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Drius, Mita; Carranza, Maria Laura; Stanisci, Angela; Jones, Laurence. 2016. **The role of Italian coastal dunes as carbon sinks and diversity sources. A multi-service perspective**.

Abstract

Coastal dunes support biodiverse habitats of conservation interest and provide other essential but often overlooked benefits to society, such as carbon sequestration, thanks to their high soil carbon accumulation rates. The recently established coastal dune Natura 2000 network in the Italian Adriatic coast aims at protecting dune habitats diversity, yet its capacity to provide other ecosystem services, and the potential trade-offs with biodiversity provision have so far not been evaluated. In this paper we conduct this analysis for a key ecosystem service: carbon storage and sequestration. We i) quantify soil carbon stocks and sequestration within four coastal dune EU habitat types along the Adriatic Natura 2000 network; ii) upscale these data to create an inventory of carbon stocks for all dune Natura 2000 sites in the study area; iii) collate biodiversity data of the selected EU habitat types using plant diversity measures as surrogates of coastal dune biodiversity and iv) explore the trade-offs between carbon storage and biodiversity value for the selected habitats. Italian Adriatic coastal dune Natura 2000 sites sequester 4,998 t of CO_2e per year, with the majority in wooded dunes. Wooded dunes showed significantly higher soil carbon density than the other dune habitats, and had a much greater area, but they were characterized by lower species richness. By contrast, the endangered fixed dunes, which survive in few residual patches along the study area, showed the highest plant diversity for both total species richness and dune focal species, but had a much lower carbon density and extent. Although further analyses of additional services would be desirable for a more comprehensive assessment, these findings suggest that conservation actions should favor restoration of the natural dune zonation, since it guarantees both dune species diversity and carbon storage. The carbon stocks and EU habitat type extents produced in this study constitute the first systematic inventory for dune systems in the Mediterranean.

Keywords

Adriatic coast; Habitats Directive; soil carbon storage; CO_2 sequestration; dunes conservation; plant diversity.

1. Introduction

Coastal dunes are dynamic systems which provide essential benefits to society, some of which have a considerable socio-economic impact (Everard et al., 2010; Jones et al., 2011; McLachlan & Brown, 2006; MA, 2005). These systems play a major role for recreation and tourism, being highly valued as a place of escape and isolation and as a source of mental well-being (Doody, 1997; Houston, 1997; Nordstrom, 2000). In addition, they provide unique habitat assemblages due to a strong environmental sea-inland gradient, which supports a highly specialized flora and fauna sharing relatively few species with other terrestrial ecosystems (Acosta et al., 2009; Martínez et al., 2004). While services such as coastal defence, groundwater storage and water purification are clearly recognized and integrated into the coastal management of many sites (French 2001; Rhymes et al. 2015; van Dijk, 1989), rather less is known about supporting ecosystem services such as nutrient cycling, soil formation and climate regulation (Barbier et al., 2011; Jones et al., 2008). Being an early successional ecosystem, coastal dunes have a high soil carbon accumulation rate (Jones et al., 2008; Olff et al., 1993; Rohani et al., 2014), a feature in common with other coastal environments (Sevink J., 1991). There is increasing interest in the role of “blue carbon” in climate regulation (Donato et al. 2011; Donato et al., 2012; Mcleod et al., 2011; Nellemann et al., 2009), and sequestration by marine and coastal ecosystems has been globally quantified as ca. 2 Gt C yr^{-1} (Chmura et al., 2003). Yet, the specific role of carbon storage in dune habitats has been little explored to date, except in the UK, where both annual CO_2 sequestered and the stock of carbon in vegetation and soil were estimated for the whole country and changes in value of the carbon sequestration service were projected under different scenarios of coastal change alteration (Beaumont et al., 2014). While carbon accumulation rates are very high, the gross contribution of dune habitats to climate regulation is relatively small due to their low area. However, in the context of widespread coastal habitat loss and land-use change at fine scale, and within a wider context of habitat management for multiple benefits, their role in regulating greenhouse gas emissions is worth taking into consideration (Everard et al., 2010).

Despite the high biodiversity value and numerous benefits provided by coastal dunes, this ecosystem is among the most threatened both globally (Schlacher et al., 2007) and in the Mediterranean (Rossi et al., 2013). Human activities in European littoral areas have been intensifying in the course of the 20^{th} century (Cori, 1999); consequently, sand dunes across Europe had lost on average 25% of their extent by 1998, compared to 1900 (EUCC, 1998), with peaks of 80% area loss in some Mediterranean countries. In order to prevent these and other endangered habitats from further degradation, European Member States adopted the Council Directive 92/43/EEC (Habitats Directive from now onwards), which lists the habitats of European interest (EU habitat types) and establishes across Europe an extended network of sites of ecological importance, called Natura 2000.

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

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

2. Materials and methods

2.1 Selection of EU coastal dune habitat types

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

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

Table 1: The selected EU habitat types with their description and the abbreviations used in this manuscript (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 *Elymus farctus*	Embryo dunes
2120	Shifting dunes along the shoreline with *Ammophila arenaria* ('white dunes')	Seaward and semi-permanent cordons of dune systems dominated by *Ammophila arenaria*	Mobile dunes
2250*	Coastal dunes with *Juniperus* spp.	Fixed dunes with pioneer maquis dominated by *Juniperus oxycedrus* subsp. *macrocarpa*	Fixed dunes
2270*	Wooded dunes with *Pinus pinea* and/or *Pinus pinaster*	Backdunes with forest dominated by *Pinus halepensis*, *P. pinea* and *P. pinaster*	Wooded dunes

