The challenge of managing the commercial harvesting of *Paracentrotus lividus*: are novel approaches required?

Simone Farina [Corresp., 1] , **Maura Baroli** [1] , **Roberto Brundu** [2] , **Alessandro Conforti** [3] , **Andrea Cucco** [3] , **Giovanni De Falco** [3] , **Ivan Guala** [1] , **Stefano Guerzoni** [1] , **Giorgio Massaro** [3] , **Giovanni Quattrocchi** [3] , **Giovanni Romagnoni** [4, 5] , **Walter Brambilla** [3]

[1] IMC-International Marine Centre, Oristano, Italy

[2] Marine Protected Area "Penisola del Sinis-Isola di Mal di Ventre, Cabras, OR, Italy

[3] IAS -Institute of Anthropic Impacts and Sustainability in Marine Environment, CNR - National Research Council, Oristano, Italy

[4] COISPA Tecnologia & Ricerca, Bari, Italy

[5] Dept. of Biosciences, University of Oslo, 5Centre for Ecological and Evolutionary Synthesis (CEES), Oslo, Norway

Corresponding Author: Simone Farina
Email address: simone.farina@szn.it

Many fish species are overexploited, and many stocks have collapsed. This crisis, along with increasing concerns over flow-on effects on ecosystems, has caused a re-evaluation of fisheries management practices and the approach of ecosystem-based fisheries management. The aim of this work is to highlight the role of ecological key-factors in planning a sustainable harvesting of the functional species *Paracentrotus lividus* and preserve the marine coastal ecosystems. Recruitment and predation processes that mainly drive population dynamic of this species are strongly related with the environment. Sea urchin density and population structures of the Peninsula of Sinis (Western coast of Sardinia, Italy) were evaluated in relation environmental constrains in five different sectors identified for type of habitats and their spatial organization, average bottom current speed of water circulation and predatory fish abundance (inside/outside the local Marine Protected Area). Results show how sea urchins are more abundant in rocky habitat configured in high patch density. Negative correlations are found between densities of recruits with average bottom current speed as well as between densities of under-commercial size (middle-size sea urchins) with predatory fish abundance. The results of this work underlines the necessity to integrate ecological processes that regulate sea urchin population dynamic with standard management measures, providing the foundation for scientifically sound management that embeds spatio-temporal environmental process at the relevant scale for the assessment of the stock sustainability.

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S.[1], Massaro G.[2], Quattrocchi G.[2], Romagnoni G.[4,5], Brambilla W.[2]

[1]IMC- International Marine Centre, Loc. Sa Mardini, Torre Grande, 09170 Oristano, Italy

[2] CNR - National Research Council, IAS -Institute of Anthropic Impacts and Sustainability in

Marine Environment, Loc. Sa Mardini, Torre Grande, 09170 Oristano, Italy.

[3]Marine Protected Area "Penisola del Sinis-Isola di Mal di Ventre", Cabras, Italy

[4]COISPA Tecnologia & Ricerca, Via dei trulli 18/20, Bari, Italy

[5]Centre for Ecological and Evolutionary Synthesis (CEES), Dept. of Biosciences, University of

Oslo, Norway

*corresponding author: presently working at Stazione Zoologica Anton Dohrn, email:

simone.farina@snz.it

14 **Abstract**

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33 stock sustainability.

Introduction

35 **Introduction**

37   The continuous decline of fishery catches during the last decades pushed many fishermen

38 to switch to new species at lower-trophic levels (Anderson et al., 2011). One of the clearest

39 examples, reported for several temperate coastal ecosystems, is the overexploitation of target

40 species involved in the typical tri-trophic interaction ''fish-sea urchins-macroalgae''. In general,

41 overfishing can seriously alter these trophic relationships and reducing populations of predatory

42 fishes in many coastal areas. This can trigger an uncontrolled proliferation of sea urchins that can

43 often lead to overgrazing of algal cover and, consequently, to the creation of ecosystem barrens

44 (Steneck et al., 2002; Steneck, Vavrinec & Leland, 2004).

45   In addition, the intensive harvesting of sea urchins also increased (Andrew et al., 2002;

46   James et al., 2016). Generally, sea urchin fisheries start as small activities that experience a

47   phase of rapid expansion followed by a phase of full exploitation before the exhaustion of the

48   resource (Andrew et al., 2002), following the short-term "boom-and-bust" patter of many

49   invertebrate fisheries. In fact, the systematic removal of hundreds of thousands of commercial-

50   size individuals, which are the main reproducers, leads populations to the collapse (Tegner &

51   Dayton, 1977; Pennington, 1985; Levitan, Sewell & Fu-Shiang Chia, 1992; Levitan & Sewell,

52   1998). Thus, the typical slow-growth of these organisms does not hold up the market demand.

53   From the ecological standpoint, in many cases, the drastic reduction of the sea urchin

54   density determines a rapid development of large brown algae stands that leads to changes in the

55   relative composition of fish and benthic community (e.g. Steneck et al., 2002). Among them,

56   also the urchin predators increase and further weaken populations. This leads to a new steady

57   state of the ecosystem structure that is generally unsustainable for the yield of the harvesting

58   (Johnson and Wilson, 2012).

59   In light of these considerations, an integrated management strategy for social-ecological

60   systems has been developed in many regions where this situation was verified, including Chile

61   (the world's largest fishery), Maine (U.S.), New Zealand, Canada, and Norway (James et al.,

62   2016).

63   In the Mediterranean Sea, sea urchin fishery focuses on the functional species

64   *Paracentrotus lividus* that is among one of the most important herbivores of benthic ecosystems

65   (e.g. Hereu et al., 2005; Prado et al., 2012). *P. lividus* is generally observed to overgraze

66   macrophyte communities, especially in the areas heavily exploited by fishery (Wallner-Hahn et

67   al., 2015). The impact of overfishing through the impairment of predatory control on sea urchin

68 populations seems to be much more important than the overharvesting that takes place in few

69 areas of the Mediterranean (McClanahan & Sala, 1997; Guidetti & Sala, 2007; Sala et al., 2012).

70   However, in other regions, including Sardinia (Western Mediterranean Sea), this species

71 is intensively harvested for commercial purposes and populations suffered high human pressure

72 since decades (Pais et al., 2007, 2012; Ceccherelli et al., 2011; Loi et al., 2017). The Peninsula of

73 Sinis, in the central western coast of this region, is one of the largest high-pressure zone of the

74 harvesting activity and it includes the Marine Protected Area "Penisola del Sinis, Isola di Mal di

75 Ventre" (MPA). Accordingly, the rules governing the exploitation inside the MPA are more

76 restrictive than outside, e.g. several no-take areas and only spearfishing.

77   Despite these restrictions have been in place from the early 2000s, individuals greater

78 than 5 cm diameter (minimum commercial size or stock) are still uncommon in populations both

79 inside and outside the MPA. From 2015 to 2017 scientific monitoring showed further decrease of

80 both the total population of *P. lividus* and stock that in thirteen years has been reduced more than

81 80% (Coppa et al., 2018). The steep decline of sea urchin populations emphasizes the need to

82 increase enforcement further the control actions and to evaluate even more restrictive

83 management measures. However, such actions could be insufficient for long-term stock preserve

84 unless they capture and effectively address the factors affecting the dynamics of sea urchin

85 population in the area.

86   Thus, it appears evident that the management strategies should undergo a major

87 transformation to avoid a fisheries collapse in this area (Ouréns, Naya & Freire, 2015). In this

88 sense, there are a number of well managed and sustainable sea urchin fisheries around the world

89 that tend to rely on a good overview of biology of the urchin species present in the area as well

90 as sound knowledge of the dynamics of the sea urchin populations (James et al., 2016)

91   For example, in New Zealand, sea urchin fishery reached a very stable status thanks to

92   the realization of a quota management system that has been integrated into the management

93   system with measures such as the number of licences and the fishing limitations (season,

94   commercial size classes, fishing gears etc.). The quota management system sets a total allowable

95   catch and determines the individual fishing quota according to the assessment of the stock

96   sustainability (Eddy et al., 2015).

