

1 **Assessment of coastal protection as an ecosystem service in Europe**

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10

11 **Abstract**

12 Mapping and assessment of ecosystem services is essential to provide scientific

13 support to global and EU biodiversity policy. Coastal protection has been mostly

14 analysed in the frame of coastal vulnerability studies or in local, habitat-specific

15 assessments. This paper provides a conceptual and methodological approach to

16 assess coastal protection as an ecosystem service at different spatial–temporal

17 scales, and applies it to the entire EU coastal zone. The assessment of coastal

18 protection incorporates 14 biophysical and socio-economic variables from both

19 terrestrial and marine datasets. Those variables define three indicators: coastal

20 protection capacity, coastal exposure and human demand for protection. A

21 questionnaire filled by coastal researchers helped assign ranks to categorical

22 parameters and weights to the individual variables. The three indicators are then

23 framed into the ecosystem services cascade model to estimate how coastal

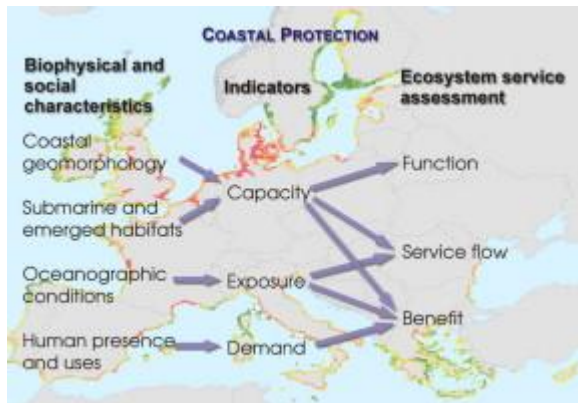
24 ecosystems provide protection, in particular describing the service function, flow and

25 benefit. The results are comparative and aim to support integrated land and marine

26 spatial planning. The main drivers of change for the provision of coastal protection
27 come from the widespread anthropogenic pressures in the European coastal zone,
28 for which a short quantitative analysis is provided.

29

30 **Graphical abstract**



31

32 **Highlights**

- 33 - We provide indicators of coastal protection capacity, exposure and demand.
- 34 - The spatial analysis includes ecological, geomorphological, physical and
35 anthropogenic parameters.
- 36 - We assess and map the ecosystem service capacity, flow and benefit in
37 Europe.
- 38 - This study supports the European and international biodiversity policy.

39

40 **Keywords**

41 Ecosystem service; Coastal erosion; Coastal inundation; Coastal protection;
42 Biodiversity; Exposure; Vulnerability

43

44 **1. Introduction**

45 Coastal areas provide essential resources for wildlife (e.g. key nursery habitats),
46 human well-being (e.g. recreation opportunities) and economy (e.g. fisheries).
47 Coasts are the preferred space for human settlement with three times the average
48 population density compared to the global average density (Small and Nicholls,
49 2003). Nearly half of the EU population (more than 200 million people) live at the
50 coast, where the rate of population growth is larger than in other EU regions
51 (Eurostat, 2011). The increasing pressure and demand for coastal resources causes
52 habitat loss and degradation, pollution and overexploitation, thus leading to the
53 degradation of coastal ecosystems (EEA, 2010). The first report by Member States
54 on the conservation of wildlife pursuing the EU Habitats Directive showed that over
55 two-thirds of coastal habitats and over half of coastal species have an 'unfavourable'
56 status (European Commission, 2009). On top of the loss of ecological values, this
57 degradation has large negative social and economic consequences.

58 The EU Biodiversity Strategy to 2020 (European Commission, 2011) aims to prevent
59 further loss of biodiversity. The Strategy's approach includes assessing, mapping
60 and valuing all ecosystem services in EU. Ecosystem services are the benefits
61 supplied by natural ecosystems that contribute to the well-being of human
62 populations. Last decade has seen a proliferation of studies on ecosystem services
63 as a response to an increase in the demand of policies containing clear and
64 objective messages able to raise awareness on environmental issues while
65 considering also socio-economic aspects. In the EU, ecosystem services are an
66 integral part of the biodiversity policy, which requires Member States to complete the
67 first mapping and assessment by 2014 as one of its supporting actions.

68 This study provides a practical example to assess the ecosystem service coastal
69 protection (CP) at EU scale. Coastal ecosystems may contribute between 36%
70 (Costanza, 1999) and 77% (Martínez et al., 2007) of global ecosystem services
71 value. However, given the complexity of coastal systems and the lack of precise
72 economic valuations, both land and marine spatial planning usually neglect natural
73 CP and other important ecosystem services. The consequences of natural hazards
74 on the coastal zone and their impacts on humans (coastal vulnerability) have been
75 subject of much research for many years (e.g. Capobianco et al., 1999, Pethick and
76 Crooks, 2000, Bryan et al., 2001, Adger et al., 2005, Green and McFadden,
77 2007, Harvey and Woodroffe, 2008, Nicholls et al., 2008 and McLaughlin and
78 Cooper, 2010). The assessment of CP as an ecosystem service has been only
79 recently addressed with a focus on the action of mangrove forests (Granek and
80 Ruttenberg, 2007, Barbier et al., 2008 and Das and Vincent, 2009), seagrass
81 meadows (Bos et al., 2007), coastal wetlands (Costanza et al., 2008 and Shepard et
82 al., 2011), sand dunes (Everard et al., 2010), several of these habitats (Rönnbäck et
83 al., 2007 and Koch et al., 2009), the specific case of coastal managed realignment
84 policy in England (Turner et al., 2007 and Luisetti et al., 2008), or even the attempt to
85 quantify bioshield protection against tsunamis (Cochard et al., 2008 and Sanford,
86 2009). Most studies focus on specific ecosystem types or local case studies, and
87 provide useful examples of the application of the ecosystems service approach as a
88 way to show the important role that particular natural environments play in coastal
89 protection. However, none of these studies proposes a conceptual framework and
90 specific metrics that can be replicated and compared across different areas or
91 spatial–temporal scales. The only integrated and geographically explicit approach
92 similar to the one proposed in this paper is the coastal vulnerability/protection model