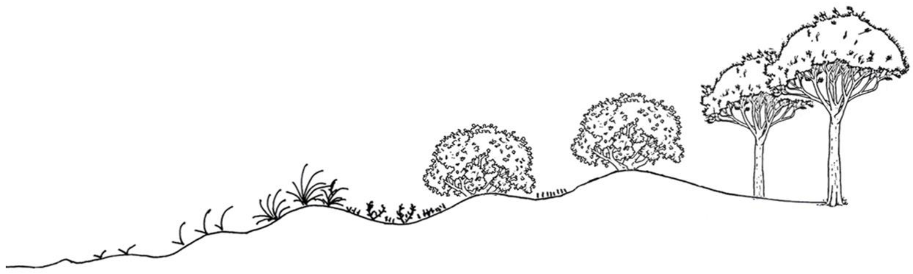


Figure 1: Scheme of a typical Mediterranean coastal dune zonation evidencing the selected EU habitat types. For habitats abbreviations refer to Table 1. Modified from Prisco et al., 2012 and from www.midisegni.it

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

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

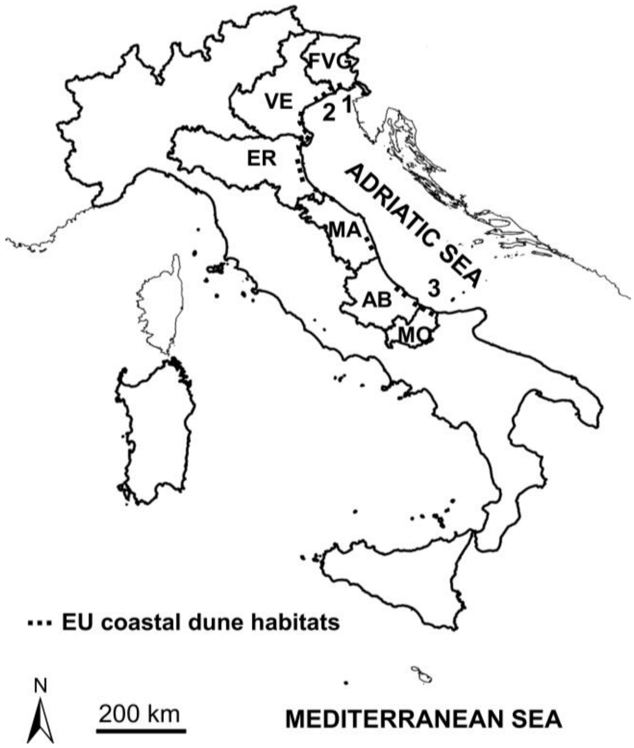


Figure 2: Study area. Administrative regions included in the study are Friuli-Venezia Giulia (FVG), Veneto (VE), Emilia-Romagna (ER), Marche (MA), Abruzzo (AB) and Molise (MO). The dotted lines show the distribution of the EU coastal dune habitats in the study area. Soil samples were collected in three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

Table 2: Extent in hectares of the four EU sand dune habitat types within the Adriatic coastal Natura 2000 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

2.3 Soil sample collection and treatment

Seventy soil samples were collected across three Natura 2000 sites along the Northern and Central Adriatic coast (Figure 2). The three sites are: "Val Cavanata e Banco Mula di Muggia", in Friuli-Venezia Giulia (13.43°E, 45.68°N), "Laguna di Caorle - Foce del Tagliamento" in Veneto (13.09°E, 45.62°N) and "Foce Saccione - Bonifica Ramitelli" in Molise (15.10°E, 41.93°N). The selected Natura 2000 sites are representative of the latitudinal gradient along Adriatic coast. The habitat type classes were identified on the ground based on a detailed cartography produced for Natura 2000 sites management plans (for "Val Cavanata e Banco Mula di Muggia", see Regione Autonoma Friuli-Venezia Giulia, 2012; for "Laguna di Caorle - Foce del Tagliamento", see http://www.regione.veneto.it/web/ambiente-e-territorio/rete-natura-2000-download; for "Foce Saccione - Bonifica Ramitelli", see Berardo et al., 2012).

For each soil sample, a 15 cm-deep core with 5 cm diameter was collected and its geographic location was recorded with a GPS. Organic profile depth was measured directly in the field. In a few cases, due to fieldwork constraints, samples were only 10 cm deep but, even so, they included the full organic profile. Subsequently in the laboratory, all samples were weighed (fresh weight), all roots and vegetation were removed and then the soils were homogenized following standard procedures. Next, moisture content was determined by drying subsamples at oven temperature of 105° for 24 h and reweighing them (MAFF, 1986); pH of the fresh soil was measured in deionised water (1:2.5). Then, organic matter content was estimated for all samples through Loss On Ignition (LOI) method, at 375°C for 16 h. The oven temperature of 375°C is sufficient to combust organic matter without dissociating too much CO_2 from the carbonates (Ball, 1964).

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

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

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

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

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

2.4 Conversion to carbon sequestration and upscaling of carbon values

Carbon stock refers to carbon stored in the biosphere; carbon sequestration is the rate of capture and long-term storage of atmospheric carbon dioxide (CO_2) (Beaumont et al*.,* 2014).

Rates of long-term carbon sequestration were estimated from a study on land cover change in coastal Molise which compared land cover maps for the years 1954, 1986 and 2006, focusing on changes in the spatial pattern of coastal dune cover types in relation to the anthropogenic ones (Malavasi et al., 2013). From comparison among the multi-temporal ortho-photographs, it was possible to deduce that the pine plantation present in the Natura 2000 site “Foce Saccione - Bonifica Ramitelli” (Figure 2) was planted after 1954. Assuming a constant sequestration rate and that reforestation took place in 1960, the soil carbon stock measured in wooded dunes was divided by its presumed age (55 years) to obtain an estimate of the annual rate of carbon sequestration into soil. The same age was assumed for the other three dune habitats as there was no information from which to assess their age. Subsequently, CO_2 sequestration rates were calculated for each habitat using IPCC conversion factor: 1 t C = 3.67 t CO_2.