97   In this regard, scientific monitoring can provide valuable information to estimate

98   biological parameters and reference points useful for stock assessment. However, given the role

99   of sea urchin as a functional species for coastal ecosystems, advanced approaches are required

100   for proper management of its fisheries that can account for population and ecosystem dynamics,

101   environmental interaction and spatial complexity (Andrew et al., 2002; James et al., 2016).

102   In the Mediterranean Sea, the sea urchin abundance vary widely from region to region

103   and it is well known that it is primarily driven by variability in recruitment (Turon et al., 1995;

104   López et al., 1998). Larval supply is strongly influenced by the oceanographic conditions

105   (Fenaux, Cellario & Rassoulzadegan, 1988; Harmelin-Vivien et al., 2000; Prado et al., 2012;

106   Farina et al., 2018), while other environmental constraints such as the substrate, type of habitat

107   and predators influence the success of the settlement and post-settlement survival (Boudouresque

108   & Verlaque, 2001; Tomas, Turon & Romero, 2004; Hereu et al., 2005; Oliva et al., 2016).

109   Specifically, while settlement on the rocky substrata colonised by macraolgal assemblages

110   appears to be coupled to larval supply, high post-settlement mortality limits the recruitment of

111   sea urchin populations in the three-dimensional structure of seagrass meadows (Tomas, Turon &

112   Romero, 2004; Farina et al., 2009).

113   Once in the benthos, structural complexity of the habitat is crucial for the population

114   outcome as well as its spatial configuration that can strongly influence sea urchin distribution in

115   relation of food availability and shelter (Pagès et al., 2012; Farina et al., 2014, 2016, 2017). In

116   fact, fish predation is the prevalent mechanism of top-down control on sea urchin abundance and

117   serves as a critical bottle-neck for urchin populations, representing a significant pressure until

118   individuals reach the refuge size of ~ 5 cm (Fig.1; Guidetti et al., 2004; Hereu et al., 2005). The

119   main sea urchin fish predators in the Mediterranean Sea are the labrid species *Coris julis* and the

120   commercial sea breams *Diplodus spp.* and *Sparus aurata*, visual hunters of small and medium

121   size classes respectively (Sala, 1997; Guidetti, Boero & Bussotti, 2005). In addition to these,

122   there are also average bottom predators like some species of whelks (e.g. the muricidae

123   gastropod *Hexaplex trunculus*) or the carnivore sea star *Marthasterias glacialis* that are well

124   known to be consumers of sea urchins (Sala & Zabala, 1996) and whose effect on populations

125   can be locally important (Bonaviri et al., 2009; Gianguzza et al., 2009; Farina et al., 2016).

126   Thus, recruitment and predation are ecological processes that strongly shape population

127   structure acting on different spatial scales and influencing abundance and distribution of sea

128   urchins (Harmelin-Vivien et al., 2000; Prado et al., 2012).

129   As one of the largest high-pressure zone of the harvesting in Sardinia, the coasts of

130   Peninsula of Sinis has been widely monitored and the analysis of data gathered during the period

131   2004 to 2007 has provided relevant information about the sea urchin populations' structure. In

132   fact, also due to a decade of intensive harvesting (Loi et al., 2017), this period precedes the most

133   significant reduction of the sea urchin population which occurred from the 2007 (Pieraccini,

134   Coppa & De Lucia, 2016) and that can be considered as a *pre-crisis era*. Therefore, the *pre-crisis*

135   *era* represents a reference environmental status that could provides the identification of any

136   natural relationships among population structure, ecological processes influencing population

137   dynamic and environmental constraints in terms of hydrodynamism, habitat and substrate, and

138   pool of predators from the areas of total fishing prohibition up to the mildest restrictions and the

139   outside fishing areas.

140   We are confident that results of the present work will be useful for future fishery

141   management plans, incline to ecosystem preservation, will certainly profit from not negligible

142   results that arise from this research.

143

Material & Methods

145

146   **Study Area**

147   The study was conducted along a stretch of coast of about 40 km on the West Coast of

148   Sardinia, Italy (Sinis coastal area; Fig. 2, Fig. S1) between the Gulf of Oristano (39.8377° N,

149   8.4844° E) and Su Pallosu Bay (40.0379° N, 8.3938° E). The middle and southern parts of the

150   study area are included in the Marine Protected Area of "Penisola del Sinis, Isola di Mal di

151   Ventre", which covers a surface of 250 Km^2 (Fig. 2). The surface area with full protection is

152   relatively small (5 Km^2, Guala et al., 2008), while the remaining zones are intensively frequented

153   by commercial and recreational fishermen (Pieraccini, Coppa & De Lucia, 2016).

154   In the *pre-crisis era*, sea urchin harvesting was allowed only to resident professional

155   fishermen inside the MPA, from November to April, for a maximum catch quota of 1000 sea

156   urchin (with diameter without spines >5 cm) per day per fisherman. The number of licensed

157   fishermen varied from 125 in the 2001 up to over 270 in the 2004-2007 three-year period.

158   Outside the MPA, sea urchin harvesting is managed by a regional decree (RAS, Regione

159   Autonoma della Sardegna decree no. 2524/DecA/102 of October 7, 2009 and subsequent

160   amendments). Before 2007, along the whole coast of Sardinia, approximately 150 professional

161   fishermen were authorized to collect sea urchins by scuba diving from November to April with

162   each diver allowed to collect up to 2000 sea urchins per day.

163   The study area is limited to the bathymetry of $5 \pm 1m$ (mean depth at which the

164   harvesters usually work) and it is subdivided in five sectors (Fig. S1). Study sector 1 is identified

165   in the portion of coast located outside MPA from Su Pallosu Bay to the northern boundary of the

166   MPA, including Cape Mannu (Fig.2). Sectors 2 and 3 enclose the stretch of coast inside the

167   MPA exposed to the open sea, while sector 4 represents the MPA islands of Mal di Ventre and

168   Catalano. Finally, sector 5 represents the Gulf of Oristano inside MPA at the southern limit.

169   On the study area seabed, the bedrock has three different natures: Palaeozoic granite

170   basement, cropping out around Mal di Ventre Island; Pliocene basalt rock, in the Cape San

171   Marco area and surrounding Catalano island (Fais, Klingele & Lecca, 1996; De Falco et al.,

172   2003; Duncan et al., 2011; Conforti et al., 2016); the Miocene and Quaternary calcareous rocks

173   located all along the study area coastline (Lecca & Carboni, 2007). The substrate morphologies

174   influence the distribution of *Posidonia oceanica*; the meadow shows a patchy pattern where the

175   matte is on the bedrock and continuous pattern where the matte leys on the unconsolidated

176   sediments (Fig.2). The meadow is continuous on the eastern side of Mal di Ventre Island and

177   inside the Gulf of Oristano, while in the rest of the study area *P. oceanica* shows a patchy

178   meadows pattern.

179   Along the coastal area, the average bottom current speed (Fig.3) strongly influences the

180   abundance of sea urchin recruits, (Farina et al., 2018). Average bottom current speed is mainly

181 generated by the action of the frequent and intense wind events, mostly from the North-West

182 (Mistral wind) and, to a lesser degree, from the South-West (Libeccio wind), characterized by a

183 yearly mean speed of 7m/s and a peak speed higher than 20 m/s (Zecchetto et al., 2016). Such

184 two prevalent wind regimes may generate intense flows toward south, in the case of Mistral

185 events, and weaker northward flows, in the case of Libeccio events. In both cases, within the

186 Gulf of Oristano, recirculation cells develop in correspondence of the leeway side of the main

187 two Gulf capes. We refer to Cucco et al. (2006, 2012) for a detailed description of sea current

188 circulation in the study area.

