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2016. **The role of Italian coastal dunes as carbon sinks and diversity sources. A multi-service perspective.**

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1 **Abstract**

2  
3 Coastal dunes support biodiverse habitats of conservation interest and provide other essential but  
4 often overlooked benefits to society, such as carbon sequestration, thanks to their high soil carbon  
5 accumulation rates. The recently established coastal dune Natura 2000 network in the Italian Adriatic  
6 coast aims at protecting dune habitats diversity, yet its capacity to provide other ecosystem services,  
7 and the potential trade-offs with biodiversity provision have so far not been evaluated. In this paper  
8 we conduct this analysis for a key ecosystem service: carbon storage and sequestration. We i)  
9 quantify soil carbon stocks and sequestration within four coastal dune EU habitat types along the  
10 Adriatic Natura 2000 network; ii) upscale these data to create an inventory of carbon stocks for all  
11 dune Natura 2000 sites in the study area; iii) collate biodiversity data of the selected EU habitat types  
12 using plant diversity measures as surrogates of coastal dune biodiversity and iv) explore the trade-  
13 offs between carbon storage and biodiversity value for the selected habitats. Italian Adriatic coastal  
14 dune Natura 2000 sites sequester 4,998 t of CO<sub>2</sub>e per year, with the majority in wooded dunes.  
15 Wooded dunes showed significantly higher soil carbon density than the other dune habitats, and had  
16 a much greater area, but they were characterized by lower species richness. By contrast, the  
17 endangered fixed dunes, which survive in few residual patches along the study area, showed the  
18 highest plant diversity for both total species richness and dune focal species, but had a much lower  
19 carbon density and extent. Although further analyses of additional services would be desirable for a  
20 more comprehensive assessment, these findings suggest that conservation actions should favor  
21 restoration of the natural dune zonation, since it guarantees both dune species diversity and carbon  
22 storage. The carbon stocks and EU habitat type extents produced in this study constitute the first  
23 systematic inventory for dune systems in the Mediterranean.

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33 **Keywords**

34 Adriatic coast; Habitats Directive; soil carbon storage; CO<sub>2</sub> sequestration; dunes conservation; plant  
35 diversity.

## 36 **1. Introduction**

37

38 Coastal dunes are dynamic systems which provide essential benefits to society, some of which have a  
39 considerable socio-economic impact (Everard et al., 2010; Jones et al., 2011; McLachlan & Brown,  
40 2006; MA, 2005). These systems play a major role for recreation and tourism, being highly valued as  
41 a place of escape and isolation and as a source of mental well-being (Doody, 1997; Houston, 1997;  
42 Nordstrom, 2000). In addition, they provide unique habitat assemblages due to a strong  
43 environmental sea-inland gradient, which supports a highly specialized flora and fauna sharing  
44 relatively few species with other terrestrial ecosystems (Acosta et al., 2009; Martínez et al., 2004).  
45 While services such as coastal defence, groundwater storage and water purification are clearly  
46 recognized and integrated into the coastal management of many sites (French 2001; Rhymes et al.  
47 2015; van Dijk, 1989), rather less is known about supporting ecosystem services such as nutrient  
48 cycling, soil formation and climate regulation (Barbier et al., 2011; Jones et al., 2008). Being an early  
49 successional ecosystem, coastal dunes have a high soil carbon accumulation rate (Jones et al., 2008;  
50 Olf et al., 1993; Rohani et al., 2014), a feature in common with other coastal environments  
51 (Sevink J., 1991). There is increasing interest in the role of “blue carbon” in climate regulation  
52 (Donato et al. 2011; Donato et al., 2012; Mcleod et al., 2011; Nellemann et al., 2009), and  
53 sequestration by marine and coastal ecosystems has been globally quantified as ca. 2 Gt C yr<sup>-1</sup>  
54 (Chmura et al., 2003). Yet, the specific role of carbon storage in dune habitats has been little  
55 explored to date, except in the UK, where both annual CO<sub>2</sub> sequestered and the stock of carbon in  
56 vegetation and soil were estimated for the whole country and changes in value of the carbon  
57 sequestration service were projected under different scenarios of coastal change alteration  
58 (Beaumont et al., 2014). While carbon accumulation rates are very high, the gross contribution of  
59 dune habitats to climate regulation is relatively small due to their low area. However, in the context  
60 of widespread coastal habitat loss and land-use change at fine scale, and within a wider context of  
61 habitat management for multiple benefits, their role in regulating greenhouse gas emissions is worth  
62 taking into consideration (Everard et al., 2010).

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64 Despite the high biodiversity value and numerous benefits provided by coastal dunes, this ecosystem  
65 is among the most threatened both globally (Schlacher et al., 2007) and in the Mediterranean (Rossi  
66 et al., 2013). Human activities in European littoral areas have been intensifying in the course of the  
67 20<sup>th</sup> century (Cori, 1999); consequently, sand dunes across Europe had lost on average 25% of their  
68 extent by 1998, compared to 1900 (EUCC, 1998), with peaks of 80% area loss in some Mediterranean  
69 countries. In order to prevent these and other endangered habitats from further degradation,  
70 European Member States adopted the Council Directive 92/43/EEC (Habitats Directive from now

71 onwards), which lists the habitats of European interest (EU habitat types) and establishes across  
72 Europe an extended network of sites of ecological importance, called Natura 2000.  
73 In Italy, 86.7% of EU coastal habitats currently have an unsatisfactory (bad or inadequate)  
74 conservation status, having suffered a drastic reduction in both extent and ecological quality, mainly  
75 due to urban sprawl (Genovesi et al., 2014). Of the Italian 3,000 km coastline, the Northern and  
76 Central Adriatic sector is probably the most developed and industrialized (with more than 70% of its  
77 seaside urbanized), hosting several international tourist resorts and important port cities, as well as  
78 an intense transportation network (Highway A14, State Road No 16 and railway line) which have  
79 destroyed the natural coastline in many points (Romano & Zullo, 2014). Therefore, in order to  
80 preserve the last intact coastal landscapes in this area, there is a need to study in more detail the role  
81 of Adriatic Natura 2000 sites both for biodiversity protection and their capacity to provide additional  
82 ecosystem services and, in particular, the interplay between those potentially conflicting functions. In  
83 this study we focus on two coastal services: biodiversity protection and carbon storage and  
84 sequestration. We selected carbon storage first because a consistent approach to measure and  
85 assess carbon storage service in coastal dunes is still lacking (Laffoley D. & Grimsditch G., 2009;  
86 Beaumont et al., 2014); and secondly, because of the potential for conflicts with biodiversity  
87 provision, since carbon storage requires stabilised systems while much of the unique dune  
88 biodiversity relies on natural dune dynamics.

89 Thus, the aims of this work were i) to quantify soil carbon storage and sequestration provided by a  
90 set of coastal dune EU habitat types within Natura 2000 network along the Northern and Central  
91 Adriatic Sea; ii) to compare their relative contribution and to create the first inventory of carbon  
92 stocks for the Adriatic Natura 2000 sites; iii) to characterise coastal dune biodiversity value, using  
93 various metrics of plant species richness as a proxy; iv) lastly, to explore the trade-offs between  
94 carbon storage and biodiversity value for the selected habitats and to discuss their relative value in a  
95 multi-service perspective.

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97           **2. Materials and methods**

98

99           **2.1 Selection of EU coastal dune habitat types**

100 For data collection and upscaling we adopted the EU habitat types classification, as it entails spatial  
101 data at sufficient detail to distinguish between habitats but at an appropriate spatial scale and  
102 consistency required for upscaling. The use of more detailed classifications of dune habitats creates  
103 difficulties because dunes usually occur as long, narrow strips following the coastline but they are  
104 mapped at a coarse resolution, which makes it problematic to define fine variation in plant  
105 communities (Acosta et al., 2005; Lucas et al., 2002). Secondly, EU habitat types are standardized and  
106 recognizable across all EU Member States, allowing transferability of these data to other studies  
107 across Europe with the same habitat types. Both factors are important considerations for upscaling  
108 of results. Moreover, all EU habitat types present in Italy have been matched to national  
109 phytosociological types (Biondi et al., 2009), allowing cross-reference with Italian vegetation  
110 classifications, and EU dune habitat types in particular have been already adopted in previous studies  
111 (Berardo et al., 2015; Malavasi et al., 2014; Stanisci et al., 2014).