Mean carbon stock and sequestration values were scaled up to the total extent of coastal dune habitats in the Adriatic Natura 2000 network (Table 2), by multiplying the average per hectare carbon values and their standard deviations by the total habitat extents. The habitats extents of each Natura 2000 site were collated from multiple sources, since no single source of this information is available. The 2012 and 2013 official Natura 2000 Standard data forms for each site, downloadable from the portal of the Italian Ministry of the Environment (ftp://ftp.dpn.minambiente.it/Natura2000/TrasmissionECE_2013/schede_mappe), were adopted as primary data source. Where the extents reported in the data forms were inaccurate or obsolete, they were derived from Natura 2000 sites management plans reports, regional cartography or unpublished studies, based on an accurate and systematic case-by-case research.

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.

3. Results

3.1 Soil characteristics

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

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

Table 3: Bulk density, soil %C, soil C density and pH for the four EU sand dune habitat types considered and for bare sand. *N* is the number of samples collected for each habitat type. Percentage of carbonate (% $CaCO_3$) is based on 13 samples. All values are reported as mean ± s.d. Letters represent homogenous subsets according to Kruskal-Wallis tests.

EU habitat type	*N*	Bulk density (g cm^{-3})	Soil %C	Soil C density (g cm^{-3})	pH (H_2O)	% $CaCO_3$
Embryo dunes	10	1.606 ± 0.057^{a}	0.131 ± 0.053^{a}	0.0021 ± 0.0008^{a}	8.64 ± 0.55	-
Mobile dunes	20	1.577 ± 0.107^{a}	0.148 ± 0.119^{a}	0.0023 ± 0.0016^{a}	8.85 ± 0.25	-
Fixed dunes	10	1.547 ± 0.084^{ab}	0.179 ± 0.066^{b*}	0.0027 ± 0.0009^{b*}	8.56 ± 0.35	-
Wooded dunes	20	1.088 ± 0.362^{c**}	2.838 ± 2.556^{c**}	0.0227 ± 0.0120^{c**}	8.35 ± 0.47	23.14 ± 13.80
bare sand	10	1.527 ± 0.055^{b*}	0.196 ± 0.125^{b*}	0.0029 ± 0.0019^{b*}	8.79 ± 0.48	33.42 ± 3.17

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

3.2 Carbon storage and sequestration

Soil carbon per ha and total soil carbon stocks of the whole Adriatic coastal dune Natura 2000 network, split by habitat type, are reported in Table 4. For each tonne of soil carbon stock per ha in embryo, mobile and fixed coastal dunes there are about 10 tonnes in the soil of wooded dunes. Multiplying unitary carbon stock for each total coastal dune habitat type surface within the Adriatic coastal Natura 2000 network (Table 2), the ratio between wooded dunes and natural (embryo, mobile and fixed dunes) becomes much greater, owing to wooded dunes having a much larger extent along the study area. Taking into account the mean values of carbon stored along Adriatic coastline, the total coastal dune soil carbon sink amounts to nearly 75,000 t (Table 4).

The estimates of average unitary sequestration rates are reported in Table 4. While mean carbon sequestration rates provided by natural dunes are quite comparable (from 5.57 g m^{-2} yr^{-1} of mobile dunes to 7.49 g m^{-2} yr^{-1} of fixed dunes), mean carbon sequestration rate provided by wooded dunes is ten times greater (56.35 g m^{-2} yr^{-1}). The overall estimated mean CO_2 sequestration capacity of the Northern and Central Adriatic coastal dunes is almost 5,000 t per year (Table 4).

Table 4: Estimated unitary soil organic carbon content, total soil organic carbon stocks, unitary soil organic carbon sequestration rates and total CO_2 sequestration rates of the selected EU sand dune habitat types present in the Adriatic Natura 2000 network. All values are reported as mean ± s.d.

EU habitat type	Soil C (t ha^{-1})	Soil C stock (t)	C seq rate (g m^{-2} yr^{-1})	C seq rate (t CO_2 yr^{-1})
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

3.3 Biodiversity value of EU coastal dune habitat types

The fixed dunes have the highest number of endangered dune taxa. Wooded dunes come second, while embryo and mobile dunes show lower numbers (Table 5). With respect to the number of focal plant taxa, fixed dunes and wooded dunes have similar numbers while embryo dunes and mobile dunes have lower numbers but are similar to each other. Regarding the vascular flora richness, expressed by the average number of recorded taxa by plot, fixed dunes, embryo dunes and mobile dunes host higher plant diversity than wooded dunes, with fixed dunes being the richest habitat type (Table 5). Kruskal-Wallis tests applied to the number of taxa collected in each habitat type revealed highly significant differences (H = 21.06, P < 0.001). In particular, the number of taxa in wooded dunes was significantly lower than in fixed and in mobile dunes ($P < 0.001$) and in embryo dunes ($P < 0.05$). The embryo dunes showed significantly fewer taxa than fixed and mobile dunes.

No significant difference was revealed between fixed and mobile dunes.

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

EU habitat type	N endangered taxa [(a)]	N focal taxa [(b)]	Average N taxa by plot [(c)]
Embryo dunes	7	10	13.70^{a}
Mobile dunes	8	10	16.95^{b*}
Fixed dunes	13	13	17.75^{b*}
Wooded dunes	11	13	11.92^{c**}