189   Finally, field monitoring between 2004-2012 showed no clear patterns of fish abundance

190 in time nor between protected and unprotected sites (Marra et al., 2016). However, during the

191 *pre-crisis era* (before 2007), larger abundances of sea breams were found inside than outside

192 (Marra et al., 2016; Table.1). Thus, although boundaries and management of the protection zones

193 of the MPA have been changing over the years, study sectors falling inside the Marine Protected

194 Area should be expected to present higher predatory fish activity respect to the outside zone and

195 this should be evident on sea urchin population structures (Shears & Babcock, 2003; Guidetti &

196 Sala, 2007).

197   Within sectors, on the base of the occurrence of different rocky substrates and type of

198 *Posidonia oceanica* meadows, the environmental areas inhabited by sea urchins are defined as

199 types of habitat (Abercrombie, Hickman & Johnson, 1966). Accordingly, sea urchin population

200 structure in terms of size class ranges -recruits, under-commercial size (middle-size sea urchins)

201 and commercial sea urchins- is compared in function of different types of habitat and sectors in

202 the *pre-crisis era*. Moreover, a predictive model was run to predict spatial variability of the

203 whole sea urchin density in relation with the spatial configuration of the types of habitat. Finally,

204   average bottom current speed measured through numerical model solutions (Farina et al., 2018)

205   and predatory fish density derived by Marra et al., (2016) are related to the study sectors and

206   their relationships with the abundance of recruits and middle-size sea urchins are investigated

207   respectively.

208

209   **Environmental constrains**

210   Geomorphology was described through habitat mapping (Fig. 2). Available data consist

211   of morpho-bathymetric data, aerial image and several geo-datasets. To ease processing and data

212   sharing among researchers, all available data were integrated and organized in a geodatabase

213   implemented through a GIS and the software suite Geoinformation Enabling Toolkit StarterKit

214   ® (GET-IT), (Fugazza, Oggioni & Carrara; Pavesi et al., 2016; Lanucara et al., 2017; Brambilla

215   et al., 2019) developed by researchers of the Italian National Research Council for RITMARE

216   project.

217   The distribution and extent of habitats have been plotted to create a map with complete

218   coverage of the seabed (MESH, 2008). Seafloor mapping has been made imposing discrete

219   boundaries between different morphotypes (Fig. 2) to provide a representation of how are

220   structured. Five of them are considered suiTable habitats for sea urchin colonization and are

221   calcareous rock substrata (CR), granite substrata (GR), basalt substrata (BA), *Posidonia*

222   *oceanica* patchy meadow (PM) and *Posidonia oceanica* continuous meadow (CM). These types

223   of habitat are alternate heterogeneously along the coast. A pool of variables describing the basic

224   characteristic of habitat spatial configuration was estimated for each sector with the free software

225   Fragstats 4.1 (McGarial & Marks, 1995). The variable estimated are Patch Density on the total

226   landscape area (PD, patch/Km^2), Perimeter-to-area ratio (P/A ratio, 1/m), Mean Patch Size

227   (MPS, Km^2), the Largest Patch Index (LPI, %) as the percentage of landscape area occupied by

228   the largest patch of a class and Interspersion/Juxtaposition Index (IJI, %) that measures the

229   degree of aggregation or "clumpiness" of a map based on adjacency of patches (O'Neill et al.,

230   1988).

231   The hydrodynamic features of the investigated area were inferred from meteo-marine

232   numerical model application. Specifically, the results obtained by the application of a three-

233   dimensional, finite element hydrodynamic and wind wave model, SHYFEM-WWM (Umgiesser

234   et al., 2004), were used to describe the average of water circulation in the area. The model was

235   already used to reproduce the wind-wave and the 3D water circulation along the Sinis coastal

236   areas (Cucco et al., 2006, 2016; De Falco et al., 2008). In Farina et al., (2018), a simulation run

237   was performed to reproduce the water circulation for the biennium 2009 and 2010. The model

238   and simulation setup accounted for both oceanic and meteorological seasonal variability. In

239   particular, the 2009-2010 biennium was selected for its meteorological conditions that were

240   highly representative of the local climate (Farina et al., 2018). In this work the same simulation

241   run was carried out to reproduce the water circulation in the first 10 meters of water depth during

242   the same biennium. We refer to Farina et al, (2018) for details of the model and simulation setup.

243   The results, consisting in hourly data of 3D current fields in the Sinis area, were averaged in time

244   considering the first six months of the year only. The obtained dataset consisted in the average

245   distribution of the average water speeds at the bottom between January and June that corresponds

246   to the period of recruitment is active (Fig.3; (Prado et al., 2012; Farina et al., 2018).

247   From a multi-year series of fish biomass data recollection, we extrapolated abundance of

248   sea urchin predatory fish for each sector from 2004 to 2007 with the exception of sector 5 (Marra

249   et al., 2016). Data represents abundance of Sparidae (*Diplodus spp.* and *Sparus aurata*) and

250   Labridae (*Coris julis*), on the rocky bottoms of shallow waters (5 metres in depth) collected

251   using Underwater Visual Census (Marra et al., 2016). In the *pre-crisis era*, the reserve effect of

252   MPA on fish biomass was not evident and no differences between inside and outside zones was

253   detected (Marra et al., 2016), except for the commercial sea bream which showed a higher

254   abundance inside the MPA than outside.

255

256   **Sea urchin population structure**

257   Sea urchin population structure was estimated in each type of habitat in the study sectors

258   from multi-year series of data from 2004 to 2007 (*pre-crisis era*). During this period, 79

259   samplings were carried out following a standard protocol at depths between 2 and 10 m (Guala et

260   al., 2008). Specifically, for each site and type of habitat, sea urchin density was estimated as the

261   number of individuals per square meter (ind/m^2) as the mean of five plots of one square meter

262   each, placed randomly for a total of three times. The sizes of the individuals (without spines)

263   were measured with callipers to the closest mm.

264   We define as recruits the size-classes *a* and *b* composed with individuals with diameter $\leq$

265   2 cm that survived approximately until two years after their settlement (Ouréns et al., 2013).

266   Middle-size sea urchins between 2 and 5 cm (class *c*, *d*, and *e*) are vulnerable to predatory fish

267   (see above) and over the 3.5 cm, individuals become the main contributors to the reproductive

268   capacity of population (Loi et al., 2017). Finally, large sizes of sea urchins, 5-6 cm (class *f*) and

269   over 6 cm (class *g*), represent the commercial stock of the current years.

270   The whole sea urchin density and population structure in the *pre-crisis era* are estimated

271   for each type of habitat and sector (Table S2). We carried out an analysis of variance for the

272   whole sea urchin density in function of "sector" and "habitat" as fixed factors and to compare

273   density of recruits (classes *a* and *b*), middle-size sea urchins (*c, d, e*) and commercial sea urchins

274   (classes *f* and *g*) among the different populations. Assumptions of normal distribution and

275   homogeneity of response variables were tested using D'Agostino-Pearson and Cochran's tests.

276   Total sea urchin density and middle-size sea urchin density following normal distribution with

277   unbalanced replicates were analysed with Linear Model (Zuur et al., 2009). Whereas, given the

278   non-normal distribution followed by density of recruits and commercial size sea urchins, the

279   analysis of variance was performed with no-parametric Kruskal-wallis test (Kruskal & Wallis,

280   1952). Pairwise multicomparisons were conducted among factors. All the analysis were

281   performed using R Studio (R Core Team, 2014).