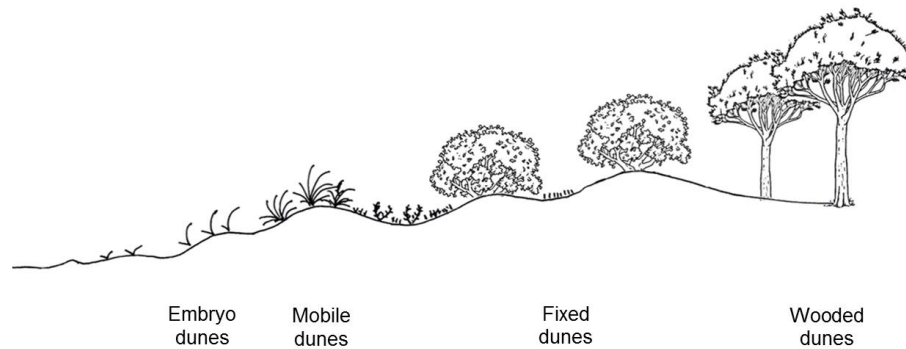
112 Four of the 11 EU coastal dune habitat types (Biondi et al., 2009; Carranza et al., 2008) found in Italy  
113 were characterised in this work: 2110 “Embryonic shifting dunes”, 2120 “Shifting dunes along the  
114 shoreline with *Ammophila arenaria* (‘white dunes’)”, 2250\* “Coastal dunes with *Juniperus* spp.”,  
115 2270\* “Wooded dunes with *Pinus pinea* and/or *Pinus pinaster*” (Table 1). These habitat types were  
116 selected for four main reasons: first, they represent the most common Mediterranean vegetation  
117 zonation, shaped by a harsh sea-inland gradient chiefly determined by variations in substrate and  
118 wind action (Acosta et al., 2003; Frederiksen et al., 2006; Figure 1); secondly, they are present along  
119 the entire Adriatic Natura 2000 network; third, two of them (fixed dunes and wooded dunes) are  
120 priority habitats for conservation at European level; lastly, three of them (embryo dunes, mobile  
121 dunes and fixed dunes) currently are in poor conservation status in Italy (La Posta et al., 2008) and  
122 Europe (European Commission, 2008), requiring urgent protection efforts.

123

124 **Table 1: The selected EU habitat types with their description and the abbreviations used in this manuscript**  
 125 **(EU priority habitats are marked with an asterisk).**

EU habitat type code	EU habitat type name	Habitat description	Abbreviation
2110	Embryonic shifting dunes	Formation of the first sandy drift with <i>Elymus farctus</i>	Embryo dunes
2120	Shifting dunes along the shoreline with <i>Ammophila arenaria</i> ('white dunes')	Seaward and semi-permanent cordons of dune systems dominated by <i>Ammophila arenaria</i>	Mobile dunes
2250*	Coastal dunes with <i>Juniperus</i> spp.	Fixed dunes with pioneer maquis dominated by <i>Juniperus oxycedrus</i> subsp. <i>macrocarpa</i>	Fixed dunes
2270*	Wooded dunes with <i>Pinus pinea</i> and/or <i>Pinus pinaster</i>	Backdunes with forest dominated by <i>Pinus halepensis</i> , <i>P. pinea</i> and <i>P. pinaster</i>	Wooded dunes

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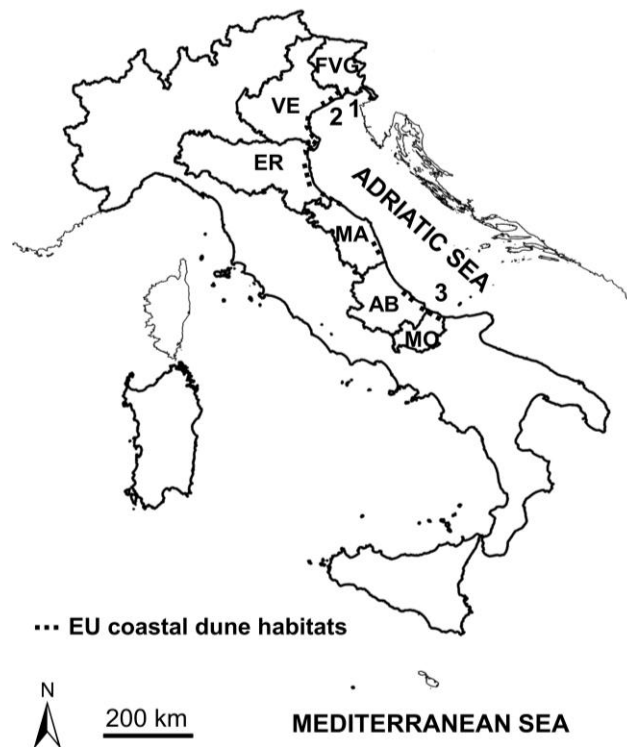
129 **Figure 1: Scheme of a typical Mediterranean coastal dune zonation evidencing the selected EU habitat types.**130 **For habitats abbreviations refer to Table 1. Modified from Prisco et al., 2012 and from [www.midisegni.it](http://www.midisegni.it)**

131

132 **2.2 Distribution of the selected EU habitat types along the Adriatic Natura 2000 network**

133 The Northern and Central Adriatic coastal dune Natura 2000 network is included in six administrative  
 134 regions (from north to south): Friuli-Venezia Giulia, Veneto, Emilia-Romagna, Marche, Abruzzo and  
 135 Molise (Figure 2). The network in this study area extends for 74,014 ha, which is roughly 1% of the  
 136 administrative regions total surface. The four EU sand dune habitat types occupy nearly 3,000 ha of  
 137 the network (Table 2). Emilia-Romagna hosts overall the largest extent of the selected EU sand  
 138 dunes, with nearly 1,800 ha occupied by wooded dunes alone, some of which have historical value  
 139 for the local population (Table 2). Veneto's coastal Natura 2000 network hosts a valuable portion of  
 140 mobile dunes and includes nearly 450 ha of wooded dunes. Fixed dunes are present in scattered  
 141 stations along Friuli-Venezia Giulia and Veneto, disappear in Central Italy and then occur again in the  
 142 southern sector of Molise. Across Marche and Abruzzo Natura 2000 network, there is relatively little  
 143 remaining area of the hind-dune habitats (Table 2). Overall, while embryo and mobile dunes occur  
 144 throughout the study area, wooded dunes are particularly widespread in the last sector of Po Plain  
 145 (between Veneto and Emilia-Romagna), due to pine afforestation occurred from the late 19<sup>th</sup> century  
 146 to the post WW II in order to protect inland crops (CFS, 2004; Curr et al., 2000). Fixed dunes instead  
 147 have a far more scarce distribution, with the most widespread intact patch occurring in Molise (20  
 148 ha).