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

3.4 Carbon storage and biodiversity along the Adriatic Natura 2000 sites

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

Figure 3 depicts soil carbon storage and dune habitat diversity provided by each of the selected Natura 2000 sites. To clearly express the biodiversity value of each Natura 2000 site, a value from 1 to 4 is assigned, according to the total number of coastal dune habitat types present in the site, among those analysed in this study. Total carbon values range from 1 t (site "Valle Cavanata e Banco Mula di Muggia") to 14,682 t (site "Pineta di Classe"). The richest coastal dune Natura 2000 sites for soil carbon are located in the Central sector of Adriatic, precisely in Emilia-Romagna. Other hotspots for carbon storage in the study area are the site "Laguna di Caorle foce Tagliamento" and the site "Delta del Po: tratto terminale e delta veneto", both in Veneto region. Instead, the coastal dune Natura 2000 sites of Marche and Abruzzo include the smallest carbon sinks. Lastly, the Natura 2000 sites of Molise and Friuli-Venezia Giulia represent valuable carbon pools which cover most of the regional coastal area in both cases. As to dune habitat richness, the most diverse area is Veneto region, with four sites comprising all the selected habitat types. Other Natura 2000 sites including the four habitats are located in Emilia-Romagna and Molise. Marche and Abruzzo do not contain any Natura 2000 site counting all four habitat types. Considering both services, the Northern Adriatic coast includes the richest coastal dune Natura 2000 sites for biodiversity and carbon storage, with a peak in the site "Ortazzo, Ortazzino, Foce del Torrente Bevano" (four habitats and more than 6,000 t of carbon stored), followed by the site "Delta del Po: tratto terminale e delta veneto" (four habitats and 4,597 t carbon). Instead, the least dune carbon and biodiversity rich areas are the central regions of Marche and Abruzzo, where none of the sites include all dune habitats. Last, the southern part of the study area, represented by the three Natura 2000 sites of Molise, is a very relevant diversity source as it includes the greatest area of fixed dunes, while it is relatively less significant for carbon storage.

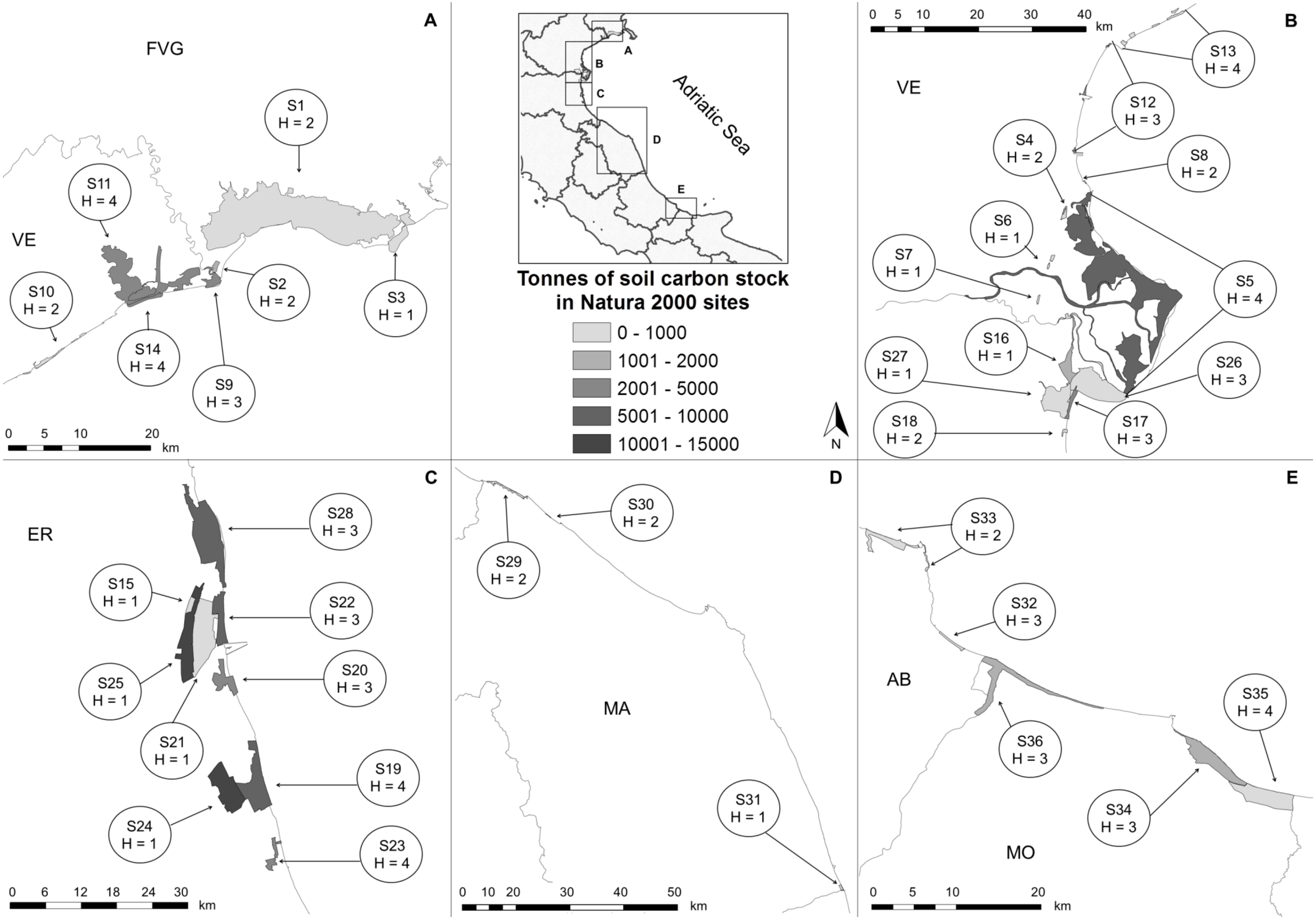
Table 6: List of the coastal dune Natura 2000 sites (S) along the Northern and Central Adriatic coast comprising the selected EU habitat types. For each site, identified by its official name and code according to Habitats Directive, the administrative region, the status, the total area, the extent of the coastal dune EU habitat types included and their contribution as soil carbon sinks (mean values) are reported. For administrative regions abbreviations, refer to Figure 2. 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
S1ʒ	IT3320037	Laguna di Marano e Grado	FVG	SAC/SPA	16,364	30	63.26	-	-	94.29	193.77	-	-
S2ʒ	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
S12ʒ	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
S29ঌ	IT5310024	Colle San Bartolo e litorale pesarese	MA	SPA	4,031	6.05	0.4	-	-	19.02	1.23	-	-
S30ঌ	IT5310007	Litorale della Baia del Re	MA	SCI	17	5.96	0.2	-	-	18.73	0.61	-	-
S31ঌ	IT5340001	Litorale di Porto d'Ascoli	MA	SCI/SPA	109	6.76	-	-	-	21.25	-	-	-
S32ǂ	IT7140109	Marina di Vasto	AB	SCI	57	1.25	3.1	-	2.01	3.93	9.5	-	62.29
S33ǂ	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
				Totals	**75,829**	**224.73**	**247.94**	**49.07**	**2,514.73**	**706.33**	**759.44**	**202.17**	**77,936.36**

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): 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-territorio/rete-natura-2000-download; ঌ (S1,S2,S12,S29,S30,S31): Natura 2000 Standard data forms 2013 ftp://ftp.dpn.minambiente.it/Natura2000/TrasmissionECE_2013/schede_mappe; ¥ (S34,S35,S36): Berardo et al., 2012; ǂ (S32,S33): de Chiro, 2014; ∞ (S3): Regione Autonoma Friuli-Venezia Giulia, 2012.