93 of InVEST (<http://www.naturalcapitalproject.org/InVEST.html>, Guerry et al., 2012), a
94 decision support tool for mapping ecosystem services mostly at local scale.
95 This paper aims at assessing and mapping the CP ecosystem service at a
96 continental (European) scale. The first part of the paper introduces the conceptual
97 background and updates it with new, spatially explicit indicators that allow
98 quantifying each step of the so called ecosystem services cascade model (Haines-
99 Young and Potschin, 2010), namely protection capacity, coastal exposure and
100 human demand for CP. Then we describe the study area, the main variables and the
101 sources of information. The second part of the paper presents the distribution of the
102 three novel CP indicators along European coastlines, and includes an analysis of the
103 main anthropogenic pressures on the coastal zone. Finally, we map and assess the
104 ecosystem service flow and the associated benefit, discuss the applicability of our
105 approach, and propose future areas of improvement and lines of work.

106

107 **2. Methods and data**

108 **2.1. Conceptual approach**

109 For the purpose of this study, the CP ecosystem service is defined as the natural
110 defence of the coastal zone against inundation and erosion from waves, storms or
111 sea level rise. Protection here refers to the physical defence of any asset present in
112 the coastal zone (e.g. property, people, or infrastructure). Therefore, this assessment
113 includes several processes like attenuation of wave energy, flood regulation, erosion
114 control or sediment retention.

115 Several approaches to map ecosystem services have been developed and their
116 methodologies are reviewed in Burkhard et al. (2009) and Eigenbrod et al. (2010). In
117 particular the ecosystem services cascade model, which links biodiversity and

118 ecosystems to human wellbeing through the flow of ecosystem services (Haines-
119 Young and Potschin, 2010 and De Groot et al., 2010), proves to be useful for
120 framing spatial indicators of ecosystem services at multiple scales (e.g. Kienast et
121 al., 2009, Haines-Young et al., 2012, Liqueste et al., 2011, Maes et al., 2012 and van
122 Oudenhoven et al., 2012).

123 The ecosystem services cascade model is adapted here for the particular case of CP
124 (Fig. 1). In the cascade model, the biophysical structure and processes of an
125 ecosystem determine its ecological functions, which define the capacity of an
126 ecosystem to deliver a service. Those functions eventually provide a flow of
127 ecosystem services that contribute to human well-being through specific benefits.
128 Different methodologies, then, allow allocating monetary values to those benefits.
129 While this model provides a valuable conceptual framework there is a need to
130 include a set of quantitative indicators for each step of the cascade. This paper
131 proposes such set of indicators and their metrics for the regulating service CP. The
132 basic structure of those indicators is flexible to allow for replication at different scales
133 or locations. The three novel indicators for CP are:

134

135 (a) *Capacity* (CP_{cap}): The natural potential that coastal ecosystems possess to
136 protect the coast against inundation or erosion. This is based on geological
137 and ecological characteristics. This indicator links to the second compartment
138 of the cascade scheme (i.e. function or capacity).

139 (b) *Natural exposure* (CP_{exp}): The predicted need of CP based on the climatic and
140 oceanographic conditions of each area. CP_{exp} together with CP_{cap} give an
141 indication of the service flow (middle box in the cascade scheme) from a

142 natural perspective, i.e. the use of the service will be higher where the coastal
143 systems are exposed and do have protection capacity.

144 (c) *Human demand* (CP_{dem}): The estimated necessity of protection of the coastal
145 populations based on the presence of residents and assets in the coastal
146 zone. This indicator connects with one of the bottom compartments of the
147 cascade scheme, benefit.

148

149 Some similar methodological approaches (McLaughlin and Cooper, 2010 and Tallis
150 et al., 2011), defining indicators of coastal characteristics tend to merge them in a
151 final vulnerability index. In this paper we avoid such a mathematical aggregation and,
152 instead, provide a geographically explicit qualitative comparison of the three
153 indicators as an estimation of final service flow and benefit (cf. Section 4.1). Other
154 differences between our methodology and those two previous approaches are the
155 application of the cascade model, a well-defined coastal zone, the inclusion of more
156 variables, experts-based ranking and the continental scale.

157 Another novel approach of this study is to consider all types of habitats and natural
158 structures in the analysis. Usually, ecosystem services tend to be associated only to
159 the main habitats able to provide that service (see the literature review in Section 1).