282

283   **Relationships among population structure and environmental conditions**

284   Spearman's rank correlation coefficient as no-parametric measure of rank correlation was

285   carried out between non-normal distributed recruit density and the average bottom current speed,

286   while Pearson's rank correlation, as parametric linear regression test, was used to estimate

287   statistical relationship between density of middle-size sea urchins and density of predatory fish.

288   Generalized Linear Model (GLM) with Poisson family distribution was performed to

289   assess prediction of spatial configuration of habitats on the future stock (diameter < 5cm).

290   Given the lack of data of fish visual census in *Posidonia oceanica* and since recruits are

291   considerably underestimated inside meadows (Oliva et al., 2016), the habitats Patchy Meadow

292   and Continuous Meadow were excluded from these analysis. All the analysis were performed

293   using R Studio (R Core Team, 2014).

294

295   **Results**

296

297 **Environmental constrains**

298   Study sector 1 is the largest sector with an area of 12.7 Km² (Fig.2). The average current

299 speed was 0.05 ± 0.003 m/s (Fig.3) that is the slowest current measured in the period of

300 recruitment (from January to June; see Table 1). Conversely, study sector 4 is the smaller sector

301 with a total area of 3.8 Km² (Fig.3) and the highest predatory fish abundance of 84.6 ± 12.6 ind/

302 125m² (Table 1). Sectors 2 and 3 are extended 5.1 Km² and 4.4 Km² respectively (Fig.2) with

303 intermediate values of average bottom current speed and predatory fish abundance (see Table 1

304 and Fig.3). Finally sector 5 covers a total area of 11.9 Km² with the same average bottom current

305 speed of sector 3, while predatory fish abundance was not available.

306   In terms of habitat organization, calcareous rock substrate (CR) covers a surface of 4.5

307 km² in the sector 1 with a mean patch density of 1 patch for Km² (CR-1; Table 2). While

308 *Posidonia oceanica* patchy meadow is the most extend habitat of this sector with a surface of 7.2

309 Km² (PM-1; Table 2). CR-2 is the most extent habitat and with the highest level of patch

310 aggregation with respect to all the others habitats in all the sectors (98.9% IJI; see Table 2). PM-

311 3 and CR-3 cover 2 and 1 Km² respectively (Table 2) with a Mean Patch Density of 0.32 Km² for

312 both of habitats. BA-3 covers 0.1 km² of the sector 3 (Table 2). BA-4 and GR-4 cover 0.1 km²

313 and 1.8 Km² respectively (Table 2). Finally *Posidonia oceanica* continuous meadow represents

314 the total surface of sector 5 (CM-5) covering 11.1 Km² with the largest patch covering 42.6% of

315 the total landscape (see Table 2). Continuous meadow is also present in sector 4 but it has never

316 been sampled and a variable proportion of sand, unsuitable habitat for sea urchins, is present

317 along all the sectors with the except ion of the sector 4 (Table 2).

318

319 **Sea urchin population structure**

320   The whole sea urchin density is significantly different among habitats and sectors (Table

321 3 and Fig. 4). Sector 1 outside MPA had the highest density of 9.9 ± 1.1 ind/m^2 with the lowest

322 proportion of commercial sea urchins (15.1 $\pm$2.3%; Table 1 and Table S2). Inside the MPA the

323 whole sea urchin density ranged from 2.5 ± 0.2 ind/m^2 in correspondence of the Sector 5 to $9.8 \pm$

324 1.2 ind/m^2 in the sector 4 (Table 1). In the sector 4 the lowest proportion of middle-size sea

325 urchins was found (21.2 $\pm$ 5.5%; Fig.4 and Table S2).

326   Among types of habitat, the highest significant density was found in CR-1 with a whole

327 density of 16.3 ± 1.4 ind/m^2 (Table S3). High values of whole sea urchin density were also found

328 in CR-2 and CR-3 (10.6 $\pm$1.3 and 10.1 $\pm$0.8 ind/m^2 respectively) and in GR-4 (11$\pm$1.1 ind/m^2;

329 Table S2). Otherwise, the lowest sea urchin density was estimated in correspondence of CM-5

330 with a mean density of 2.5 ± 0.2 ind/m^2 (Table 1).

331   Recruit and middle-size sea urchin densities were significantly different among

332 populations as the combination of habitats and sectors (Fig. 4; Table S4). Recruit density (size-

333 classes *a* and *b*) was higher in CR-1 (7.7 $\pm$1.3 ind/m^2) than in CR-2, CR-3, GR-4 and BA-4 and it

334 was significantly higher than PM-2, PM-3 and BA-3 characterized by the low values of 0.3 $\pm$0.1,

335 0.3 $\pm$0.2, 0.1 ± 0 ind/m^2 respectively (Table S4). Whilst recruit density was found zero in PM-1

336 and CM-5 (Fig.4).

337   Density of middle-size sea urchins was significantly higher in CR-1 (7.2 $\pm$0.8 ind/m^2) and

338 higher in CR-2 and CR-3 (6.3 $\pm$0.9 and 5.4 $\pm$0.7 ind/m^2 respectively) than BA-3, BA-4 and GR-4

339 (3.1 $\pm$1.1, 0.5 $\pm$0.2 and 3.3 $\pm$0.8 ind/m^2 respectively). In CM-5 density of middle-size sea urchins

340 was 1.9 ± 0.8 ind/m^2 (Table S2).

341

342   **Relationships among population structure and environmental conditions**

343   In rocky habitats CR, BA, GR recruit density does not follow a normal distribution due

344   to the high number of sampled zeros and values are significantly correlated with the average

345   bottom current speed (Spearman's rank correlation p-value = 0.02574; *rho* = -0.3184671; Fig.5a).

346   Whereas, density of middle-size sea urchins follows a normal distribution and it resulted

347   significantly correlated with predatory fish density (Pearson's correlation p-value = 0.04268,

348   *correlation coefficient* = -0.5118654; Fig. 5b). Finally General Linear Model highlights high

349   significant influence of Patch Density (PD; p-value<0.01) and significant influence of the Mean

350   Patch Size (MPS; p-value=0.01) on density distribution of on the future stock (diameter < 5cm;

351   see Table 4 and Fig. S5).

352

353   **Discussion**

354

355   During the *pre-crisis era* (samplings realized during the period 2004 to 2007)

356   conspicuous differences in sea urchin density were found across study sectors and type of

357   habitats. Calcareous rock, basalt and granite support larger populations of sea urchins than

358   *Posidonia oceanica*. However, differences in whole density were found also into the types of

359   habitat: for example density in CR-1 was 1.5 and 1.6 times higher than in CR-2 and CR-3

360   respectively. The highest density of recruits was found in CR-1 and was approximately 3 times

361   higher than in CR of the other sectors; 1.5 times higher than in GR and even more than 5 times

362   higher than in BA. Conversely, density of recruits found in *Posidonia oceanica* was most of the

363   times around zero. Density of middle-size sea urchins was still significantly higher in CR: for

364   example, it was 4 times higher than in BA-4 and GR-4.

365   Considering results obtained from the analysis on the habitat configuration, high values

366   of Patch Density and Mean Patch Size seem to further increase sea urchin population even if they

367   have practically continuous distribution over the surface of the habitats. Surprisingly, although

368   sector 1 (outside the MPA) had the lowest proportion of commercial stock and considering the

369   large extensions of CR-1 characterize by a high Patch Density (one for square kilometre), the

370   whole sea urchin density in CR-1 was approximately two times higher than in the sectors 2 and 3

371   (inside the MPA).