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 number of coastal dune habitat types (H) present in each site. Administrative regions abbreviations are clarified in Figure 2. Natura 2000 sites and administrative regions boundaries are available from GIS NATURA (2005).


A
FVG
VE
S1 H = 2
S2 H = 2
S3 H = 1
S9 H = 3
S10 H = 2
S11 H = 4
S14 H = 4
0 5 10 20 km
A
B
C
D
E
Adriatic Sea
Tonnes of soil carbon stock in Natura 2000 sites
0 - 1000
1001 - 2000
2001 - 5000
5001 - 10000
10001 - 15000
N
B
0 5 10 20 30 40 km
VE
S4 H = 2
S5 H = 4
S6 H = 1
S7 H = 1
S8 H = 2
S12 H = 3
S13 H = 4
S16 H = 1
S17 H = 3
S18 H = 2
S26 H = 3
S27 H = 1
C
ER
S15 H = 1
S19 H = 4
S20 H = 3
S21 H = 1
S22 H = 3
S23 H = 4
S24 H = 1
S25 H = 1
S28 H = 3
0 6 12 18 24 30 km
D
MA
S29 H = 2
S30 H = 2
S31 H = 1
0 10 20 30 40 50 km
E
AB
MO
S32 H = 3
S33 H = 2
S34 H = 3
S35 H = 4
S36 H = 3
0 5 10 20 km

4. Discussion

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

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

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

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

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

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

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

Embryo and mobile dunes are natural habitats widespread throughout the study area and in general all over Italian coasts, and share very few plant species with other terrestrial habitats (Acosta et al., 2009). Such exclusive species have an intrinsic and irreplaceable value and are crucial for maintaining connectivity with inland dunes (Acosta et al., 2003). Unfortunately, their ecological quality is poor in both Mediterranean and Continental biogeographical regions, mainly due to human trampling and beach levelling (Santoro et al., 2012b; Prisco et al., 2012), which favour alien plant invasions (Carboni et al., 2010; Carboni et al., 2011; Carranza et al., 2010), thus reducing focal species richness (Del Vecchio et al., 2013; Santoro et al., 2012a) and changing soil properties, as demonstrated for *Carpobrotus* spp. and its multi-factor negative effects on foredunes (Santoro et al., 2011). Other anthropogenic threats, such as coastal erosion, sea level rise and storm surges, exacerbated by climate change effects, are particularly worrying along the Northern Adriatic Sea, where some coastal areas are already below sea level and therefore at high risk of flooding (Bondesan et al., 1995). If the foredunes become eroded, then the landward dunes will be equally damaged, failing the vegetation zonation functionality (Feagin et al., 2005). This reduction in integrity of dune system would be detrimental not only for biodiversity but also for other ecosystem services provision (in particular for economically crucial benefits such as seaside tourism). Therefore, it is imperative to preserve natural coastal dunes as a whole (Acosta et al., 2003; Buffa et al., 2005; Drius et al., 2013).

Even supposing an increase in soil carbon storage for Mediterranean coastal dunes due to enhanced vegetation cover as an effect of climate change (Del Vecchio et al. 2015), their irreplaceable value as biodiversity sources goes beyond their carbon sink potential, since coastal dune diversity is unique, while other ecosystems can act as soil carbon pools. Although carbon storage and sequestration are significant for climate change mitigation, exclusive focus on carbon benefits could concentrate land use pressures to non-forest ecosystems, with potentially deleterious impacts on coastal dune biodiversity and functionality (Campbell et al., 2009). For these reasons, even if semi-natural wooded dunes represent valuable soil carbon pools, they should be managed primarily to favour natural dune zonation restoration and recovery for biodiversity, particularly within Natura 2000 sites. Such practices are already in place in various locations, from UK (Edmondson & Velmans, 2001) to Denmark (Jensen, 1994). In the study area, specific conservation actions for wooded dune requalification and maquis restoration are currently carried out in Molise, within the LIFE+ project MAESTRALE (NAT/IT/000262; see also http://lifemaestrale.eu/azioni/azioni_concrete_di_conservazione.php).
Outside the Natura 2000 network, in those cases where wooded dunes are already established but are of poor ecological quality, they could be managed either to improve their dune biodiversity role, or to support other coastal services, taking the pressure off natural dune habitats.
That said, more insights into the multi-service capacity of coastal dunes are desirable in order to comprehensively guide policy makers in their conservation and management planning schemes.