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151

152 **Figure 2: Study area. Administrative regions included in the study are Friuli-Venezia Giulia (FVG), Veneto**  
 153 **(VE), Emilia-Romagna (ER), Marche (MA), Abruzzo (AB) and Molise (MO). The dotted lines show the**  
 154 **distribution of the EU coastal dune habitats in the study area. Soil samples were collected in three Natura**  
 155 **2000 sites, marked with numbers: 1: IT3330006 “Val Cavanata e Banco Mula di Muggia”; 2: IT3250033**  
 156 **“Laguna di Caorle - Foce del Tagliamento”; 3: IT7222217 “Foce Saccione - Bonifica Ramitelli”.**

157

158 **Table 2: Extent in hectares of the four EU sand dune habitat types within the Adriatic coastal Natura 2000**  
 159 **network, split by administrative region.**

EU habitat type	Friuli-Venezia Giulia	Veneto	Emilia Romagna	Marche	Abruzzo	Molise	Adriatic coastal N2000 network
Embryo dunes	30.00	47.19	84.86	18.77	2.24	31.02	214.08
Mobile dunes	63.47	101.61	48.43	0.60	5.10	20.26	239.47
Fixed dunes	10.94	16.13	0.64	-	-	20.60	48.31
Wooded dunes	49.60	442.69	1,775.48	-	2.01	95.03	2,364.81
Total	154.01	607.61	1,909.41	19.37	9.35	166.91	2,866.66

160

### 161 2.3 Soil sample collection and treatment

162 Seventy soil samples were collected across three Natura 2000 sites along the Northern and Central  
 163 Adriatic coast (Figure 2). The three sites are: “Val Cavanata e Banco Mula di Muggia”, in Friuli-  
 164 Venezia Giulia (13.43°E, 45.68°N), “Laguna di Caorle - Foce del Tagliamento” in Veneto (13.09°E,  
 165 45.62°N) and “Foce Saccione - Bonifica Ramitelli” in Molise (15.10°E, 41.93°N). The selected Natura  
 166 2000 sites are representative of the latitudinal gradient along Adriatic coast. The habitat type classes



167 were identified on the ground based on a detailed cartography produced for Natura 2000 sites  
168 management plans (for “Val Cavanata e Banco Mula di Muggia”, see Regione Autonoma Friuli-  
169 Venezia Giulia, 2012; for “Laguna di Caorle - Foce del Tagliamento”, see  
170 <http://www.regione.veneto.it/web/ambiente-e-territorio/rete-natura-2000-download>; for “Foce  
171 Saccione - Bonifica Ramitelli”, see Berardo et al., 2012).

172 For each soil sample, a 15 cm-deep core with 5 cm diameter was collected and its geographic  
173 location was recorded with a GPS. Organic profile depth was measured directly in the field. In a few  
174 cases, due to fieldwork constraints, samples were only 10 cm deep but, even so, they included the  
175 full organic profile. Subsequently in the laboratory, all samples were weighed (fresh weight), all roots  
176 and vegetation were removed and then the soils were homogenized following standard procedures.  
177 Next, moisture content was determined by drying subsamples at oven temperature of 105° for 24 h  
178 and reweighing them (MAFF, 1986); pH of the fresh soil was measured in deionised water (1:2.5).  
179 Then, organic matter content was estimated for all samples through Loss On Ignition (LOI) method,  
180 at 375°C for 16 h. The oven temperature of 375°C is sufficient to combust organic matter without  
181 dissociating too much CO<sub>2</sub> from the carbonates (Ball, 1964).

182 Percentage C was directly measured on a subset of 46 samples chosen from the various habitats, by  
183 combustion on a Carlo Erba CSN analyser, after acidification with 1M HCl to gradually remove  
184 carbonates. Then, the results from %LOI and %C were compared and a regression equation was  
185 computed with no intercept, in order to predict the ratio between %C and %LOI for all the samples  
186 collected. A simple linear regression equation (given in Equation 1 below, R<sup>2</sup> = 0.9022) gave the best  
187 prediction; adding soil pH as an additional variable did not improve the relationship.

$$188 \quad \text{Percentage of organic carbon} = 0.4946 \text{ LOI} \quad (1)$$

189 Once the estimates of carbon content were obtained for all the samples from Equation (1), soil C  
190 density was also derived. Bulk density was computed from fresh soil weight, %moisture and core  
191 volume. Soil carbon stocks per unit area (expressed as carbon tonnes per hectare) at sample depth  
192 were computed from the estimated carbon content through Equation (1), fresh soil weight,  
193 %moisture and core area.

194 Since data were not normally distributed, non-parametric two-tailed Kruskal-Wallis statistical tests  
195 with Mann-Whitney pairwise comparisons were performed on bulk density, soil %C and soil C density  
196 in order to explore differences among the four habitat types and bare sand (taken as reference  
197 value).

198 Carbonate content was measured on a subset of oven-dried samples (n = 13) from bare sand and  
199 wooded dunes, using the gravimetric method (Bauer et al., 1972), applying 5M HCl to gradually  
200 remove carbonates.

201

## 2.4 Conversion to carbon sequestration and upscaling of carbon values

202 Carbon stock refers to carbon stored in the biosphere; carbon sequestration is the rate of capture  
203 and long-term storage of atmospheric carbon dioxide (CO<sub>2</sub>) (Beaumont et al., 2014).  
204 Rates of long-term carbon sequestration were estimated from a study on land cover change in  
205 coastal Molise which compared land cover maps for the years 1954, 1986 and 2006, focusing on  
206 changes in the spatial pattern of coastal dune cover types in relation to the anthropogenic ones  
207 (Malavasi et al., 2013). From comparison among the multi-temporal ortho-photographs, it was  
208 possible to deduce that the pine plantation present in the Natura 2000 site “Foce Saccione - Bonifica  
209 Ramitelli” (Figure 2) was planted after 1954. Assuming a constant sequestration rate and that  
210 reforestation took place in 1960, the soil carbon stock measured in wooded dunes was divided by its  
211 presumed age (55 years) to obtain an estimate of the annual rate of carbon sequestration into soil.  
212 The same age was assumed for the other three dune habitats as there was no information from  
213 which to assess their age. Subsequently, CO<sub>2</sub> sequestration rates were calculated for each habitat  
214 using IPCC conversion factor: 1 t C = 3.67 t CO<sub>2</sub>.  
215 Mean carbon stock and sequestration values were scaled up to the total extent of coastal dune  
216 habitats in the Adriatic Natura 2000 network (Table 2), by multiplying the average per hectare carbon  
217 values and their standard deviations by the total habitat extents. The habitats extents of each Natura  
218 2000 site were collated from multiple sources, since no single source of this information is available.  
219 The 2012 and 2013 official Natura 2000 Standard data forms for each site, downloadable from the  
220 portal of the Italian Ministry of the Environment  
221 ([ftp://ftp.dpn.minambiente.it/Natura2000/TrasmissionECE\\_2013/schede\\_mappe](ftp://ftp.dpn.minambiente.it/Natura2000/TrasmissionECE_2013/schede_mappe)), were adopted as  
222 primary data source. Where the extents reported in the data forms were inaccurate or obsolete, they  
223 were derived from Natura 2000 sites management plans reports, regional cartography or  
224 unpublished studies, based on an accurate and systematic case-by-case research.  
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## 2.5 Biodiversity value of coastal dune habitat types

In order to compare the biodiversity value of the EU coastal dune habitat types with their carbon sequestration value, three plant diversity measures were adopted as possible indicators. Vascular plant species and vegetation in fact are considered good indicators of overall biodiversity and specifically of ecosystem integrity of coastal dune systems (Araújo et al., 2002; Carboni et al., 2009). The three measures are a) the number of endangered plant taxa, b) the number of focal plant taxa (those which are crucial in determining ecosystem functioning and structure (Santoro et al. 2012a)) and c) the vascular flora richness. The number of endangered plant taxa was derived from a recent study evaluating the occurrence of regionally endangered and rare (of biogeographical interest) species along the Central Adriatic coast (Stanisci et al., 2007). The number of focal plant taxa was obtained from the Italian Interpretation Manual of the 92/43/EEC Directive habitats, available from <http://vnr.unipg.it/habitat/index.jsp> (Biondi et al., 2009) and limited to the taxa present along Central Adriatic coast (Del Vecchio et al., 2013; Del Vecchio et al., 2015). The focal taxa checklist is reported in the Appendix. Lastly, vascular flora richness was assessed as the average number of vascular plants per plot, from a field survey carried out along Central Adriatic coast in 2007. Plant species data were collected following a random stratified sampling design where the number of plots (squared sampling units of 8 m x 8 m) was proportional to the total surface of each habitat, resulting in the following distribution: 33 plots on embryo dunes, 22 on mobile dunes, 12 on fixed dunes and 25 on wooded dunes (see also Acosta et al., 2009). Non-parametric two-tailed Kruskal-Wallis tests with Mann-Whitney pairwise comparisons were performed to test for statistical differences in richness of vascular plants per plot among habitat types.