160 In this study, based on the opinion of 20 experts in coastal research through the
161 compilation of individual questionnaires, a long list of habitats and natural structures
162 could be ordered in a meaningful sequence corresponding to their influence on
163 coastal protection. The prioritisation of the main categories of the variables coastal
164 geomorphology and habitats is shown in Table 1. This classification allows assigning
165 ranks to qualitative variables, which is a relatively common practice in coastal
166 studies (e.g. McLaughlin and Cooper, 2010, Özyurt and Ergin, 2010, Pendleton et

167 al., 2010 and Tallis et al., 2011). In general terms, the feedback given by the group
 168 of experts agrees well with the ranking adopted by other researchers (e.g. Pendleton
 169 et al., 2010).

170

171 Table 1.

172 Main types of coastal geomorphology and coastal habitats ordered by their

173 protective capacity following expert opinion.

Coastline geomorphology	Seabed coastal habitats	Emerged coastal habitats
Rocks or hard-rock cliffs	Rock, hard substrata or biogenic reef	Beaches, dunes, sands
Developed beaches of coarse material	Coarse or mixed sediments	Forests
Developed sandy beaches	Shallow sands	Wetlands
Conglomerates or soft-rock cliffs	Seagrass meadows	Estuaries
Small beaches separated by rocky capes	Shallow muds	Coastal lagoons
Soft sediments with rocky flats		Scrub or herbaceous vegetation
Soft non-cohesive sediments		Permanent crops
Artificial beaches		Heterogeneous agricultural areas
Muddy sediments or intertidal marshes		Arable land
Estuaries		Pastures
Vegetated strands (lake shore type)		Open spaces with little or no vegetation

174

175 The questionnaires filled by the group of experts allowed also selecting or confirming
 176 the most relevant variables for the construction of the three indicators mentioned
 177 above, as well as fixing relative weights for CP_{cap} and CP_{exp} . In the case of the
 178 CP_{dem} indicator, weighting was applied depending on the relative importance of the
 179 variables and the distribution of values. The final formulae are as follows:

180

181 $CP_{cap} = 0.33 \textit{ geo} + 0.25 \textit{ slo} + 0.21 \textit{ sea} + 0.21 \textit{ lan}$

182

183 $CP_{exp} = 0.29 \text{ wav} + 0.29 \text{ sur} + 0.23 \text{ lev} - 0.19 \text{ tid}$

184

185 $CP_{dem} = 0.35 \text{ pop} + 0.30 \text{ inf} + 0.20 \text{ art} + 0.15 \text{ cul}$

186

187 where *geo* refers to geomorphology, *slo* to slope, *sea* to seabed habitats, *lan* to land
 188 cover, *wav* to wave regime, *sur* to storm surge, *lev* to relative sea level change, *tid* to
 189 tidal amplitude, *pop* to population density, *inf* to infrastructures, *art* to artificial
 190 surface, and *cul* to cultural sites (Table 2).

191

192 Table 2.

193 List of variables and data sources considered in this study and their corresponding
 194 use for building indicators and for assessing the CP ecosystem service.

Variable	Data source	Reference	Use for indicators	Use for ecosystem service assessment
Bathymetry	GEBCO global bathymetric data with a resolution of 30 arc-seconds	BODC (2009)	Delimitation of the study area	
Topography	Global digital elevation data based on the NASA Shuttle Radar Topographic Mission (SRTM) of 3 arc-second resolution	Farr et al. (2007) post-processed by Jarvis et al. (2008)		
	Digital topographic maps for Scandinavian countries at different resolutions	De Ferranti (2009)		
Slope	Same as Topography	Same as above	CP Capacity	Capacity, flow and benefit
Geomorphology	EU coastal geomorphology data and defence works at approx. 1:100 000 resolution	Eurosion (2005)		
Submarine habitats	Modelled seabed habitat maps from the Baltic Sea, the Celtic Sea, the North Sea, and the Western Mediterranean from the EUSeaMap	JNCC (2010)		
	Modelled seabed habitat maps from the Brittany and Pays de la Loire French regions	MESH (2010)		
Emerged habitats	EU Corine Land Cover (CLC) dataset v.15 from the year 2000 with a resolution of 100 m	EEA (2011)		

Variable	Data source	Reference	Use for indicators	Use for ecosystem service assessment
Wave regime	Modelled data of maximum significant wave height estimated with the WAM 'Wave prediction Model' cycle 4.5 as implemented at the European Centre for Medium range Weather Forecasting. WAM is a continually updated spectral wave model specifically designed for global and shelf sea applications (for deep or shallow waters). It predicts directional spectra and wave characteristics of both wind sea and swell. The values used in this study represent the average of 10 years model run.	WAM model from WAMDI Group (1988) and Kommen et al. (1994)	CP Exposure	Flow and benefit
Tidal range	Tidal amplitude from the principal constituent of tide, in this case the M2 or lunar semi-diurnal wave at 1/8 of a degree resolution extracted from the FES2004 global tidal atlas	Lyard et al. (2006)		
Relative sea level	Global grid of mean sea level trends measured from satellite altimetry between 1992 and 2010 with a resolution of 1/3 of a degree. The altimeter products are produced by Ssalto/Duacs and distributed by Aviso with support from Cnes (http://www.aviso.oceanobs.com/duacs/)	CNES (2010)		
Storm surge	Global storm surge height data extracted from the Dynamic Interactive Vulnerability Assessment (DIVA) database (http://www.diva-model.net/), which collects the output data from the Storm Surge Model Systems of Delft Hydraulics. The variable used in this study is the surge height for a 1:100 year return period	Vafeidis et al. (2008)		
Population density	EU population density disaggregated with CLC 2000 at 100 m resolution	Gallego (2010)	CP Demand	Benefit
Infrastructures	Main infrastructures in the coastal zone represented here by the road network	MapCruzin (2011) dataset		
Artificial surface	Presence of artificial surface (land dedicated to urban and industrial areas) in the coastal zone extracted from CLC 2000	EEA (2011)		
Main cultural sites	Main historical, religious and cultural sites broadly represented by the UNESCO World Heritage List	UNESCO-WHC (2011)		