372   Population structures that we analysed are consistent with the high variability of the

373   environmental constrains found along the Peninsula. From January, the spawning period, to June,

374   when recruitment process generally ended, average bottom current speed was slowest in sector 1.

375   It was almost half speed than in sectors 2 and 4 and a third less than speed in sectors 3 and 5.

376   Recruit densities resulted negatively correlated with average bottom current speed. Specifically,

377   to low values of average bottom current speed (< 0.1 m/s) correspond recruit densities above 3.5

378   ind/m^2. It is interesting to notice that the average bottom current speed in CR-1 is under this

379   critical threshold. In effect, this condition seems to support the existence of local standing

380   circulation structures that determine a higher regime of natural recruitment (Farina et al., 2018).

381   Predation is the process regulating sea urchin population structure at local scale (Guidetti,

382   2004; Hereu, Zabala & Sala, 2008; Boada et al., 2015). During the *pre-crisis era*, density of

383   middle-size sea urchins in rocky habitats resulted negatively correlated with density of predatory

384   fish. In the sector 4 (the two Islands inside MPA), density of sea breams was found 1.2 higher

385   than in sector 1 (outside the MPA; Marra et al. 2016). The low abundance of sea breams in sector

386   1 is most likely due to the strong pressure by recreational spear fishermen (Marra et al., 2016),

387   while the considerable distance from the coast could have made the islands of sector 4 less

388   accessible to spear fishermen, protecting the local predatory fish community (Stallings, 2009).

389   Consistently with this, in correspondence of the sector 4 was found the lowest density of middle-

390   size sea urchins that suggests a high predation activity in this area. Conversely, the highest

391   density was found in the sector 1.

392   Our results confirm how certain environmental constrains driving sea urchin population

393   dynamic and are not quite as homogenous as it might seem in the Peninsula of Sinis. Thus, a

394   management plan for sustainable harvesting should start from the assumption that sea urchin

395   population in this region could be composed of multiple smaller populations with their own

396   population dynamic.

397   However, the planktonic early life-stage could make sea urchin populations

398   demographically open (López et al., 1998; Morgan et al., 2000; Prado et al., 2012; Treml et al.,

399   2012) and could have a degree of identifiable demographic influence from surrounding

400   populations, which could be connected via process of larval dispersal (Knight & Landres,

401   2002). This concept emphasizes the importance of connectivity in generating a system of discrete

402   local populations from inside to outside the MPA. In effect, the phenomenon where "source"

403   populations supplement "sink" populations via dispersing individuals is a rescue effect that

404   should be considered crucial for planning management actions and sustainable fisheries

405   especially for the conservation requirements of an MPA (Paterno et al., 2017).

406   After all, a system of local sea urchin populations could be connected also by the spread

407   of predators from the MPA that however, maintain a strong inter-habitat variability of predation

408   pressure in all the surrounding area. In effect, a high proportions of middle-size sea urchins in the

409   populations were generally found in patchy meadows (PM) in accordance with the efficient

410   shelter effect that *Posidonia oceanica* provide versus predatory fish (Farina et al., 2009, 2014).

411   However, density of sea urchin population in the sector 5 in the Gulf of Oristano was the

412   lowest then the whole study area. The high presence of whelks (bottom predators) in the

413   continuous meadow is probably the potential cause of the scarcity of sea urchins in this habitat

414   (authors pers. obs.). In effect, if for any reason the local pool of predators is dominated by

415   bottom predators, the three-dimensional structure of a large seagrass meadow convert in a 'death

416   trap' for sea urchins more than a protective habitat (Farina et al., 2014, 2016; Schmidt & Kuijper,

417   2015).

418   Fisheries management that aim to provide long-term sustainable exploitation of the

419   resources should take in consideration not only the monitoring but also population dynamic, its

420   ecological drivers and what they depend on (Hilborn & Walters, 1992). Accordingly, a clear

421   understanding about the processes regulating realistic population dynamics at relevant spatial

422   and temporal scale is a prerequisite of any management strategy and the results obtained in this

423   study shed new light that might help management plans for sea urchin in this area.

424   Thus, there is increasing attention to identify and explicitly consider the key aspects

425   regulating population dynamics in formal stock assessment and management (Skern-Mauritzen

426   et al., 2016), including consideration of the spatial structure (Kerr et al., 2016; Cadrin et al.,

427   2019) and food web interactions (Fulton et al., 2004).

428   Fisheries models can be strategic management tools for assessing and testing hypotheses

429   about direct and indirect human impacts on the environment. Simulations obtained by fisheries

430   models with ecosystem approach can allow to test alternative management strategies such as, for

431   example, inclusion of total allowable catches, reduction of fishing effort and changes in gear

432   (e.g. Spedicato et al., 2010). These measures should allow modulating fishing effort on specific

433   components of the populations (for example, to reduce harvesting on the most productive age

434   classes or areas). These tools, however, rely strongly on the basic understanding about

435   population dynamics, its spatial structure, and the interaction with other elements of the

436   ecosystem, including other species and environmental variables.

437   The Sinis Area offers a peculiar case study, where ecological and economic information

438   and data is building up, and the involved stakeholders, including small-scale fisheries

439   organisations, MPA and local administration are demanding a science-based management

440   system. There is currently momentum toward implementation of a long-term vision entailing a

441   data collection strategy aiming to provide management strategy plans toward a sustainable

442   management of the sea urchin fishery, sharing the objectives of conservation of ecological

443   features and of traditional and socio-economics values. Moreover, to be able to achieve values of

444   sustainable fishing in the two main resources, as sea urchins and sea breams, that are compatible

445   with preserving well-structured macrophyte communities, permit to provide in the sustainable

446   way the ecosystem services needed for a high environmental quality.

447

Conclusion

448

449

450   Although the rates of recruitment and mortality from predation have not yet been studied

451   in depth in this area, this study suggests how these mechanisms are of crucial importance to

452   ensure long-term sustainable exploitation of the resource. Strong natural relationships have been

453   demonstrated to exist between sea urchin population structures and the variability of certain

454   environmental constrains and interactions with other species in this region. In this system, the

455   continuous and inexorable decrease of the natural resource from 2007 is chased by frantic

456   adjustments of the management measures. Hence, testing alternative management strategies

457   through the development of a local fisheries model with an ecosystem approach would foster a

458   systemic territorial planning addressed both to support environmental protection actions and to

459   promote the sustainable use of the fishing resources.

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Figure 1

Figure 1. Diagram describing sea urchin population dynamic.