250 **3. Results**

251

252 **3.1 Soil characteristics**

253 All habitats showed a high pH, ranging from 8.35 (wooded dunes) to 8.85 (mobile dunes) on average  
 254 (Table 3). The carbonate results suggest Adriatic sand dunes have high carbonate content, averaging  
 255 33% in bare sand. The percentage of carbonate in wooded dunes showed a greater variability than in  
 256 bare sand (Table 3).

257 Results for bulk density, soil %C and soil C density are reported in Table 3. Kruskal-Wallis tests  
 258 applied on these parameters revealed a clear statistical difference ( $P < 0.001$ ) between wooded  
 259 dunes and all the other habitats. While soil %C and soil C density are much higher in wooded dunes  
 260 than in the other habitat types, bulk density is consistently lower in wooded dunes compared to the  
 261 other habitats. There was high variation in the wooded dunes results in all parameters, because  
 262 some areas sampled within this habitat type include low-lying depressions, often in contact with the  
 263 water table where fine sediments accumulate. Bare sand bulk density was significantly higher than  
 264 wooded dunes but lower ( $P < 0.05$ ) than embryo and mobile dunes bulk densities. Fixed dunes didn't  
 265 differ from embryo dunes, mobile dunes and bare sand for bulk density. There was no statistical  
 266 difference in soil C density or soil %C between embryo dunes and mobile dunes, and between fixed  
 267 dunes and bare sand. Embryo dunes showed the lowest value for both measures. Fixed dunes and  
 268 bare sand were significantly higher than embryo and mobile dunes for both soil C density and soil %C  
 269 ( $P < 0.05$ ).

270

271 **Table 3: Bulk density, soil %C, soil C density and pH for the four EU sand dune habitat types considered and**  
 272 **for bare sand. *N* is the number of samples collected for each habitat type. Percentage of carbonate (% CaCO<sub>3</sub>)**  
 273 **is based on 13 samples. All values are reported as mean ± s.d. Letters represent homogenous subsets**  
 274 **according to Kruskal-Wallis tests.**

EU habitat type	<i>N</i>	Bulk density (g cm <sup>-3</sup> )	Soil %C	Soil C density (g cm <sup>-3</sup> )	pH (H <sub>2</sub> O)	% CaCO <sub>3</sub>
Embryo dunes	10	1.606 ± 0.057 <sup>a</sup>	0.131 ± 0.053 <sup>a</sup>	0.0021 ± 0.0008 <sup>a</sup>	8.64 ± 0.55	-
Mobile dunes	20	1.577 ± 0.107 <sup>a</sup>	0.148 ± 0.119 <sup>a</sup>	0.0023 ± 0.0016 <sup>a</sup>	8.85 ± 0.25	-
Fixed dunes	10	1.547 ± 0.084 <sup>ab</sup>	0.179 ± 0.066 <sup>b*</sup>	0.0027 ± 0.0009 <sup>b*</sup>	8.56 ± 0.35	-
Wooded dunes	20	1.088 ± 0.362 <sup>c**</sup>	2.838 ± 2.556 <sup>c**</sup>	0.0227 ± 0.0120 <sup>c**</sup>	8.35 ± 0.47	23.14 ± 13.80
<i>bare sand</i>	10	1.527 ± 0.055 <sup>b*</sup>	0.196 ± 0.125 <sup>b*</sup>	0.0029 ± 0.0019 <sup>b*</sup>	8.79 ± 0.48	33.42 ± 3.17

275 \*:  $P < 0.05$ ; \*\*:  $P < 0.001$ .

276

277 **3.2 Carbon storage and sequestration**

278 Soil carbon per ha and total soil carbon stocks of the whole Adriatic coastal dune Natura 2000  
 279 network, split by habitat type, are reported in Table 4. For each tonne of soil carbon stock per ha in  
 280 embryo, mobile and fixed coastal dunes there are about 10 tonnes in the soil of wooded dunes.  
 281 Multiplying unitary carbon stock for each total coastal dune habitat type surface within the Adriatic  
 282 coastal Natura 2000 network (Table 2), the ratio between wooded dunes and natural (embryo,  
 283 mobile and fixed dunes) becomes much greater, owing to wooded dunes having a much larger extent  
 284 along the study area. Taking into account the mean values of carbon stored along Adriatic coastline,  
 285 the total coastal dune soil carbon sink amounts to nearly 75,000 t (Table 4).  
 286 The estimates of average unitary sequestration rates are reported in Table 4. While mean carbon  
 287 sequestration rates provided by natural dunes are quite comparable (from 5.57 g m<sup>-2</sup> yr<sup>-1</sup> of mobile  
 288 dunes to 7.49 g m<sup>-2</sup> yr<sup>-1</sup> of fixed dunes), mean carbon sequestration rate provided by wooded dunes  
 289 is ten times greater (56.35 g m<sup>-2</sup> yr<sup>-1</sup>). The overall estimated mean CO<sub>2</sub> sequestration capacity of the  
 290 Northern and Central Adriatic coastal dunes is almost 5,000 t per year (Table 4).

291

292 **Table 4: Estimated unitary soil organic carbon content, total soil organic carbon stocks, unitary soil organic**  
 293 **carbon sequestration rates and total CO<sub>2</sub> sequestration rates of the selected EU sand dune habitat types**  
 294 **present in the Adriatic Natura 2000 network. All values are reported as mean ± s.d.**

EU habitat type	Soil C (t ha <sup>-1</sup> )	Soil C stock (t)	C seq rate (g m <sup>-2</sup> yr <sup>-1</sup> )	C seq rate (t CO <sub>2</sub> yr <sup>-1</sup> )
Embryo dunes	3.14 ± 1.25	672 ± 268	5.72 ± 2.28	45 ± 18
Mobile dunes	3.06 ± 1.71	733 ± 409	5.57 ± 3.10	49 ± 27
Fixed dunes	4.12 ± 1.41	199 ± 68	7.49 ± 2.56	13 ± 5
Wooded dunes	30.99 ± 19.71	73,285 ± 46,610	56.35 ± 35.83	4,890 ± 3,110
Adriatic coastal N2000 network		74,889 ± 46,613		4,998 ± 3,110

295

296

297 **3.3 Biodiversity value of EU coastal dune habitat types**

298 The fixed dunes have the highest number of endangered dune taxa. Wooded dunes come second,  
 299 while embryo and mobile dunes show lower numbers (Table 5). With respect to the number of focal  
 300 plant taxa, fixed dunes and wooded dunes have similar numbers while embryo dunes and mobile  
 301 dunes have lower numbers but are similar to each other. Regarding the vascular flora richness,  
 302 expressed by the average number of recorded taxa by plot, fixed dunes, embryo dunes and mobile  
 303 dunes host higher plant diversity than wooded dunes, with fixed dunes being the richest habitat type  
 304 (Table 5). Kruskal-Wallis tests applied to the number of taxa collected in each habitat type revealed  
 305 highly significant differences ( $H = 21.06, P < 0.001$ ). In particular, the number of taxa in wooded

306 dunes was significantly lower than in fixed and in mobile dunes ( $P < 0.001$ ) and in embryo dunes ( $P <$   
 307  $0.05$ ). The embryo dunes showed significantly fewer taxa than fixed and mobile dunes.  
 308 No significant difference was revealed between fixed and mobile dunes.

309

310 **Table 5: Measures of plant diversity. Sources of data: (a) Stanisci et al., 2007; (b) Biondi et al., 2009; Del**  
 311 **Vecchio et al., 2013; 2015; (c) Acosta et al., 2009. Habitat types with the same letters are not statistically**  
 312 **different (Kruskal-Wallis test)**

EU habitat type	N endangered taxa <sup>(a)</sup>	N focal taxa <sup>(b)</sup>	Average N taxa by plot <sup>(c)</sup>
Embryo dunes	7	10	13.70 <sup>a</sup>
Mobile dunes	8	10	16.95 <sup>b*</sup>
Fixed dunes	13	13	17.75 <sup>b*</sup>
Wooded dunes	11	13	11.92 <sup>c**</sup>

\*:  $P < 0.05$ ; \*\*:  $P < 0.001$ .