196 We use an additive aggregation method to construct the indicators for several
197 reasons, namely: it is the simplest aggregation method, it assumes linear
198 relationships, it is appropriate for the introduction of different weights, and it allows
199 for negative weighting. All variables were normalised and indicators are
200 dimensionless. Thus, the indicators have no meaning in absolute terms, they are
201 applied to comparative studies along EU, although this methodology can be
202 replicated at other scales (e.g. national) to highlight optimal areas for conservation or
203 restoration, most vulnerable zones, etc. Through this paper we will illustrate these
204 indicators as low, medium or high based on their statistical distribution (i.e.
205 thresholds between these classes are the 33rd and 66th percentiles).

206 **2.2. Variables and data sources**

207 The number of variables to be included in the analysis and the resolution depend on
208 the scale of the study and on data availability. Also for the construction of indicators,
209 the spatial scale determines the relationship between resolution and simplification.
210 Table 2 lists the main variables identified in this study affecting the CP in Europe, as
211 well as their link with the indicators defined in the previous section and the
212 compartments of the cascade model (Fig. 1). Other variables, such as wave direction
213 or sand availability may be relevant in local case studies but are not taken into
214 account in this continental-scale assessment. Bathymetry and topography were used
215 to establish the boundaries of the study area (Section 2.3). It is assumed here that
216 while physical processes (*wav*, *sur*, *lev* and *tid*) may trigger very different responses
217 at the coast (e.g. coastal erosion and/or inundation), they are likely to be mitigated
218 by similar geomorphological or ecological characteristics (*geo*, *slo*, *sea* and *lan*).
219 Note that this paper focuses on the natural provision of CP, i.e. CP as an ecosystem

220 service. Thus, human-made structures (e.g. coastal works, ports) are extracted from
221 the analysis and their eventual protection is not considered herein.

222 **2.3. Delimitation of the study area**

223 The coastal zone is generally perceived as the land-sea interface. However, its
224 geographical boundaries cannot be universally established; they depend directly on
225 the problem posed, on the objective of the study, and on the scale of the analysis.
226 The coastal zone considered in this study embraces the area potentially affected by
227 extreme hydrodynamic conditions. This area is delimited in general by the 50 m
228 depth isobath and the 50 m height contour line, although a minimum width of 1 nm
229 offshore and 1 km inland from the coastline are also established (Fig. 2). These
230 minimum limits avoid the total exclusion of some coastal areas due to relatively low
231 data resolution (e.g. bathymetry) or due to the presence of very steep slopes (like
232 the Irish cliffs or the Canarian continental shelf). Besides, a maximum extent of
233 50 km landwards from the shoreline is fixed to avoid identifying far inland habitats
234 and populations (like Dusseldorf in Germany) as 'coastal'. The same distance limits
235 were used, for example, in the delimitation of coastal waters by the Water
236 Framework Directive (Directive, 2000/60/EC) that established 1 nm offshore from the
237 territorial baseline; in the immediate coastal strip up to 1 km inland defined by
238 the EEA (2006) and McLaughlin and Cooper (2010); or in the coastal area extending
239 up to 50 m height after the Millennium Ecosystem Assessment (MEA, 2005).
240 Once the coastal zone was delimited, operational units of a length of approximately
241 30 km were delineated perpendicular to the coast and the main topographic and
242 bathymetry trends. This sums up a total of 1414 units or 'blocks' along the EU-27
243 coast (excluding Azores, Madeira and Canary Islands). Territorial borders inland and
244 EEZ limits offshore were respected to allow for national aggregation.

245 **2.4. Analysis and geoprocessing**

246 Data covering the variables listed in Table 2 at continental scale (EU-27) were
247 compiled and harmonised with ArcGIS® 10. Several tools of this software and a new
248 designed model were used for geoprocessing and analysis. A simplified scheme of
249 the processing of these datasets is shown in Fig. 3. All data were projected to
250 Lambert Azimutal Equal Area L52 M10 datum ETRS 1989, the same projection used
251 in all the maps of this paper.

252 After data extraction, each variable was aggregated at block level. The statistical and
253 spatial operations depend on the nature of the data. Where necessary, data gaps
254 were filled with (a) the nearest value for the oceanographic variables (wave, tide, sea
255 level, surge), (b) zeros for the absence of a particular feature (roads, UNESCO sites,
256 artificial land), and (c) the mean value for the large gaps in geomorphology and
257 seabed habitats (see points *a* and *b* in Section 4.2). Finally, all the results (the value
258 per block for each variable) were normalised based on minimum and maximum
259 values. This allows for comparability while at the same time it reflects the variability
260 within each variable.