5. Conclusions

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

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References

Acosta, A., Blasi, C., Carranza, M.L, Ricotta, C. & Stanisci, A. (2003). Quantifying ecological mosaic connectivity and with a new topoecological index. *Phytocoenologia*, *33(4)*, 623-631

Acosta, A., Carranza M.L. & Izzi C.F. (2005). Combining land cover mapping of coastal dune with vegetation analysis. *Applied Vegetation Science*, *8*, 133-138

Acosta, A., Carranza, M.L. & Izzi, C.F. (2009). Are there habitats that contribute best to plant species diversity in coastal dunes? *Biodiversity and Conservation*, *18*, 1087-1098

Araújo, R., Honrado, J., Granja, H.M., De Pinho, S.N. & Caldas, F.B. (2002). Vegetation complexes of coastal sand dunes as an evaluation instrument of geomorphologic changes in the coastline. In: Littoral 2002. The Changing Coast. EUROCOAST/EUCC, pp. 337-339, Porto, Portugal

Ball, D.F. (1964). Loss-on-ignition as an estimate of organic matter and organic carbon in non-calcareous soils. *Journal of Soil Science*, *15*, 84-92

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W, Stier, A.C. & Silliman, B.R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs*, *81(2)*, 169-193

Bauer, H.P., Beckett, P.H.T. & Bie, S.W. (1972). A rapid gravimetric method for estimating calcium carbonate in soils. *Plant and Soil*, 37, 689-690

Beaumont, N.J., Jones L., Garbutt A., Hansom J.D. & Toberman, M. (2014). The value of carbon sequestration and storage in coastal habitats. *Estuarine, Coastal and Shelf Science*, *137*, 32-40

Berardo, F., Carranza, M.L., Ciccorelli, G., Del Vecchio, S., Fusco, S., Iannotta, F., Loy, A., Roscioni, F. & Stanisci, A., (2012). Un SIT per la gestione, e la conservazione della biodiversità nelle dune costiere. Il caso di MAESTRALE (LIFE 10NAT/IT/000262). Proceedings 16th National Conference ASITA Vicenza, November 6-9, 2012; 203-209

Berardo, F., Carranza, M.L., Frate, L., Stanisci, A. & Loy, A. (2015). Seasonal habitat preference by the flagship species *Testudo hermanni*: Implications for the conservation of coastal dunes. *Comptes Rendus Biologies*, *338(5)*, 343-350

Bini, C., Buffa, G., Gamper, U., Sburlino, G. & Zilocchi, L. (2002). Soils and vegetation of coastal and wetland areas in Northern Adriatic (NE Italy). 7th Int. Meet. Soils with Mediterranean Type Climate (Selected Papers), Options Méditerranéennes, Ser. A, Vol. 50, pp. 31-36

Biondi, E., Blasi, C., Burrascano, S., Casavecchia, S., Copiz, R., Del Vico, E., Galdenzi, D., Gigante, D., Lasen, C., Spampinato, G., Venanzoni, R. & Zivkovic, L. (2009). Manuale Italiano di interpretazione degli habitat della Direttiva 92/43/CEE (Italian Interpretation Manual of the 92/43/EEC Directive Habitats). Retrieved from http://vnr.unipg.it/habitat/index.jsp.

Bondesan, M., Castiglioni, G.B., Elmi, C., Gabbianelli, G., Marocco, R., Pirazzoli, P.A. & Tomasin, A. (1995). Coastal areas at risk from storm surges and sea-level rise in North Eastern Italy. *Journal of Coastal Research*, *11(4)*, 1354-1379

Buffa, G., Mion, D., Gamper, U., Ghirelli, L., & Sburlino, G. (2005). Valutazione della qualità e dello stato di conservazione degli ambienti litoranei: l'esempio del S.I.C. "Penisola del Cavallino: biotopi litoranei" (Venezia, NE-Italia). *Fitosociologia*, *42*, 3-13

Buffa, G., Filesi, L., Gamper, U., & Sburlino, G. (2007). Qualità e grado di conservazione del paesaggio vegetale del litorale sabbioso del Veneto (Italia settentrionale). *Fitosociologia*, *44*, 49-58

Campbell, A., Kapos, V., Scharlemann, J. P.W., Bubb, P., Chenery, A., Coad, L., Dickson, B., Doswald, N., Khan, M. S. I., Kershaw, F. & Rashid, M. (2009). Review of the literature on the links between biodiversity and climate change: impacts, adaptation and mitigation. Secretariat of the Convention on Biological Diversity, Montreal. Technical Series No. 42, 124 pp.

Carboni, M., Carranza, M.L. & Acosta, A.T.R. (2009). Assessing conservation status on coastal dunes: a multiscale approach. *Landscape and Urban Planning*, *91(1)*, 17-25

Carboni, M., Thuiller, W., Izzi, F. & Acosta, A.T.R. (2010). Disentangling the relative effects of environmental versus human factors on the abundance of native and alien plant species in Mediterranean sandy shores. *Diversity and Distributions*, *16*, 537-546

Carboni, M., Santoro, R. & Acosta, A.T.R. (2011). Dealing with scarce data to understand how environmental gradients and propagule pressure shape fine-scale alien distribution patterns on coastal dunes. *Journal of Vegetation Science*, *22*, 751-765

Carranza, M.L., Acosta, A., Stanisci, A., Pirone, G. & Ciaschetti, G. (2008). Ecosystem classification for EU habitat distribution assessment in sandy coastal environments: an application in Central Italy. *Environmental Monitoring and Assessment*, *140(1-3)*, 99-107

Carranza, M.L., Carboni, M., Feola, S. & Acosta, A.T.R. (2010). Landscape-scale patterns of alien plant species on coastal dunes. The case of iceplant in central Italy. *Journal of Applied Vegetation Science*, *13*, 135-145

Chmura, G.L., Anisfeld, S.C., Cahoon, D.R. & Lynch, J.C. (2003). Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochemical Cycles*, *11*, 1111-11120. doi: 10.1029/2002gb001917

Cori, B. (1999). Spatial dynamics of Mediterranean coastal regions. *Journal of Coastal Conservation*, *5*, 105-112

Corpo Forestale dello Stato UTB Ravenna (2004). Le pinete demaniali litoranee dell'Alto Adriatico. Project LIFE - Natura 2004 "Tutela di siti Natura 2000 gestiti dal Corpo Forestale dello Stato" LIFE04NAT/IT/000190

Curr, R.H.F., Koh, A., Edwards, E., Williams, A. T., & Davies, P. (2000). Assessing anthropogenic impact on Mediterranean sand dunes from aerial digital photography. *Journal of Coastal Conservation*, *6*, 15-22