313

### 3.4 Carbon storage and biodiversity along the Adriatic Natura 2000 sites

314 Using the mean values of soil carbon per ha, carbon values for the selected habitat types within each  
 315 coastal dune Natura 2000 site in the study area were calculated. The values are reported in Table 6,  
 316 along with Natura 2000 site official names, Natura 2000 codes, the administrative region they  
 317 belong, the site current status and the updated and cross-referenced extents for each site and  
 318 habitat type.

319 Figure 3 depicts soil carbon storage and dune habitat diversity provided by each of the selected  
 320 Natura 2000 sites. To clearly express the biodiversity value of each Natura 2000 site, a value from 1  
 321 to 4 is assigned, according to the total number of coastal dune habitat types present in the site,  
 322 among those analysed in this study. Total carbon values range from 1 t (site “Valle Cavanata e Banco  
 323 Mula di Muggia”) to 14,682 t (site “Pineta di Classe”). The richest coastal dune Natura 2000 sites for  
 324 soil carbon are located in the Central sector of Adriatic, precisely in Emilia-Romagna. Other hotspots  
 325 for carbon storage in the study area are the site “Laguna di Caorle foce Tagliamento” and the site  
 326 “Delta del Po: tratto terminale e delta veneto”, both in Veneto region. Instead, the coastal dune  
 327 Natura 2000 sites of Marche and Abruzzo include the smallest carbon sinks. Lastly, the Natura 2000  
 328 sites of Molise and Friuli-Venezia Giulia represent valuable carbon pools which cover most of the  
 329 regional coastal area in both cases. As to dune habitat richness, the most diverse area is Veneto  
 330 region, with four sites comprising all the selected habitat types. Other Natura 2000 sites including the  
 331 four habitats are located in Emilia-Romagna and Molise. Marche and Abruzzo do not contain any  
 332 Natura 2000 site counting all four habitat types. Considering both services, the Northern Adriatic  
 333 coast includes the richest coastal dune Natura 2000 sites for biodiversity and carbon storage, with a

334 peak in the site “Ortazzo, Ortazzino, Foce del Torrente Bevano” (four habitats and more than 6,000 t  
335 of carbon stored), followed by the site “Delta del Po: tratto terminale e delta veneto” (four habitats  
336 and 4,597 t carbon). Instead, the least dune carbon and biodiversity rich areas are the central regions  
337 of Marche and Abruzzo, where none of the sites include all dune habitats. Last, the southern part of  
338 the study area, represented by the three Natura 2000 sites of Molise, is a very relevant diversity  
339 source as it includes the greatest area of fixed dunes, while it is relatively less significant for carbon  
340 storage.

341 **Table 6: List of the coastal dune Natura 2000 sites (S) along the Northern and Central Adriatic coast comprising the selected EU habitat types. For each site, identified by**  
342 **its official name and code according to Habitats Directive, the administrative region, the status, the total area, the extent of the coastal dune EU habitat types included**  
343 **and their contribution as soil carbon sinks (mean values) are reported. For administrative regions abbreviations, refer to Figure 2.**  
344 **Status acronyms: SCI: Site of Community Importance; SPA: Special Protection Area; SAC: Special Area of Conservation.**

S	Site code	Natura 2000 site name	Region	Status	Area (ha)	EU habitat type area (ha)				Dune soil C stock (t)			
						Embryo	Mobile	Fixed	Wooded	Embryo	Mobile	Fixed	Wooded
S1	IT3320037	Laguna di Marano e Grado	FVG	SAC/SPA	16,364	30	63.26	-	-	94.29	193.77	-	-
S2	IT3320038	Pineta di Lignano	FVG	SCI	118	-	-	10.94	49.6	-	-	45.07	1,537.2
S3	IT3330006	Valle Cavanata e Banco Mula di Muggia	FVG	SAC/SPA	860	-	0.21	-	-	-	0.64	-	-
S4	IT3250032	Bosco Nordio	VE	SCI/SPA	157	-	-	0.25	16.75	-	-	1.03	519.12
S5	IT3270017	Delta del Po: tratto terminale e delta veneto	VE	SCI	25,362	30.67	58.8	15.06	137.42	96.4	180.1	62.05	4,258.92
S6	IT3270003	Dune di Donada e Contarina	VE	SCI	105	-	-	-	26.06	-	-	-	807.65
S7	IT3270005	Dune fossili Ariano Polesine	VE	SCI	101	-	-	-	0.28	-	-	-	8.52
S8	IT3250034	Dune residue Bacucco	VE	SCI	13	0.36	4.46	-	-	1.13	13.66	-	-
S9	IT3250040	Foce Tagliamento	VE	SPA	280	2.22	3.09	-	70.62	6.98	9.46	-	2,188.66
S10	IT3250013	Laguna del Mort e Pinete di Eraclea	VE	SCI	214	-	3.35	-	29.99	-	10.26	-	929.45
S11	IT3250033	Laguna di Caorle foce Tagliamento	VE	SCI	4,386	7.35	6.61	0.78	148.99	23.1	20.25	3.19	4,617.5
S12	IT3250023	Lido di Venezia: biotopi litoranei	VE	SCI/SPA	166	8.3	21.48	-	49.8	26.09	65.79	-	1,543.4
S13	IT3250003	Penisola del Cavallino: biotopi litoranei	VE	SCI/SPA	315	0.51	6.91	0.04	33.4	1.6	21.17	0.16	1,035.13
S14	IT3250041	Valle Vecchia Zumelle Bibione	VE	SPA	2,089	8.43	5.38	0.78	79.3	26.5	16.48	3.19	2,457.67
S15	IT4070002	Bardello	ER	SCI/SPA	100	-	-	-	0.09	-	-	-	2.79
S16	IT4060015	Bosco della Mesola, Bosco Panfilia, Bosco di Santa Giustina, Valle Falce, La Goara	ER	SCI/SPA	1,563	-	-	-	45.55	-	-	-	1,411.69
S17	IT4060007	Bosco di Volano	ER	SCI/SPA	400	2.32	2.32	-	80.97	7.29	7.11	-	2,509.42
S18	IT4060012	Dune di San Giuseppe	ER	SCI/SPA	73	0.15	0.36	-	-	0.47	1.1	-	-
S19	IT4070009	Ortazzo, Ortazzino, Foce del Torrente Bevano	ER	SCI/SPA	1,255	23.12	7.17	0.2	197.09	72.67	21.96	0.82	6,108.21
S20	IT4070006	Pialassa dei Piomboni, Pineta di Punta Marina	ER	SCI/SPA	464	2	2.21	-	118.02	6.29	6.77	-	3,657.68
S21	IT4070004	Pialasse Baiona, Risega e Pontazzo	ER	SCI/SPA	1,596	-	-	-	9.7	-	-	-	300.62
S22	IT4070005	Pineta di Casalborsetti, Pineta Staggioni, Duna di Porto Corsini	ER	SCI/SPA	578	5.29	0.68	-	176.86	16.63	2.08	-	5,481.25
S23	IT4070008	Pineta di Cervia	ER	SCI	194	0.34	0.06	0.44	102.88	1.07	0.18	1.81	3,188.46