Letters represent different life stage of populations: a) commercial stock and main reproducers of sea urchin populations, b) larval supply for populations, c) settlement in suitable habitats, d) interactions with habitat structure for food and shelter, e) predator-prey interactions with local predator community, f) fishing pressure both on fish and sea urchins.
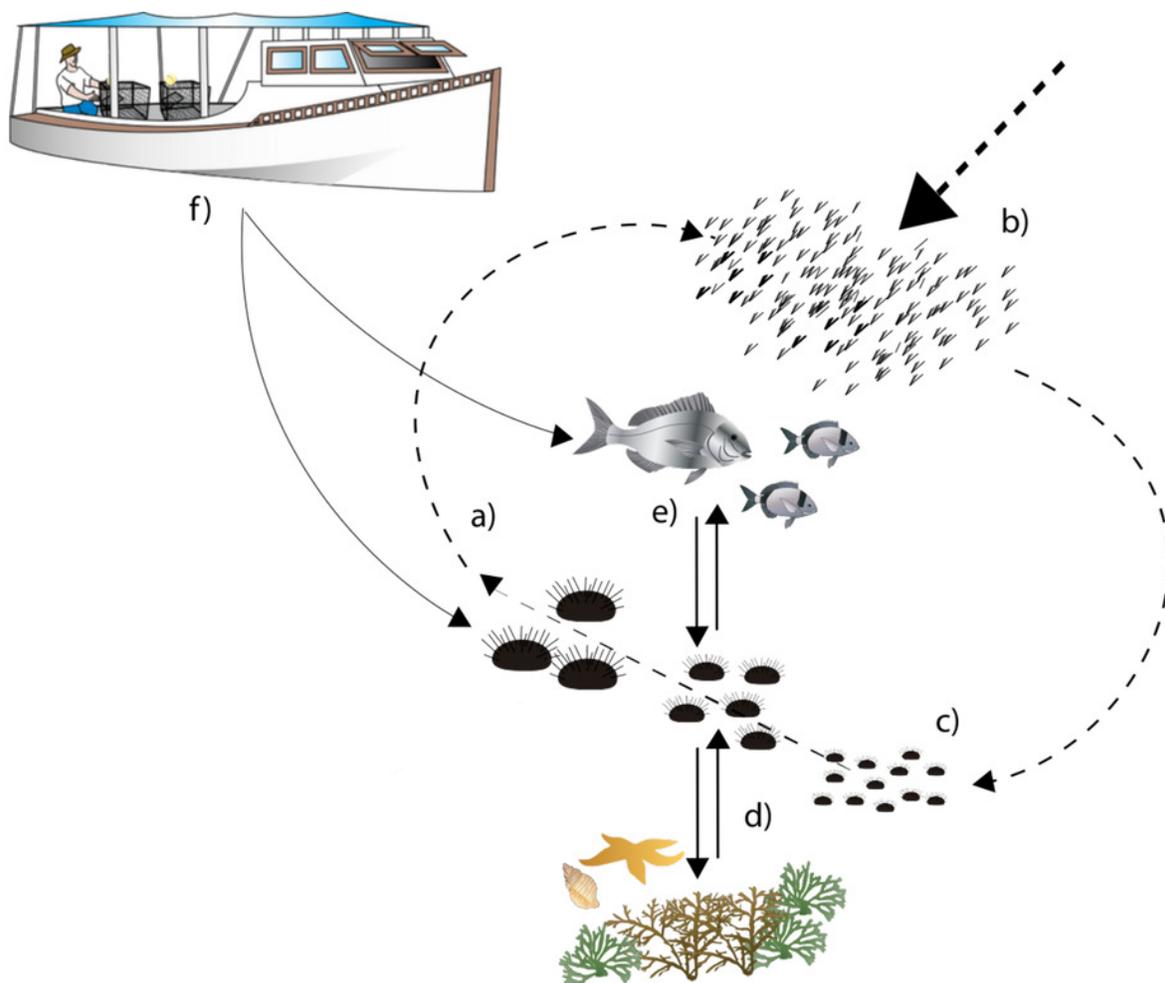
Figure 2

Figure 2. Detailed digital mapping of geomorphology in the study area.

Colours indicated different sectors and type of habitats: calcareous rock (CR in grey), granite (GR in light blue), basalt (BA in red), *Posidonia oceanica* patchy meadow (PM in dark green), *Posidonia oceanica* continuous meadow (CM in light green) and sand (in yellow).
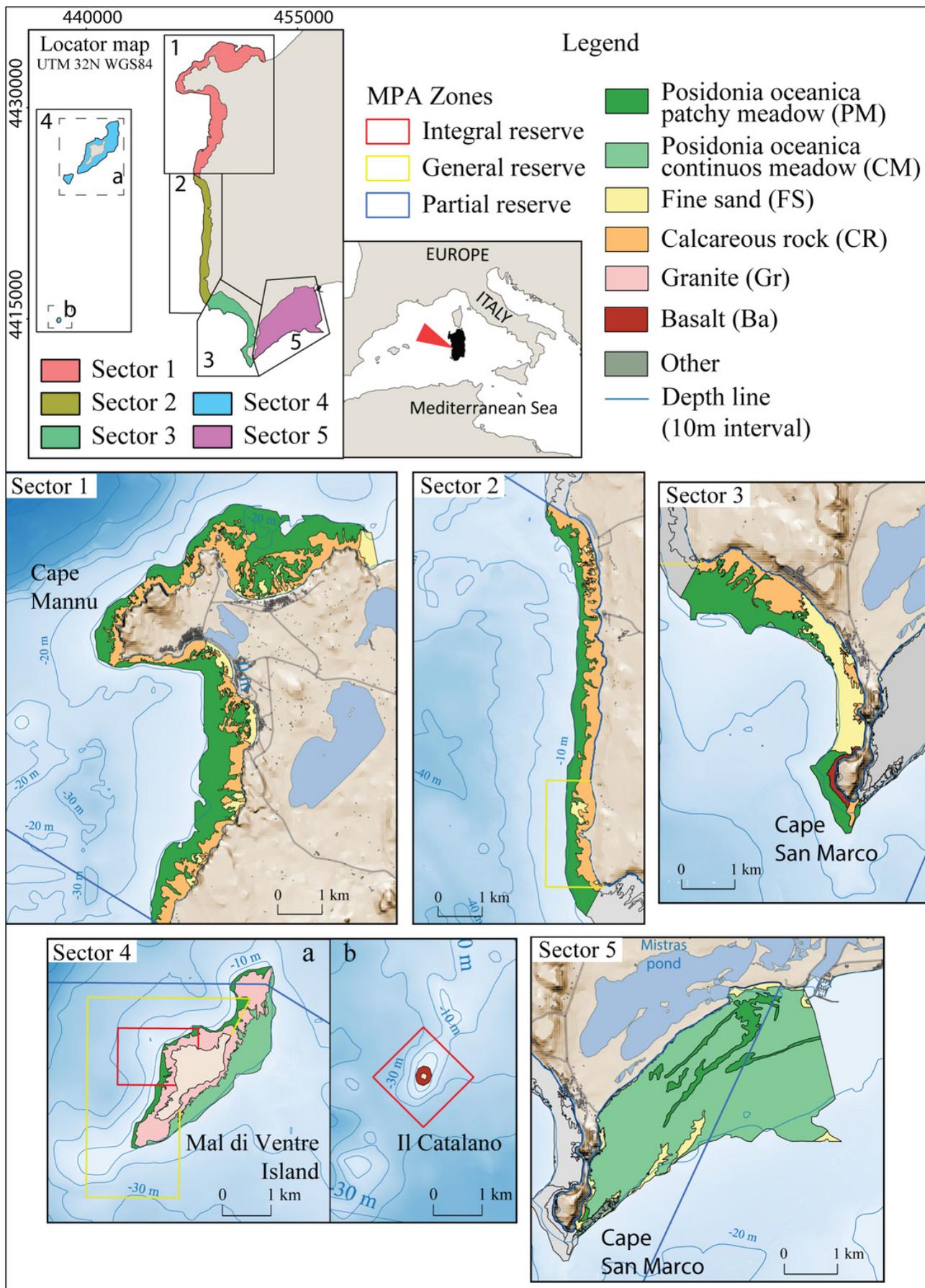
Figure 3

Figure 3. Detailed digital mapping of hydrodynamism in the study area.

Map representing average bottom current speed obtained by the oceanographic model in the area of interest during six months from spawning time to the period of settlement (January-June).