De Chiro, M., Carranza, M.L., Ciabò, S., Di Martino, L., Frattaroli, A.R., Giannelli, A., Pirone, G., Stanisci, A. (2014). Distribuzione e stato di conservazione degli habitat di interesse comunitario lungo le coste dell'Abruzzo meridionale (Italia). In: Proceedings of Fifth International Symposium "Monitoring of Mediterranean coastal areas: problems and measurement techniques" Livorno, June 17-19, 2014, Benincasa, F. (ed). CNR-IBIMET Florence; 914-923

Del Vecchio, S., Acosta, A.T.R. & Stanisci, A. (2013). The impact of *Acacia saligna* invasion on Italian coastal dune EC habitats. *Comptes Rendus Biologies*, *336*, 364-369

Del Vecchio, S., Prisco, I., Acosta, A.T.R. & Stanisci, A. (2015). Changes in plant species composition of coastal dune habitats over a 20-year period. *AoB PLANTS* 7: plv018doi: 10.1093/aobpla/plv018

Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M., & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience, 4*, 293-297. doi:10.1038/ngeo1123

Donato, D.C., Kauffman, J.B., Mackenzie, R.A., Ainsworth, A., & Pfleeger, A.Z. (2012). Whole-island carbon stocks in the tropical Pacific: Implications for mangrove conservation and upland restoration. *Journal of Environmental Management*, 97, 89-96

Doody, J.P. (1997). Coastal dunes of Europe - recreational impacts and nature conservation. In Coastal Dunes, Recreation and Planning. Drees JM (ed.). EUCC Services: Leiden; 50-59

Drius, M., Malavasi, M., Acosta, A.T.R., Ricotta C. & Carranza, M.L. (2013). Boundary-based analysis for the assessment of coastal dune landscape integrity over time. *Applied Geography*, *45*, 41-48

Edmondson S.E. & Velmans C. (2001). Public perception of nature management on a sand dune system. In Coastal Dune Management: Shared Experience of European Conservation Practice, Houston, J.A., Edmondson, S.E., Rooney, P.J. (eds). Liverpool University Press: Liverpool; 206-218

EUCC (1998). European Coastal and Marine Ecological Network (ECMEN) – Phase II report. Prepared by J.P. Doody, A.H.P.M. Salman, P. Henslenfeld & L. Valentjin. European Union for Coastal Conservation, Leiden

European Commission DG Environment (2008). Article 17 Technical Report 2001-2006 (http://bd.eionet.europa.eu/activities/Reporting/Article_17/reference_portal). European Topic Centre on Biological Diversity

Everard, M., Jones, L., & Watts, B. (2010). Have we neglected the societal importance of sand dunes? - An Ecosystem Services perspective. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *20*, 476-487

Feagin, R.A., Sherman, D.J. & Grant, W.E. (2005). Coastal erosion, global sea-level rise, and the loss of sand dune plant habitats. *Frontiers in Ecology and the Environment*, *3*, 359-364

Frederiksen, L., Kollmann, J., Vestergaard, P. & Bruun, H.H. (2006). A multivariate approach to plant community distribution in the coastal dune zonation of NW Denmark. *Phytocoenologia*, 36, 321-342. doi: 10.1127/0340-269X/2006/0036-0321

French, P.W. (2001). Coastal Defences: Processes, Problems and Solutions. Routledge: London

Genovesi, P., Angelini, P., Bianchi, E., Dupré, E., Ercole, S., Giacanelli, V., Ronchi, F. & Stoch, F. (2014). Specie e habitat di interesse comunitario in Italia: distribuzione, stato di conservazione e trend. ISPRA, Serie Rapporti 194/2014. http://www.sinanet.isprambiente.it/it/Reporting_Dir_Habitat

GIS NATURA (2005). Il GIS delle conoscenze naturalistiche in Italia. Roma: Ministero dell'Ambiente e della Tutela del Territorio e del Mare (DVD)

Houston, J. (1997). Dune recreation management: experiences and trends in the UK. In Coastal Dunes, Recreation and Planning. Drees JM (ed.). EUCC Services: Leiden; pp. 21-34

Hu, F., Shou, W., Liu, B., Liu, Z., Busso, A.C. (2015). Species composition and diversity, and carbon stocks in a dune ecosystem in the Horqin Sandy Land of northern China. *Journal of Arid Land*, 7(1): 82–93. doi: 10.1007/s40333-014-0038-0

Jensen, F. (1994). Dune management in Denmark: Application of the Nature Protection Act of 1992. *Journal of Coastal Research*, *10(2)*, 263-269

Jones, M.L.M., Sowerby, A., Williams, D.L. & Jones, R.E. (2008). Factors controlling soil development in sand dunes: evidence from a coastal dune soil chronosequence. *Plant Soil*, *307(1-2),* 219-234

Jones, M.L.M., Angus, S., Cooper, A., Doody, P., Everard, M., Garbutt, A., Gilchrist, P., Hansom, G., Nicholls, R., Pye, K., Ravenscroft, N., Rees, S., Rhind, P. & Whitehouse, A. (2011). Coastal margins [chapter 11]. In: UK National Ecosystem Assessment. Understanding nature's value to society. Technical Report. Cambridge, UNEP-WCMC, 411-457

Laffoley, D. & Grimsditch, G. (eds) (2009). The management of natural coastal carbon sinks. IUCN, Gland, Switzerland. 53 pp.

La Posta, A., Duprè, E. & Bianchi, E. (2008). Attuazione della Direttiva Habitat e stato di conservazione di habitat e specie in Italia. Ministero dell'Ambiente e della Tutela del Territorio e del Mare. Direzione per la protezione della Natura. Palombi editore, Roma

Lucas, N.S., Shanmungam, S. & Barnsley, M. (2002). Sub-pixel habitat mapping of a coastal dune ecosystem. *Applied Geography*, *22*, 253-270

MAFF, (1986).The analysis of agricultural materials. MAFF/ADAS Reference Book 427. London: HMSO.