S24#	IT4070010	Pineta di Classe	ER	SCI/SPA	1,082	-	-	-	473.72	-	-	-	14,681.53
S25#	IT4070003	Pineta di San Vitale, Bassa del Pirottolo	ER	SCI/SPA	1,222	-	-	-	380.99	-	-	-	11,807.64
S26#	IT4060005	Sacca di Goro, Po di Goro, Valle Dindona, Foce del Po di Volano	ER	SCI/SPA	4,872	28.94	12.75	-	15.76	90.96	39.05	-	488.43
S27#	IT4060004	Valle Bertuzzi, Valle Porticino-Cannevié	ER	SCI/SPA	2,691	-	-	-	3.69	-	-	-	114.36
S28#	IT4060003	Vene di Bellocchio, Sacca di Bellocchio, Foce del Fiume Reno, Pineta di Bellocchio	ER	SCI/SPA	2,244	22.7	22.88	-	170.16	71.35	70.08	-	5,273.6
S29☞	IT5310024	Colle San Bartolo e litorale pesarese	MA	SPA	4,031	6.05	0.4	-	-	19.02	1.23	-	-
S30☞	IT5310007	Litorale della Baia del Re	MA	SCI	17	5.96	0.2	-	-	18.73	0.61	-	-
S31☞	IT5340001	Litorale di Porto d'Ascoli	MA	SCI/SPA	109	6.76	-	-	-	21.25	-	-	-
S32‡	IT7140109	Marina di Vasto	AB	SCI	57	1.25	3.1	-	2.01	3.93	9.5	-	62.29
S33‡	IT7140108	Punta Aderci - Punta della Penna	AB	SCI	317	0.99	2	-	-	3.11	6.13	-	-
S34¥	IT7222216	Foce Biferno - Litorale di Campomarino	MO	SCI	817	8.87	1.06	-	43.72	27.88	3.25	-	1,354.97
S35¥	IT7222217	Foce Saccione - Bonifica Ramitelli	MO	SCI	870	8.43	9.13	20.59	3.31	26.5	27.97	84.83	102.58
S36¥	IT7228221	Foce Trigno - Marina di Petacciato	MO	SCI	747	13.72	10.07	-	48	43.12	30.84	-	1,487.62
<b>Totals</b>					<b>75,829</b>	<b>224.73</b>	<b>247.94</b>	<b>49.07</b>	<b>2,514.73</b>	<b>706.33</b>	<b>759.44</b>	<b>202.17</b>	<b>77,936.36</b>

345 **Sources adopted for obtaining the extents of Natura 2000 sites and habitat types: # (S15,S16,S17,S18,S19,S20,S21,S22,S23,S24,S25,S26,S27,S28):**

346 <http://ambiente.regione.emilia-romagna.it/parchi-natura2000/consultazione/dati>; § (S4,S5,S6,S7,S8,S9,S10,S11,S13,S14): [http://www.regione.veneto.it/web/ambiente-e-](http://www.regione.veneto.it/web/ambiente-e-territorio/rete-natura-2000-download)

347 [http://www.regione.veneto.it/web/ambiente-e-](http://www.regione.veneto.it/web/ambiente-e-territorio/rete-natura-2000-download)

348 [ftp://ftp.dpn.minambiente.it/Natura2000/TrasmissionECE\\_2013/schede\\_mappe](http://ftp.dpn.minambiente.it/Natura2000/TrasmissionECE_2013/schede_mappe); ☞ (S1,S2,S12,S29,S30,S31): Natura 2000 Standard data forms 2013

349 [ftp://ftp.dpn.minambiente.it/Natura2000/TrasmissionECE\\_2013/schede\\_mappe](http://ftp.dpn.minambiente.it/Natura2000/TrasmissionECE_2013/schede_mappe); ¥ (S34,S35,S36): Berardo et al., 2012; ‡ (S32,S33): de Chiro, 2014; ∞ (S3): Regione

350 **Autonoma Friuli-Venezia Giulia, 2012.**

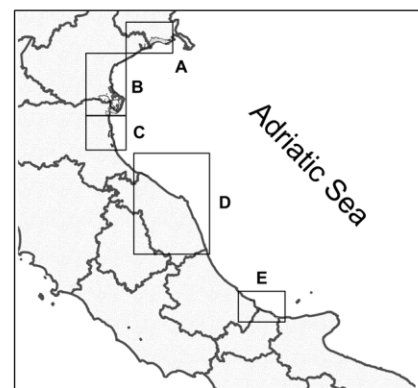
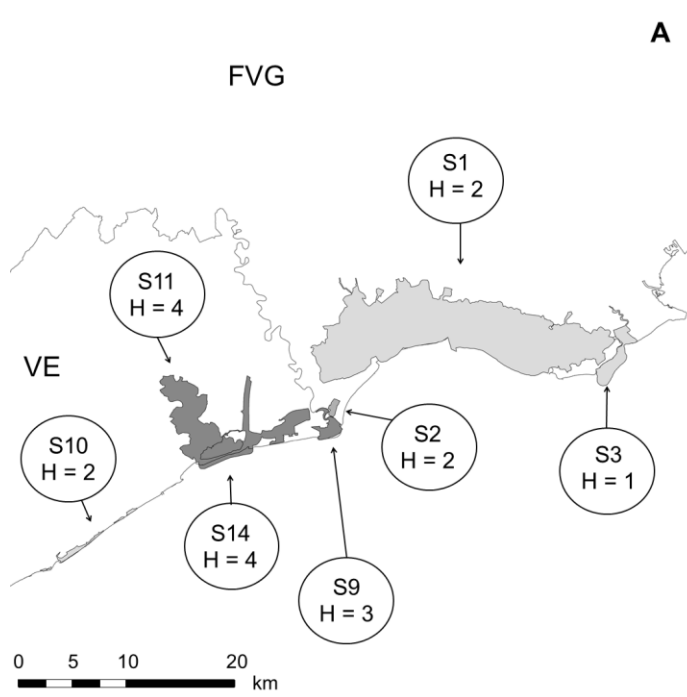
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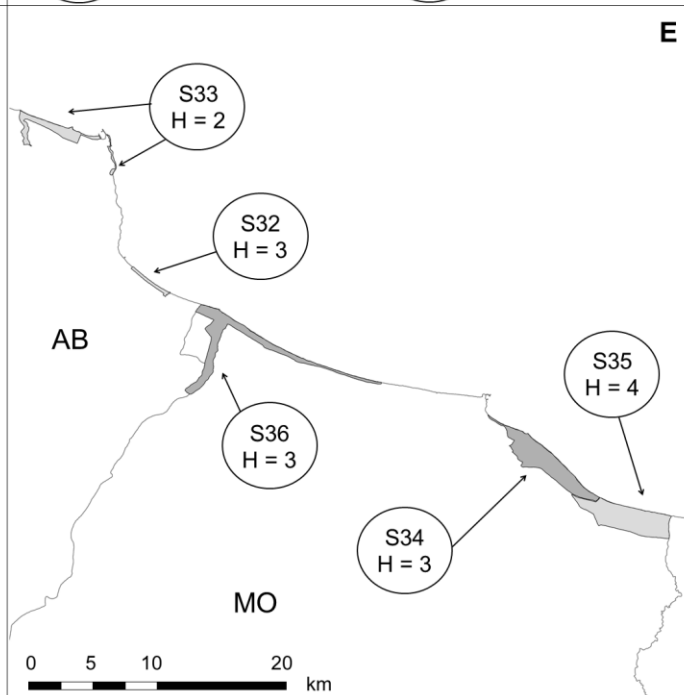
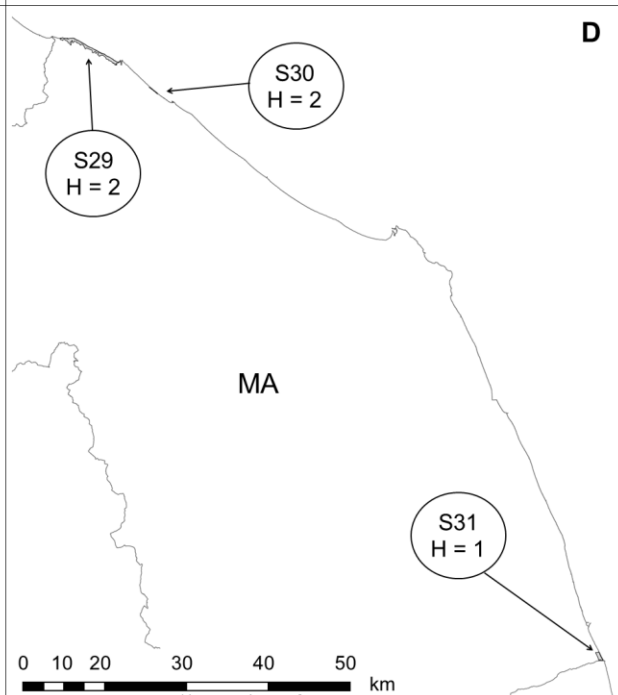
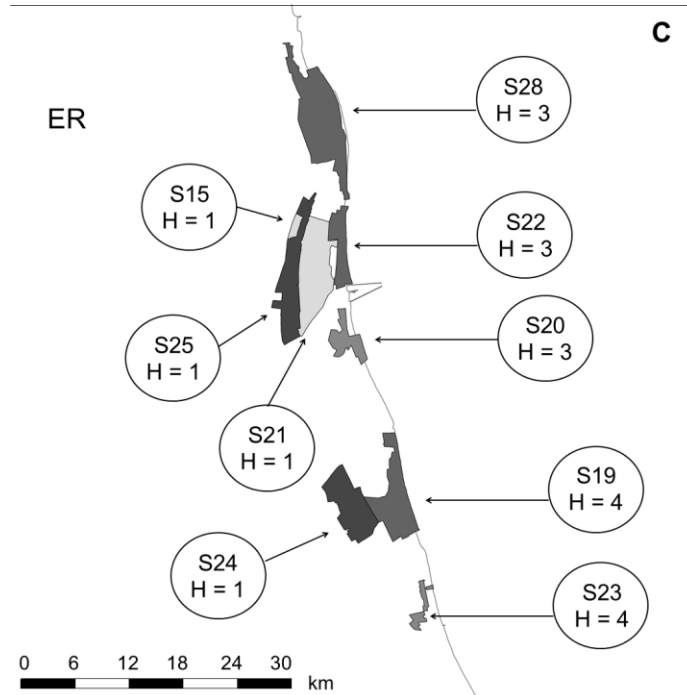
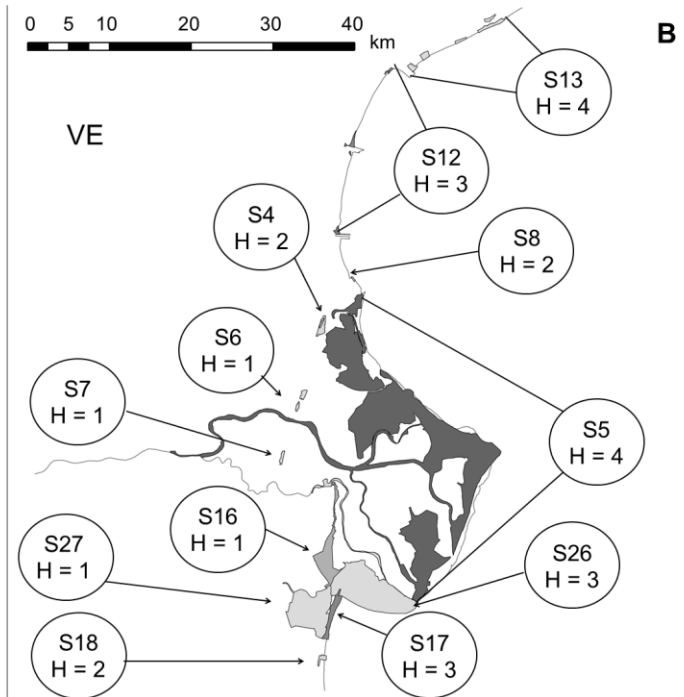
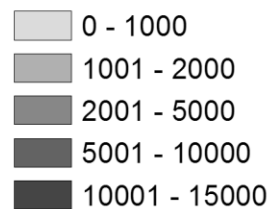
353 **Figure 3: Map of the coastal dune Natura 2000 sites considered in the study (S, see Table 6) along with their total soil organic carbon stocks (in tonnes) and the total**