N

Cape
Mannu

Mal di Ventre
Island

Average bottom current speed
(m/sec)

0	0.07	0.13	0.20

Il Catalano

Cape
San Marco

**Gulf of
Oristano**

0   2   4 km

UTM 32N WGS84 Datum
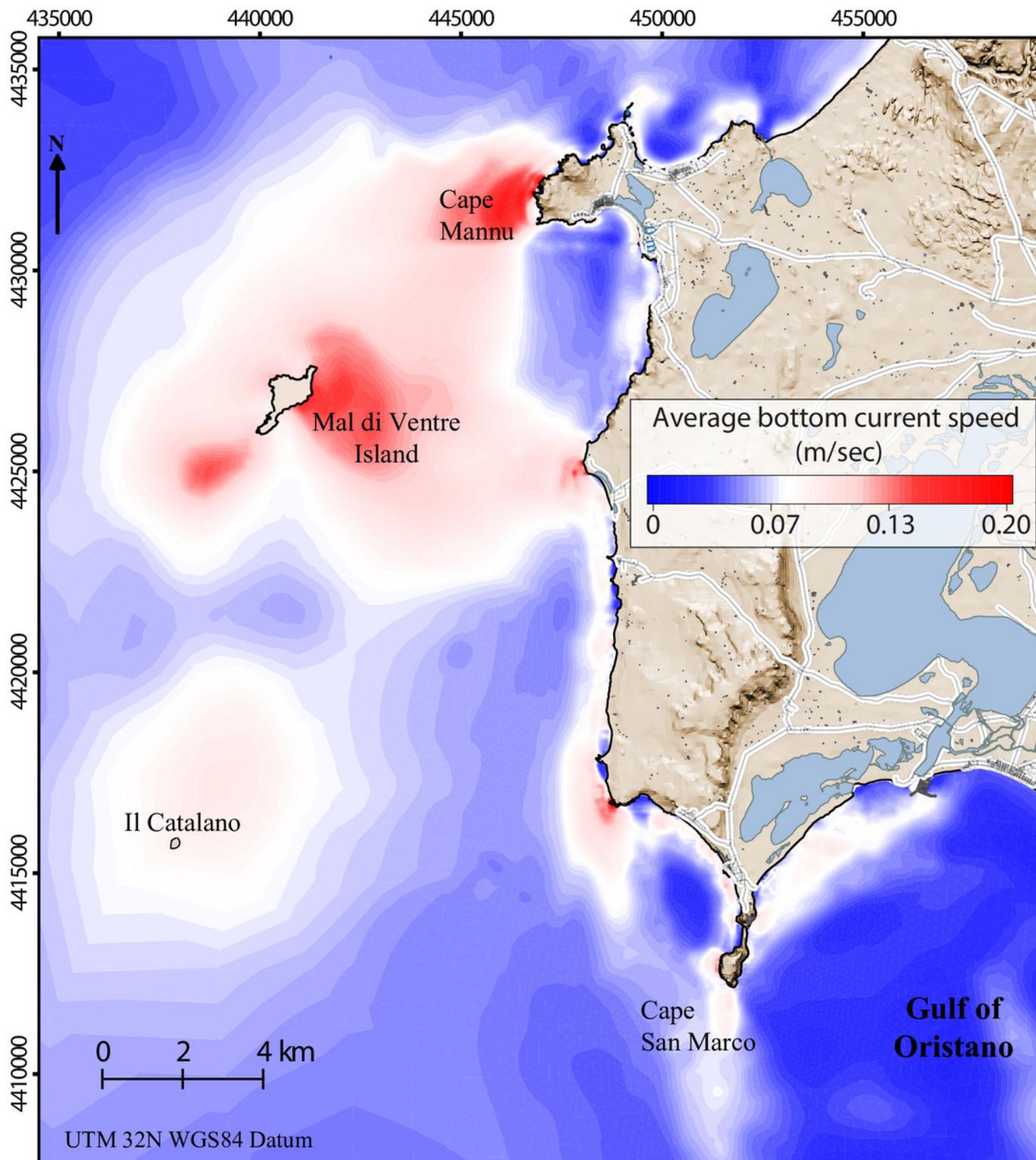
Figure 4

Figure 4. Graph representing different population structures.

Populations of each type of habitat in each sectors: calcareous rock of sector 1(CR-1), patchy meadow of sector 1 (PM-1), calcareous rock of sector 2 (CR-2), patchy meadow of sector 2 (PM-2), calcareous rock of sector 3 (CR-3), patchy meadow of sector 3 (PM-3), basalt of sector 3 (BA-3), granite of sector 4 (GR-4), basalt of sector 4 and continuous meadow of sector 5 (CM-5).

Population structures
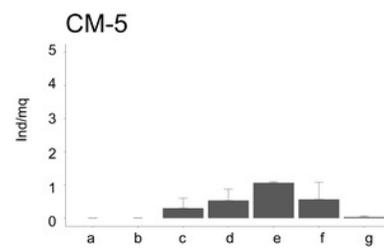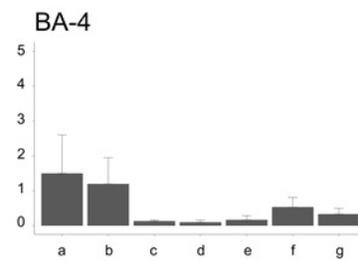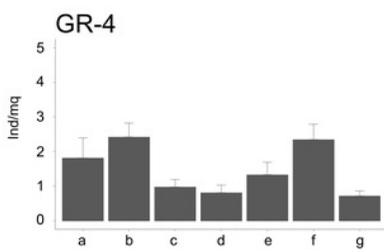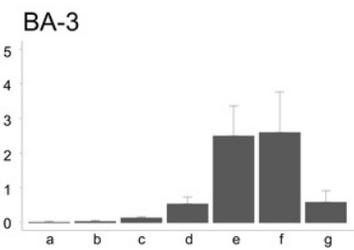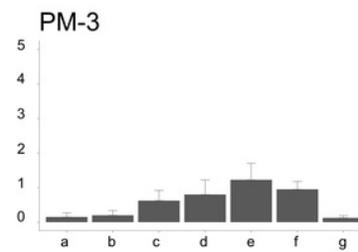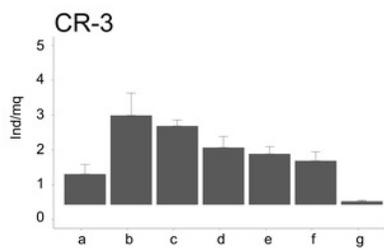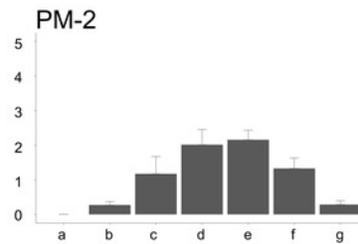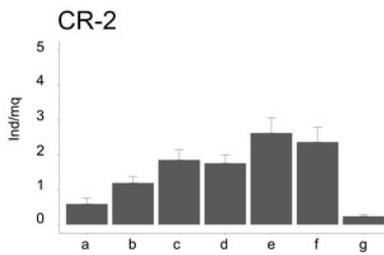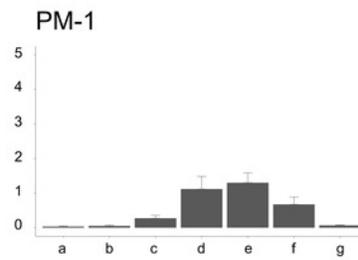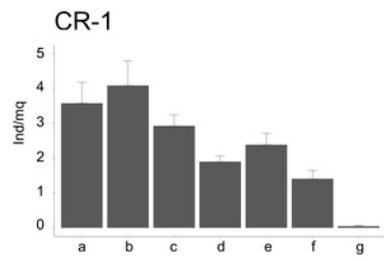
Figure 5

Figure 5. Graphs representing relationships between sea urchin densities and environmental constraints.