Malavasi, M., Santoro, R., Cutini, M., Acosta, A.T.R. & Carranza, M.L. (2013). Multitemporal analyses of coastal dune landscapes in Central Italy: what has happened in the last 60 years? *Landscape and Urban Planning*, *119*, 54-63

Malavasi, M., Santoro, R., Cutini, M., Acosta, A.T.R. & Carranza, M.L. (2014). The impact of human pressure on landscape patterns and plant species richness in Mediterranean coastal dunes. Plant Biosystems doi: 10.1080/11263504.2014.913730

Martínez, M.L., Psuty, N.P. & Lubke, R.A. (2004). A perspective on coastal dunes. In: Martínez M.L., Psuty N.P. (eds) Coastal dunes. Ecology and conservation. Springer, Heidelberg, pp. 3-10

McLachlan A. & Brown A. (2006). The Ecology of Sandy Shores. Elsevier USA pp. 357

Mcleod, E., Chmura, G.L., Bouillon, S., Salm, R., Björk, M., Duarte, C.M., Lovelock, C.E., Schlesinger, W.H., & Silliman, B.R. (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. *Frontiers in Ecology and the Environment*, *9*, 552-560 doi:10.1890/110004

Millennium Ecosystem Assessment (MA) (2005). Ecosystems and human well-being: wetlands and water Synthesis. World Resources Institute, Washington, DC

Nellemann, C., Corcoran, E., Duarte, C.M., Valdés, L., De Young, C., Fonseca, L., Grimsditch, G. (eds) (2009). Blue Carbon: the role of healthy oceans in binding carbon. A Rapid Response Assessment. United Nations Environment Programme, GRID-Arendal, www.grida.no

Nordstrom, K.F. (2000). Beaches and dunes of developed coasts. Cambridge: University Press.

Olff, H., Huisamn, J., Van Tooren, B.F. (1993). Species dynamics and nutrient accumulation during early primary succession in coastal sand dunes. *Journal of Ecology, 81*, 693-706.

Onori, L., Battisti, C. & Boccalaro, F. (eds) (2013). Convegno SOS Dune: stato, problemi, interventi, gestione. ISPRA Atti 2013

Picchi, S. (2008). Management of Natura 2000 habitats. 2250* Coastal dunes with *Juniperus* spp. European Commission

Prisco, I., Acosta, A.T.R., & Ercole, S. (2012). An overview of the Italian coastal dune EU habitats. *Annali di Botanica*, 2, 39-48

Regione Autonoma Friuli-Venezia Giulia (2012). Piano di gestione del SIC/ZPS IT3330006 “Valle Cavanata e Banco Mula di Muggia”

Rhymes, J., Jones, L., Lapworth, D.J., White, D., Fenner, N., McDonald, J.E. & Perkins, T.L. (2015). Using chemical, microbial and fluorescence techniques to understand contaminant sources and pathways to wetlands in a conservation site. *Science of the Total Environment*, *511*, 703-710

Rigoni, P. (2012). Piano di gestione del SIC/ZPS IT4070002 “Bardello”

Rohani, S., Dullo, B., Woudwijk, W., de Hoop, P., Kooijman, A., & Grootjans, A.P. (2014). Accumulation rates of soil organic matter in wet dune slacks on the Dutch Wadden Sea islands. *Plant and Soil*, *380*, 181-191

Romano, B. & Zullo, F. (2014). The urban transformation of Italy's Adriatic coastal strip: Fifty years of unsustainability. *Land Use Policy*, *38*, 26-36

Rossi, G., Montagnani, C., Gargano, D., Peruzzi, L., Abeli, T., Ravera, S., Cogoni, A., Fenu, G., Magrini, S., Gennai, M., Foggi, B., Wagensommer, R.P., Venturella, G., Blasi, C., Raimondo, F.M. & Orsenigo, S. (eds) (2013). Lista Rossa della Flora Italiana. 1. Policy Species e altre specie minacciate. Comitato Italiano IUCN e Ministero dell'Ambiente e della Tutela del Territorio e del Mare

Santoro, R., Jucker, T., Carranza, M.L. & Acosta, A.T.R. (2011). Assessing the effects of *Carpobrotus* invasion on coastal dune soils. Does the nature of the invaded habitat matter? *Community Ecology*, *12*(*2*), 234-240

Santoro, R., Carboni, M., Carranza, M.L., & Acosta, A.T.R. (2012). Focal species diversity patterns can provide diagnostic information on plant invasions. *Journal for Nature Conservation*, *20*, 85-91

Santoro, R., Jucker, T., Prisco, I., Carboni, M., Battisti, C., & Acosta, A.T.R. (2012). Effects of trampling limitation on coastal dune plant communities. *Environmental Management*, *49*, 534-542

Schlacher, T., Dugan, J., Schoeman, D.S., Lastra, M., Jones, A., Scapini, F., McLachlan, A., & Defeo, O. (2007). Sandy beaches at the brink. *Diversity and Distributions*, *13(5)*, 556-560

Sevink, J. (1991). Soil development in the coastal dunes and its relation to climate. *Landscape Ecology, 6,* 49-56

Stanisci, A., Acosta, A., Carranza, M.L., Feola, S. & Giuliano, M. (2007). Gli habitat di interesse comunitario sul litorale molisano e il loro valore naturalistico su base floristica. *Fitosociologia*, *44*(*2*), 171-175

Stanisci, A., Acosta, A.T.R., Carranza, M.L., de Chiro, M., Del Vecchio, S., Di Martino, L., Frattaroli, A.R., Fusco, S., Izzi, C.F., Pirone, G. & Prisco, I. (2014). EU habitats monitoring along the coastal dunes of the LTER sites of Abruzzo and Molise (Italy*). Plant Sociology*, *51*(*1*), 51-56

Van Dijk, H.W.J. (1989). Ecological impact of drinking-water production in Dutch coastal dunes. In: Perspectives in Coastal Dune Management. Proceedings of the European Symposium Leiden, September 7-11, 1987, van der Meulen, F., Jungerius, P.D. & Visser, J. (eds). SPB Academic Publishing: The Hague; 163-182

Appendix

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., 2013; 2015).

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