in meadows located in the eastern side. This was due to the main direction of the wind generating the storm: it formed in the southwest of Corsica and then released its force on the Ligurian coast, first along its eastern part and then along its western one (Betti *et al*. 2020). From October 26th, in fact, the wind direction was initially from south-east until the afternoon of October 29th when suddenly it increased its intensity reaching a speed of 130 km.h^{-1} and producing waves up to 10 m high (Betti *et al*. 2020). This intense storm lasted until the early morning of October 30th, when the wind turned to southwest.

Comparing damage of anchoring and storm, reduction of NC per unit area due to a single day of sea storm was about 32 times greater than the impact of anchoring over 13 years. Therefore, the force of the storm caused heavy consequences on meadows, already brittle because of the chronic impact due to seasonal anchoring.

This study allowed pointing-out different aspects of CI and NC for the evaluation of the environmental status. The comparison of the two indices in the same time frame, in fact, showed that they were consistent only in the 50% of the situations (Table IV). However, excluding the decrease in values obtained for both CI and NC due to the heavy sea storm at all sites, the indices showed discordant signals. This uncoupling can be explained considering the different nature of the two metrics.

The CI is a widely used index for the assessment of the conservation status of *P. oceanica* meadows because of its simple formulation and the ease of data collection on field. However, CI has some limitations, especially related to the fluctuating nature of soft substrates. Distribution of these substrates can vary as a function of both time and hydrodynamic conditions: dead matte areas might be buried and hidden by sand or, *vice versa*, waves and currents may remove sand and expose dead matte areas or create sand corridors due to a natural constant erosion activity on seagrass meadow (Pasqualini *et al*. 2001, Gobert *et al*. 2016, Vacchi *et al*. 2016). Dead matte surfaces might decrease (when buried), while live *P. oceanica* remains constant. CI is an intensive measure being a ratio between the cover of living *P. oceanica* and that of dead matte: an increase in the CI value might thus result without a real improvement in the meadow conservation status.

From an operational perspective, it is advisable to avoid the use of the "mosaic" notation during field activity whereas note more accurately the percentage of *P. oceanica* on sand cover and dead matte. This is expected to avoid misinterpretations and to lose some precision. It is also sometimes difficult to understand when a CI variation can be attributed to a specific human-induced or natural disturbance. Commonly the presence of dead matte has been misinterpreted as an unequivocal sign of human impact. Nonetheless, occurrence of dead matte can be due to natural events (Boudouresque *et al*. 2006), such as hydrodynamics that can alter the meadow status.

The NC, on the contrary, represents an extensive measure, because it considers the surface of each descriptor (*P. oceanica* on rock, *P. oceanica* on sand, mosaic and dead matte) and their biophysical value. When the surfaces of these descriptors change, the damage or the improvement of the system is then assessed as the sum of the lost or acquired NC values over the years. The status of the meadow is dependent by the intrinsic value of the descriptors and the surface they occupy. Indeed, dead matte, corresponding to an undesirable condition in comparison with living meadow, has a halved value compared to *P. oceanica* on sand and on rock (Paoli *et al*. 2018).

Moreover, the mosaic, consisting of 50 % living *P. oceanica* and 50 % of dead matte, represents a lower NC value than living *P. oceanica* on rock or on sand. Over time, the *P. oceanica* on sand can become mosaic and be largely replaced by dead matte losing its value. For example, in the case of the sea storm in San Rocco and Cervara, an increase of mosaic is associated with a decrease of *P. oceanica* on sand. Thus, even when the dead matte or mosaic decrease without changes of living *P. oceanica* surfaces, NC diminishes and better represents the effective meadow status.

However, in this study the surfaces of the meadows, useful to assess NC, have been drawn from the digital cartography, but one of the major problems of image processing when applied to the marine environment is the impact of water column (of variable quality and thickness) (Pasqualini *et al*. 2001). The complexity of the investigated areas in term of topography, bathymetric range and water turbidity, can also alter the perception of the data and consequently the reliability of the result. It is thus important to dispose of suitable criteria for assessing reliability of maps (Pasqualini *et al*. 2001).

Therefore, the cause of the partial inconsistency between CI and NC can be attributed to the fact that changes in CI are dictated by variations of dead matte. This was verified in Cervara and Punta Pedale meadows, where an increase of dead matte occurred, without a decrease of *P. oceanica* on sand and on rock, thus causing an overall decrease of the meadow conservation status. On the contrary, NC was able to weigh losses and rises of the considered descriptors reporting a general increase of the meadows status.

Moreover, thanks to NC, it is possible to quantitatively assess how much a single disturbance affects the meadow: variations in NC due to anchoring and the severe sea storm were measured separately.

Despite all above, results showed that in the case of strong disturbances, such as the sea storm of October 2018, CI and NC were consistent. The sea storm caused a considerable reduction of *P. oceanica* surface, which resulted in a conservation decreased and in a loss of NC.

This decline was recorded at both meadow and sites scale due to the local worsening for all the descriptors taken into account.

As a conclusive remark it can be stated that it is not enough to use a single ecological index to identify the status of seagrass meadows. It is necessary, instead, to flank qualitative information with quantitative system and extensive indicators.

Combining ecological indices with the study of NC can be a potential effective approach, also considering that nowadays it is widely accepted that the load from human activities should not exceed the carrying capacity of the environment and that the NC must be kept intact.

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