261

262 **3. Results**

263 **3.1. CP along European shorelines**

264 Table 3 compiles the results of the quantitative data extraction along the 1414
265 coastal sectors of the EU and, thus, presents a general description of the European
266 coastal zone.

267

268 Table 3.

269 Main statistical results of the quantitative variables analysed in this study along the
 270 1414 coastal sectors in which we have divided the European shores.

	Min	Max	Mean
Land slope (degrees)	0.1	28.6	4.4
Maximum wave significant height (m)	1.3	12.1	5.2
Sea level rise (mm/yr)	-1.3	20.5	2.6
Tidal range (m)	0.01	3.9	0.5
Surge potential with a return period of 100 yr (m)	0.3	8.1	2.0
Population density (hab/km ²)	0	10,868	317
Road density (km/km ²)	0	20.1	1.4
Artificial surface (%)	0	93.7	9.5
UNESCO World Heritage Sites (no.)	0	4	<1

271

272 Fig. 4 shows the distribution of the three CP indicators across Europe. CP_{cap} is
 273 mainly driven by geomorphology, but also by the presence or certain habitats whose
 274 physical structure may disrupt the water movement or adapt their form to it (e.g.
 275 beaches/dunes and shallow rock/biogenic reef are the most protective emerged and
 276 submarine habitats, respectively). Relatively low CP_{cap} is present along the shores of
 277 Denmark, Germany, The Netherlands, some UK estuaries and the Gulf of Lion. In
 278 the Gulf of Lion, even if the coastal land cover can provide some protection, the
 279 minimum values of variables *geo*, *slo* and *sea* drive the CP_{cap} results. The other
 280 areas with relatively low CP_{cap} are driven by the combination of
 281 minimum *geo*, *slo* and *lan* values, even if *sea* is not so low. In general, shores with
 282 low protection capacity will be defenceless against any potential environmental
 283 change. Relatively high CP_{cap} values are observed in Scandinavian mid-latitudes,
 284 Scotland, Ireland, NW Spain, Corsica and parts of Greece. These results are mostly
 285 controlled by extremely high *geo* values (especially in Scotland and Ireland), a
 286 combination of high *geo* and *slo* in the Mediterranean cases (Corsica and Greece), a
 287 combination of high *geo* and *lan* in the Scandinavian cases, or the mixture
 288 of *geo*, *slo* and *lan* in NW Spain.

289

290 CP_{exp} is mainly determined by wave regime and storm surge and, to a lesser extent,
291 by relative sea level change and tidal amplitude. Experts consider that tide is
292 predominantly defensive (i.e. contributing to low values of CP_{exp}) since it builds a
293 protective buffer zone around the coast. For this reason this variable has a minus
294 sign in the formula of CP_{exp} . CP_{exp} is especially low in the most enclosed shores of
295 Greece and southern Italy, the Ligurian Sea, SE Spain, the uppermost sector of
296 some UK estuaries, and the SW Baltic Sea. These minimum results around Greece
297 are mostly due to the combination of low *sur* and *wav*, while around Italy and Spain
298 also *lev* becomes a decisive variable. The UK estuaries present minimum
299 CP_{exp} results linked to minimum *wav* and maximum *tid*, even under high *sur* values,
300 In the SW Baltic Sea the results are controlled by extremely low *wav* values.

301 CP_{exp} shows the highest values along the Bothnian Bay, Eastern coast of the North
302 Sea, Western coasts of UK and Ireland, and Brittany. In the northern Baltic Sea the
303 exposure is linked to high *lev* and low *tid* values; in the eastern North Sea this is
304 generally due to high *sur* (except in Denmark), *wav* and *lev*, and around UK, Ireland
305 and Brittany high *sur* and *wav* values even compensate for high *tid*.

306 Regarding CP_{dem} , the highest values are found near densely populated or
307 constructed areas, in particular Dublin, London, Bilbao, Malaga, Barcelona, Nice,
308 Genoa, Patra and Athens. In general, these results are based on maximum levels of
309 at least two of the variables *pop*, *inf* and *art*. CP_{dem} shows minimum values around
310 the Baltic Sea, Western coasts of UK and Ireland, Greece and NE Cyprus. This
311 demand of CP is supposed to come only from the local population needs. Other
312 beneficiaries like commuters or tourists, or other natural requirements like the
313 conservation of coastal wetlands are not taken into account.

314 Our results indicate several areas that require caution and more in-depth studies. A
315 central limitation of the ecosystem services assessments in general is that they
316 require a significant amount of process understanding, both from natural and social
317 sciences. We have partially addressed this limitation by incorporating the
318 recommendations of a group of coastal scientists in the characterisation of natural
319 habitats and coastal features. This increases the robustness of the application but
320 has highlighted the difficulties of aggregating data from the local to the continental
321 scale. Hence, it should be kept in mind that the results in this paper need to be
322 interpreted in their context (i.e. the analysis of natural coastlines at a 30 km spatial
323 resolution for conservation purposes).