354 **number of coastal dune habitat types (H) present in each site. Administrative regions abbreviations are clarified in Figure 2. Natura 2000 sites and administrative**

355 **regions boundaries are available from GIS NATURA (2005).**



**Tonnes of soil carbon stock in Natura 2000 sites**



#### 356 4. Discussion

357

358 This study has enhanced our understanding of the ecological role of an important sector of the  
359 Italian coast. In total, 36 Natura 2000 coastal dune sites were characterized for soil carbon storage  
360 service and biodiversity, based on four representative dune habitat types. The figures reported in  
361 Table 6 represent the first inventory of soil carbon stocks for dune systems in the Mediterranean  
362 and are based on survey data, rather than on the literature (for instance by means of “benefit  
363 transfer” values) or arbitrary expert valuations (Everard et al., 2010). The inventory also collates the  
364 most up to date and accurate extents for the selected dune habitats in each Natura 2000 site, a  
365 crucial piece of information for conservation planning, monitoring and environmental impact  
366 assessments, thus conforming to the reporting obligations established by the EU Habitats Directive  
367 and filling an information gap highlighted in previous studies (Laffoley D. & Grimsditch G., 2009;  
368 Prisco et al., 2012).

369 The results obtained for carbon storage and sequestration are in line with previous studies. The  
370 carbon sequestration rates of Adriatic wooded dunes appear to be analogous to Welsh dry dune  
371 grasslands (Jones et al., 2008), and the carbon density is very similar to UK dune grasslands  
372 (Beaumont et al., 2014). The estimated total carbon stock for the Adriatic coastal dune Natura 2000  
373 network of 74,889 t C is rather smaller than the UK fixed dune grassland soil C stock of 1,442,900 t C  
374 (Beaumont et al., 2014), due to the smaller extent of dunes along the Adriatic coast.

375 Carbon storage service provision varies along the Adriatic Natura 2000 network, following the  
376 distribution and size of coastal dune sites, which are more concentrated and larger in the northern  
377 and central sector and more scattered and smaller in the southern area. While the Venetian site  
378 “Delta del Po: tratto terminale e delta veneto” and the Friulian site “Laguna di Marano e Grado”  
379 encompass together more than half of the total network, in Marche, Abruzzo and Molise only one  
380 site exceeds 1,000 ha. Carbon values are also much higher in the sites where wooded dunes occur  
381 massively, and often as unique coastal dune habitat type, such as in the sites “Pineta di Classe” and  
382 “Pineta di San Vitale, Bassa del Pirottolo”, where the previous open dune habitats were converted  
383 into pine plantations. By contrast, only one of the few sites including all the selected habitat types  
384 shows carbon values exceeding 5,000 tonnes (site “Ortazzo, Ortazzino, Foce del Torrente Bevano”).

385 Dune habitat types occurrence and distribution along the Adriatic coast is uneven, with the embryo,  
386 mobile and wooded dunes occurring throughout the study area, and the fixed dunes present in only  
387 nine Natura 2000 sites, with the most extended patches in Friuli (“Pineta di Lignano”, 10.94 ha),  
388 Veneto (“Delta del Po: tratto terminale e delta veneto”, 15.06 ha) and Molise (“Foce Saccione -  
389 Bonifica Ramitelli”, 20.59 ha). Therefore, the provision of biodiversity service by coastal dune

390 Adriatic Natura 2000 sites, if expressed as habitat richness, is not necessarily coupled with high  
391 carbon storage service capacity.

392 The studied habitat types showed different characteristics in terms of plant richness and carbon  
393 storage potential. The embryo and mobile dunes have low organic carbon content and little  
394 differentiation between soil horizons due to harsh environmental conditions, while in the landward  
395 dunes (fixed and wooded dunes) increased protection from physical stresses allows the  
396 development of woody shrubs in the seaward slopes and trees and upland species in the landward  
397 portions (Bini et al., 2002; Carboni et al., 2011, Hu et al., 2015). Thus, inner dunes support more  
398 developed and more carbon rich soils than seaward dunes. This fact, along with local environmental  
399 factors, leads to a complex and unique floristic composition in fixed dunes, which also host a higher  
400 number of endangered taxa as well as endemic species (Buffa et al., 2007). Despite their high  
401 biodiversity value, fixed dunes are rare along the study area, especially when compared with the  
402 other sand dune habitats extents. Yet, at EU level Italy hosts the main area of fixed dunes with  
403 *Juniperus* spp., and thus has a crucial role in improving its unfavourable status by means of specific  
404 conservation and restoration strategies (for instance through fire prevention and native species  
405 planting) (Picchi, 2008).