In rocky habitat a) density of recruits is correlated with the average bottom current speed (Spearman's rank correlation p-value = 0.02574; *rho* = -0.3184671) and b) densities of middle-size classes with predatory fish densities (Pearson's correlation p-value = 0.04268, *correlation coefficient* = -0.5118654). Number of points used in the graph *a* corresponds to the sea urchin sampling stations while in the graph *b* to the stations of fish visual census.
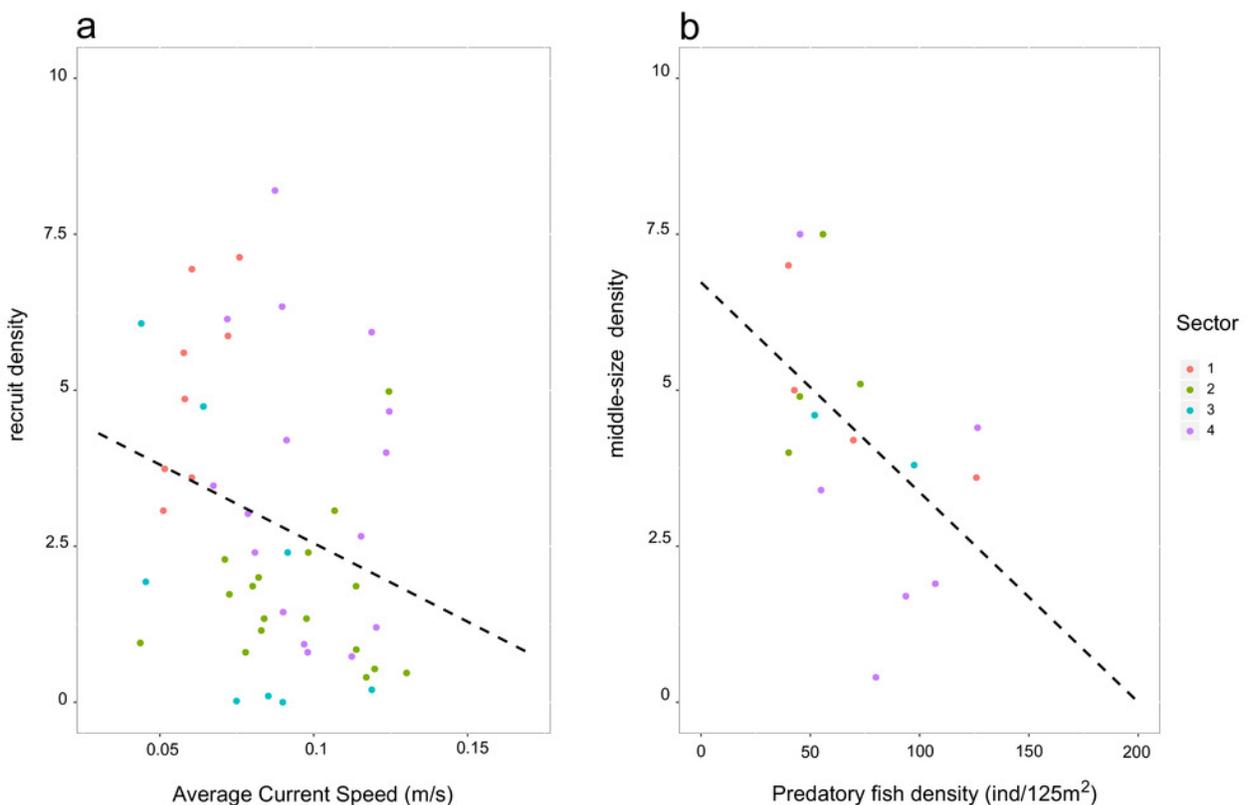
Table 1. Table showing differences among sectors of average bottom current speed and predatory fish density (in sector 5 only one observation was carried out).

1   **Table 1**

Sector	Total area (Km²)	Average Current Speed (m/s)	Average predatory fish (ind/125m²)	Total sea urchin density	Stock proportion (%)
1	12.7	0.05 ±0.003	69.6 ± 20	9.9 ±1.6	15.1 ±2.3
2	5.1	0.09 ±0.004	53.5 ± 7.2	9.5 ±1.0	23.3 ±2.2
3	4.3	0.07 ±0.007	74.8 ± 22.8	7.1 ±1.1	28.7 ±4.7
4	3.8	0.10 ±0.004	84.6 ± 12.6	9.8 ±1.2	27.8 ±3.6
5	11.9	0.07 ±0.003	-	2.5 ±0.2	20.0 ±1.8

Table 2. Spatial configuration of sampled habitats for each study sector. Dash means no samplings were realized.

1 **Table 2**

Sector	Habitat	code	Nº of samplings	Area (Km²)	PD (n/Km²)	P/A ratio (1/m)	MPS (Km²)	LPI (%)	IJI (%)
1	Calcareous Rock	CR-1	12	4.5	1.01	21.1	0.07	3	68.6
	Patchy Meadow	PM-1	12	7.2	0.16	11.0	0.72	5.3	55.3
	Sand		-	1.0	-	-	-	-	-
2	Calcareous Rock	CR-2	15	2.5	0.62	15.2	0.31	17	98.9
	Patchy Meadow	PM-2	7	2.3	0.08	13.2	2.28	17.8	46.3
	Sand		-	0.3	-	-	-	-	-
3	Calcareous Rock	CR-3	5	1.0	0.32	16.2	0.17	4.5	44.6
	Patchy Meadow	PM-3	4	2.0	0.32	10.4	0.33	8.2	61.7
	Basalt	BA-3	4	0.1	3.5	0.3	0.11	0.6	33.9
	Sand		-	1.2	-	-	-	-	-
4	Granite	GR-4	14	1.8	0.02	16.4	1.85	2.9	62.7
	Basalt	BA-4	3	0.1	0.02	21.4	0.08	0.1	0
	Patchy Meadow		-	0.5	-	-	-	-	-
	Cont. Meadow		-	1.4	-	-	-	-	-
5	Cont. Meadow	CM-5	3	11.1	2.6	2.1	3.7	42.6	5.5
	Other		-	0.1	-	-	-	-	-
	Sand		-	0.7	-	-	-	-	-

Table 3. Analysis of variance table of lm model for sea urchin total density in function of
Sector and Habitat as fixed factors.

Results of one-way Anova of rank for recruits (Kruskal-Wallis test), middle-size sea urchins

(lm) and stock (Kruskal-Wallis test) in function of populations. Degree of freedom (df), F-value

(F) and significance level (p-value) are provided for fixed effects. Significant effects are given

in bold. Multiple comparison post hoc test was carried out (see Appendix A4 and A5).

1   **Table 3**

Analysis of variance				
Response variable	*Source*	*df*	*F-value*	*p-value*
Total density	Sector Habitat residuals	4 3 72	2.8474 17.8476	**0.02992** **9.23e^{-09}**
Response variable	*Source*	*df*	*Chi-squared (or F-value)*	*p-value*
Recruit density	Population	9	63.711	**2.569e^{-10}**
Middle-size density			5.6147	**8.522e^{-06}**
Stock density			27.359	**0.00122**

Table 4. Generalized linear model (GLM).

The upper section shows the significant effects of the assessed explanatory variables (determinants) on density of commercial under-sized classes (TD<5cm). Coefficient estimates (Estimate), standard errors (SE), z-values, and significance level (p-value) for variables retained in the best model are provided for fixed effects (explanatory variables). Significant effects are given in bold.

1   **Table 4**

General Linear Model analysis					
Response variable	**Effect**	**Estimate**	**SE**	**z-value**	**P-value**
Sea urchin density	intercept	1.301309	0.288039	4.518	6.25e^{-06}
	MPS	0.310135	0.120982	2.563	**0.0104**
	PD	1.073995	0.201901	5.319	**1.04e^{-07}**
	IJI	0.001116	0.004847	0.230	0.8179
	LPI	-0.011801	0.019027	-0.620	0.5351
	P/A ratio	0.007291	0.015867	0.460	0.6459