324 **3.2. Anthropogenic pressure on the coastal zone**

325 About 6.5% of the analysed European coast is artificial based on the data the
326 EuroSION dataset. If we add the presence of coastal human-made structures or
327 works, this percentage rise to 14%, although it is unevenly distributed across EU
328 countries (Table 4 and Fig. 5). From the total emerged coastal zone defined in this
329 study (445,000 km²), nearly 9% was covered by urban areas in 2000. Mean
330 population density in the same coastal zone is estimated at 247 inhabitants per
331 square kilometre, also with great variability between countries (Table 4 and Fig. 5),
332 while mean road density is 1.5 km/km². As a result from human settlements and
333 activities, key coastal habitats like European coastal wetlands, seagrass meadows or
334 oyster reefs are threatened by the modification of their distribution, structure and
335 function (Airoldi and Beck, 2007).

336

337 Table 4.

338 Main statistical results of the anthropogenic influence in the coastal area (as defined
 339 in this paper) aggregated by EU Member State.

Country	Total coast length ^a (km)	Total coastal area ^b (10 ³ km ²)	Emerged coastal area ^b (10 ³ km ²)	Artificial surface ^c (%)	Artificial coast ^d (%)	Presence of coastal works ^e (%)	Roads density (km/km ²)	Population density ^e (inhab/km ²)	World heritage sites
Belgium	338	14	10	27	35	46	2.7	510	4
Bulgaria	410	6	2	13	17	13	0.8	236	1
Cyprus	786	3	2	12	21	8	1.9	124	1
Denmark	5869	119	35	8	11	4	1.2	133	2
Estonia	2646	37	16	3	1	0.3	0.4	44	1
Finland	16,684	87	36	5	1	0.05	0.7	64	4
France	7244	98	44	11	17	19	1.1	204	5
Germany	2653	98	43	8	17	22	2.1	187	3
Greece	14,923	49	21	5	4	4	1.1	199	5
Ireland	6769	34	16	4	3	8	0.9	113	1
Italy	7661	75	36	12	9	15	1.4	445	12
Latvia	512	30	14	3	4	6	0.5	96	1
Lithuania	91	6	3	5	12	0	0.2	97	0
Malta	214	0.4	0.2	24	7	0	6.6	1241	2
Netherlands	1295	81	19	13	64	11	4.2	463	6
Poland	527	26	12	4	3	22	0.7	157	1
Portugal	1430	15	8	10	6	7	0.7	333	3
Romania	342	14	6	5	2	12	0.3	92	1
Slovenia	40	0.3	0.1	18	18	82	2.4	593	0
Spain	6579	37	18	12	11	4	1.6	653	8
Sweden	19,860	118	44	7	1	1	0.9	106	9
United Kingdom	18,865	203	60	13	5	14	2.2	428	11

340 a - Based on the CLC coastline.

341 b - Based on the coastal zone delimited in this study.

342 c - Based on the CLC 2000 classification.

343 d - Based on the EuroSION v2 dataset.

344 e - Based on Gallego (2010).

345

346 Countries surrounding the North Sea are those with a highest proportion of
347 submarine coastal area, due to the shallow depth and large area of the continental
348 shelf. In general, countries with relatively short coastline tend to have high
349 percentages of artificial surface and artificial structures in the coastal area. Belgium,
350 Netherlands and Slovenia are the countries with the most extensive pressure on the
351 coastal zone in terms of modified coastline and infrastructures in the coastal zone.
352 Belgium and Malta show the highest share of coastal artificial surface. UK has the
353 largest coastal area and the biggest population living on it, although population
354 density peaks in Malta.

355

356 **4. Discussion**

357 **4.1. Assessment of service flow and benefit**

358 From an ecosystem service perspective, the CP service flow can be estimated as a
359 combination of CP_{cap} and CP_{exp} , which represent the potential to deliver the service
360 (capacity) and the need of it (exposure). In this case, we considered that the service
361 flow is 'sufficient' if the class of CP_{cap} equals that of CP_{exp} (Table 5A). These classes
362 are based on a qualitative description of the indicator values (low, medium or high)
363 limited by their 33rd and 66th percentiles; thus the results are comparative and
364 illustrative. A situation with relatively more CP_{exp} than CP_{cap} would be 'deficient', and
365 the contrary would be 'plentiful'. The 'plentiful' class would be the most stable in
366 terms of resilience meaning that, even under changing scenarios, it may adapt and
367 show enough protection capability.

368

369 Table 5.

370 Cross-tabulations leading to the definition of (A) service flow and (B) service benefit
 371 classes. The colour code corresponds to the flow and benefit scales, as follows:
 372 red = deficient, amber = sufficient, green = plentiful.

		CP _{exp}					CP _{dem}		
		Low	Medium	High			Low	Medium	High
CP _{cap}	Low	Amber	Red	Red	CP flow	Deficient	Amber	Red	Red
	Medium	Green	Amber	Red		Sufficient	Green	Amber	Red
	High	Green	Green	Amber		Plentiful	Green	Green	Amber

373
 374

375 As illustrated in Fig. 6A, the CP service flow is covered or plentiful mainly around
 376 Greece, the Tyrrhenian and Ligurian Seas, Scotland and part of the Baltic Sea. It
 377 seems sufficient in the shores of Cyprus, Italy and scattered areas of most of the EU
 378 countries. Deficient CP flow is found widespread across the Atlantic and Baltic
 379 shores. In summary, 28% of the EU coast falls into the deficient category, 39% into
 380 the sufficient, and 33% into the plentiful. Again, note that this classification is based
 381 on statistical distributions and, thus, it shows no absolute values or thresholds linked
 382 to natural processes.