406 The overall condition of wooded dunes is radically different, as emerged from the results. Their  
407 massive occurrence in the study area is largely a result of historical afforestation, which has altered  
408 the natural dune zonation, especially in those cases where pine woods were planted in place of  
409 natural fixed dunes with *Juniperus* spp. or *Quercus ilex* woods (Biondi et al., 2009). However,  
410 although the spread of conifer plantations had a strong impact on coastal landscapes (Malavasi et  
411 al., 2013), in the recent decades the abandonment of pastoral activities and the decreasing of  
412 understory management practices in pine plantations have been leading, in some areas, to a slow  
413 maquis vegetation recovery (Onori et al., 2013). In addition, a few pine stands along the study area  
414 are threatened by saltwater intrusion and by pine processionary moth *Thaumetopoea pityocampa*  
415 (e.g. Rigoni, 2012).

416 Embryo and mobile dunes are natural habitats widespread throughout the study area and in general  
417 all over Italian coasts, and share very few plant species with other terrestrial habitats (Acosta et al.,  
418 2009). Such exclusive species have an intrinsic and irreplaceable value and are crucial for  
419 maintaining connectivity with inland dunes (Acosta et al., 2003). Unfortunately, their ecological  
420 quality is poor in both Mediterranean and Continental biogeographical regions, mainly due to  
421 human trampling and beach levelling (Santoro et al., 2012b; Prisco et al., 2012), which favour alien  
422 plant invasions (Carboni et al., 2010; Carboni et al., 2011; Carranza et al., 2010), thus reducing focal  
423 species richness (Del Vecchio et al., 2013; Santoro et al., 2012a) and changing soil properties, as

424 demonstrated for *Carpobrotus* spp. and its multi-factor negative effects on foredunes (Santoro et al.,  
425 2011). Other anthropogenic threats, such as coastal erosion, sea level rise and storm surges,  
426 exacerbated by climate change effects, are particularly worrying along the Northern Adriatic Sea,  
427 where some coastal areas are already below sea level and therefore at high risk of flooding  
428 (Bondesan et al., 1995). If the foredunes become eroded, then the landward dunes will be equally  
429 damaged, failing the vegetation zonation functionality (Feagin et al., 2005). This reduction in  
430 integrity of dune system would be detrimental not only for biodiversity but also for other ecosystem  
431 services provision (in particular for economically crucial benefits such as seaside tourism). Therefore,  
432 it is imperative to preserve natural coastal dunes as a whole (Acosta et al., 2003; Buffa et al., 2005;  
433 Drius et al., 2013).

434

435 Even supposing an increase in soil carbon storage for Mediterranean coastal dunes due to enhanced  
436 vegetation cover as an effect of climate change (Del Vecchio et al. 2015), their irreplaceable value as  
437 biodiversity sources goes beyond their carbon sink potential, since coastal dune diversity is unique,  
438 while other ecosystems can act as soil carbon pools. Although carbon storage and sequestration are  
439 significant for climate change mitigation, exclusive focus on carbon benefits could concentrate land  
440 use pressures to non-forest ecosystems, with potentially deleterious impacts on coastal dune  
441 biodiversity and functionality (Campbell et al., 2009). For these reasons, even if semi-natural  
442 wooded dunes represent valuable soil carbon pools, they should be managed primarily to favour  
443 natural dune zonation restoration and recovery for biodiversity, particularly within Natura 2000  
444 sites. Such practices are already in place in various locations, from UK (Edmondson & Velmans, 2001)  
445 to Denmark (Jensen, 1994). In the study area, specific conservation actions for wooded dune  
446 requalification and maquis restoration are currently carried out in Molise, within the LIFE+ project  
447 MAESTRALE (NAT/IT/000262; see also  
448 [http://lifemaestrale.eu/azioni/azioni\\_concrete\\_di\\_conservazione.php](http://lifemaestrale.eu/azioni/azioni_concrete_di_conservazione.php)).

449 Outside the Natura 2000 network, in those cases where wooded dunes are already established but  
450 are of poor ecological quality, they could be managed either to improve their dune biodiversity role,  
451 or to support other coastal services, taking the pressure off natural dune habitats.

452 That said, more insights into the multi-service capacity of coastal dunes are desirable in order to  
453 comprehensively guide policy makers in their conservation and management planning schemes.

454

## 455 **5. Conclusions**

456

457 This study produced valuable data concerning soil carbon storage and sequestration service  
458 provided by biodiverse and fragile ecosystems, which are in need of high-priority protection. A  
459 complete and updated inventory of soil carbon values for four representative coastal dune habitats  
460 within the Adriatic Natura 2000 network was compiled, and their biodiversity value was compared  
461 and discussed. Wooded dunes had greater carbon density and a greater area, thus storing greater  
462 soil carbon stocks. However, while they showed similar abundance of focal species, they had lower  
463 species richness overall than fixed dunes and fewer endangered dune taxa. This reveals a potential  
464 trade-off between carbon storage and biodiversity value. Given the relatively small area of dunes  
465 nationally, the carbon stock is relatively small. By contrast, the unique diversity they support is of  
466 much greater importance, suggesting a focus on restoration to natural dune habitats is desirable.  
467 Further research would be valuable on how the quality of dune habitats governs the quantity of  
468 other ecosystem services supported by these systems, and whether they can be managed to support  
469 or improve both their valuable biodiversity as well as additional ecosystem services.

470

471

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737 Appendix

738 Table A: Checklist of the focal taxa for the selected sand dune habitats, occurring along the Central Adriatic coast (Biondi et al., 2009; Del Vecchio et al.,  
739 2013; 2015).

Embryo dunes (habitat type 2110)	Mobile dunes (habitat type 2120)	Fixed dunes (habitat type 2250)	Wooded dunes (habitat type 2270)
<i>Anthemis maritima</i>	<i>Ammophila arenaria</i> ssp. <i>australis</i>	<i>Asparagus acutifolius</i>	<i>Asparagus acutifolius</i>
<i>Calystegia soldanella</i>	<i>Anthemis maritima</i>	<i>Clematis flammula</i>	<i>Clematis flammula</i>
<i>Cyperus capitatus</i>	<i>Cyperus capitatus</i>	<i>Juniperus oxycedrus</i> ssp. <i>macrocarpa</i>	<i>Daphne gnidium</i>
<i>Elymus farctus</i>	<i>Echinophora spinosa</i>	<i>Lonicera implexa</i>	<i>Osyris alba</i>
<i>Euphorbia peplis</i>	<i>Eryngium maritimum</i>	<i>Myrtus communis</i>	<i>Phillyrea angustifolia</i>
<i>Lotus creticus</i>	<i>Euphorbia paralias</i>	<i>Phillyrea angustifolia</i>	<i>Pinus halepensis</i>
<i>Medicago marina</i>	<i>Lotus creticus</i>	<i>Phillyrea latifolia</i>	<i>Pinus pinaster</i>
<i>Otanthus maritimus</i>	<i>Medicago marina</i>	<i>Pistacia lentiscus</i>	<i>Pinus pinea</i>
<i>Polygonum maritimum</i>	<i>Otanthus maritimus</i>	<i>Prasium majus</i>	<i>Pistacia lentiscus</i>
<i>Sporobolus pungens</i>	<i>Pancratium maritimum</i>	<i>Rhamnus alaternus</i>	<i>Quercus ilex</i>
		<i>Rubia peregrina</i>	<i>Rhamnus alaternus</i>
		<i>Ruscus aculeatus</i>	<i>Rubia peregrina</i>
		<i>Smilax aspera</i>	<i>Smilax aspera</i>

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