383 To get an indication of the CP benefit for society we have to cross the
 384 CP_{dem} information with the CP flow. Thus, we condense the previous service flow
 385 categories into deficient, sufficient and plentiful and we combine them with the
 386 human demand (Table 5B). We encounter three possible situations: just enough flow
 387 to cover the demand (sufficient class), insufficient flow to face the relatively high
 388 demand (deficient class), or a service flow that may exceed the human needs
 389 (plentiful class).

390 Fig. 6B shows that covered or plentiful CP benefit is mostly concentrated in Greece,
 391 around the Mediterranean islands, along the Eastern Scottish and Irish coasts, and

392 in Scandinavian shores. On the contrary, the benefit seems deficient for human
393 needs in the Southern Baltic, most of the EU Atlantic continental coast, England,
394 Mediterranean Spain, and Italy. The sufficient category of CP benefit is scattered
395 and widespread along the study area. The proportion of EU coastline classified as
396 deficient, sufficient and plentiful for CP benefit is 31, 27 and 42%, respectively.
397 This kind of assessment can be replicated in other study areas and used to highlight
398 the most deficient coastal zones in terms of CP capacity, CP flow and CP benefit, as
399 illustrated by the following examples. In general, a good conservation strategy
400 aiming to increase the resilience of the coastal areas should focus in the restoration
401 or improvement of the status of the low capacity coastal zones ($CP_{cap} = \text{low}$).
402 Optimally, it should take into account other ecosystem services such as fish
403 provision, water purification or recreation, together with their possible trade-offs and
404 synergies, but this is out of the scope of this paper. If coastal inundation and erosion
405 is a significant problem in the study area, special attention should be devoted to the
406 deficient flow zones (CP flow = deficient). If the scope of the decision-making is to
407 maximise the benefit that coastal communities could derived from the natural CP,
408 then the focus should go to the deficient benefit zones (CP benefit = deficient).
409 However, the 'sufficient' zones should also be monitored and controlled, since they
410 stand at the borderline with degrading or unsustainable systems; a situation that is
411 especially risky in highly exposed or highly populated coastal areas.

412 **4.2. Data and methodological gaps**

413 Continental scale analyses (like this study) allow highlighting the main knowledge
414 and data gaps across regions. Concerning the study of the coastal zone in EU, there
415 are some key aspects that could improve the quality of this or similar studies,
416 namely:

417 (a) The update and extension of the EuroSION database, which covers basic
418 aspects such as geomorphology, geology of the coast, erosive trends and
419 presence of human-made structures. The dataset became public on 2005 but
420 some data date back to 1990. Shorelines from Cyprus, Bulgaria and Romania
421 are only covered around 20%.

422 (b) The extension (and plan for future updates) of the EU sea habitat maps to
423 cover the full NE Atlantic region (Bay of Biscay and Iberian Peninsula, where
424 the MESH-Atlantic project is presently working), Eastern Mediterranean and
425 Western Black Sea. To reach this kind of model outputs a lot of effort should
426 be invested in experimental benthic habitat mapping, especially in the busy
427 and productive continental shelf.

428 (c) In line with the communication from the European Commission (2010), ease
429 the access to oceanographic model results for secondary uses (data re-use),
430 such the development of new indicators for ecosystem service assessment
431 performed in this study.

432 (d) The development (or compilation) of a European bathymetry map at higher
433 resolution than the global datasets presently available.

434 (e) The development of spatially explicit socio-economic datasets at least to a
435 level that could be comparable to the available environmental data. This could
436 improve the quality and adequacy of the data input for the assessment of
437 human demand and benefit.

438 Based on the questionnaires described in Section 2.1, we could retrieve useful
439 comments from experts on potential knowledge gaps of this study. In general, the
440 present continental scale approach is seen as a rough analysis that may oversimplify
441 the local coastal processes. Indeed, specific local coastal processes cannot be taken

442 into account at this scale and resolution but the sound knowledge derived from them
443 can be used to feed broader analyses aimed at supporting EU policy. In general, in
444 coastal studies we lack the important step of the aggregation of data and knowledge
445 transfer from local case studies to regional ones, as well as from complex scientific
446 results to useful information for managers and policy makers.

447 Some important factors for CP mentioned by the experts but not included in the
448 present study due to the lack of large-scale datasets or methodologies for the
449 analysis are: local sediment budget (sand availability, beach stability, etc.);
450 subsidence; main direction of morphologic features with respect to the wave action;
451 coastal development and management; distinction between low coasts and high
452 coasts as tidal amplitude can play opposite roles in them; the local change of the
453 relative weight of the variables; habitats only within the strip between 10 m depth and
454 10 m height; the influence of new climate change conditions on the protection
455 provided by habitats (which is one of the scenarios to be develop in future research);
456 and the dynamic adaptation capability of a coastal area vs. its exposure. Apart from
457 this, we highlight as extra relevant variables to be included in local scale studies: the
458 actual condition ('health') of the ecosystems (e.g. biomass density as in Koch et al.,
459 2009), and the specific non-linear response of each habitat for protection as already
460 highlighted by Barbier et al. (2008) and Koch et al. (2009).

461 **4.3. Application of the assessment of CP**

462 The indicator architecture proposed in this paper can be applied to other studies,
463 even if the selection of variables may vary depending on the scale and objective.
464 The dimensionless indicators are devoted to comparative studies either between
465 areas (as shown in this paper) or between moments on time (including scenarios) to
466 analyse the trend of service capacity, flow and benefit through time.

467 The assessment shown in this paper is thought to assist the comparison between
468 European regions and to inspire national or regional scale studies of ecosystem
469 services. In Europe, it may have a direct application for the assessment and
470 mapping exercise required under Action 5 of the EU Biodiversity Strategy to 2020
471 (European Commission, 2011) that Member States should complete by 2014. It
472 could also be applied under Action 6 of the same Strategy as one of the approaches
473 to point out potential areas for restoration, either for their poor protection capacity or
474 for the high demand of CP. Furthermore, this work may also support the
475 implementation of the EU Floods Directive (Directive, 2007/60/EC) in particular to
476 inspire to or to compare with the national coastal flood hazard and risk maps that
477 Member States are required to submit by the end of 2013. In addition, other EU
478 policies are now integrating the ecosystem services approach into their decisions
479 and planning (Maes et al., 2012). At a broader international level, our kind of
480 approach could be applied by any country signatory to the convention on biological
481 diversity (CBD) that is bound to include ecosystem services on its biodiversity
482 strategy under the global Strategic Plan for the period 2011–2020.

483 It must be noted that valuation, the last step of the ecosystem service analysis, has
484 not been accomplished in this study. Despite the importance of the CP ecosystem
485 service, only a few economic studies have estimated a value for it using quite
486 different approaches (e.g. Pérez-Maqueo et al., 2007, Costanza et al.,
487 2008 and Barbier et al., 2011). Indeed, the valuation of ecosystem services for
488 conservation purposes, optimally linking natural models and economic valuation
489 techniques, is a controversial and complex issue. The economic valuation of CP
490 across all habitat types and all kind of hazards in an entire continent is, thus, a great

491 challenge. Our CP benefit indicator could be used as a proxy of the potential
492 distribution of that value.

493 The assessment of the capacity and flow of CP shown in this paper reflects the
494 natural provision of this ecosystem service, excluding human-made works. However,
495 due to the widespread and increasing pressure of human intervention in the
496 European coasts, a few words must be devoted to this issue. Traditionally, hard
497 defence structures to mitigate oceanographic forces have been the main response to
498 protect coastal population and assets in highly exposed areas. Even if they can be
499 unavoidable in certain cases, like the Venice lagoon, they have also demonstrated to
500 unbalance sediment dynamics and ecological processes in adjacent zones (Airoldi et
501 al., 2005) and to neglect long-term sustainability (Pethick and Crooks, 2000). Facing
502 the future consequences of climate change, the increasing coastal population, and
503 the economic constrains to maintain coastal engineering works, authors advocate for
504 an adaptive strategy that introduces the protective role of coastal ecosystems in land
505 and marine spatial planning, even knowing that major changes in attitudes are
506 required for the adoption of this principle (Cooper and Mckenna, 2008). The analysis
507 of ecosystem services can be a good communication tool to foster the sustainability
508 and resilience of coastal communities.

509

510 **5. Conclusions**

511 Natural hazard regulation services, like coastal protection (CP), show a declining
512 trend due to the rapid loss of natural buffers such as coastal wetlands, while at the
513 same time the value of those regulation services keeps rising given the increase in
514 human vulnerability to natural hazards (Elmqvist et al., 2010). Still, the role of

515 ecosystems on the moderation of extreme events is poorly understood and it is
516 rarely taken into account in management or land/marine spatial planning decisions.
517 This paper proposes a conceptual framework and spatially explicit indicators of CP
518 from an ecosystem service perspective, that is, it assesses the natural capacity, the
519 service flow and the demand of that service. We apply the proposed methodology on
520 the European continent. This work may support, amongst others, the implementation
521 of the EU Biodiversity Strategy and the EU Floods Directive. The analysis can be
522 replicated at different spatial and temporal scales. Specific data and knowledge gaps
523 for this continental scale assessment have been highlighted, as well as further
524 variables to improve the resolution at smaller scales. Next steps in this research
525 could include the monetary valuation of natural CP in Europe, and a series of
526 climatic and policy scenarios to visualise the evolution of the service capacity, flow
527 and benefit. This approach could be also used to assess how different pressures can
528 deteriorate the ability of coastal ecosystems to provide protection, leading to large
529 negative social and economic consequences.

530 Ten biophysical variables and four socio-economic ones are included in this
531 assessment. CP capacity is mainly driven by geomorphology, but also by the
532 presence or certain habitats whose physical structure may disrupt the water
533 movement or adapt their form to it. CP exposure is primarily determined by wave
534 regime and storm surge and, to a lesser extent, by relative sea level change and
535 tidal amplitude. CP demand reflects the trends in population density and the
536 presence of economic and cultural assets in the coastal zone. The combination of
537 CP capacity and CP exposure gives an insight of the CP service flow. This service
538 flow together with CP demand allows assessing the CP benefit. Our methodology
539 proposes a flexible and reproducible approach to the assessment of CP.

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786

787 **List of figures**

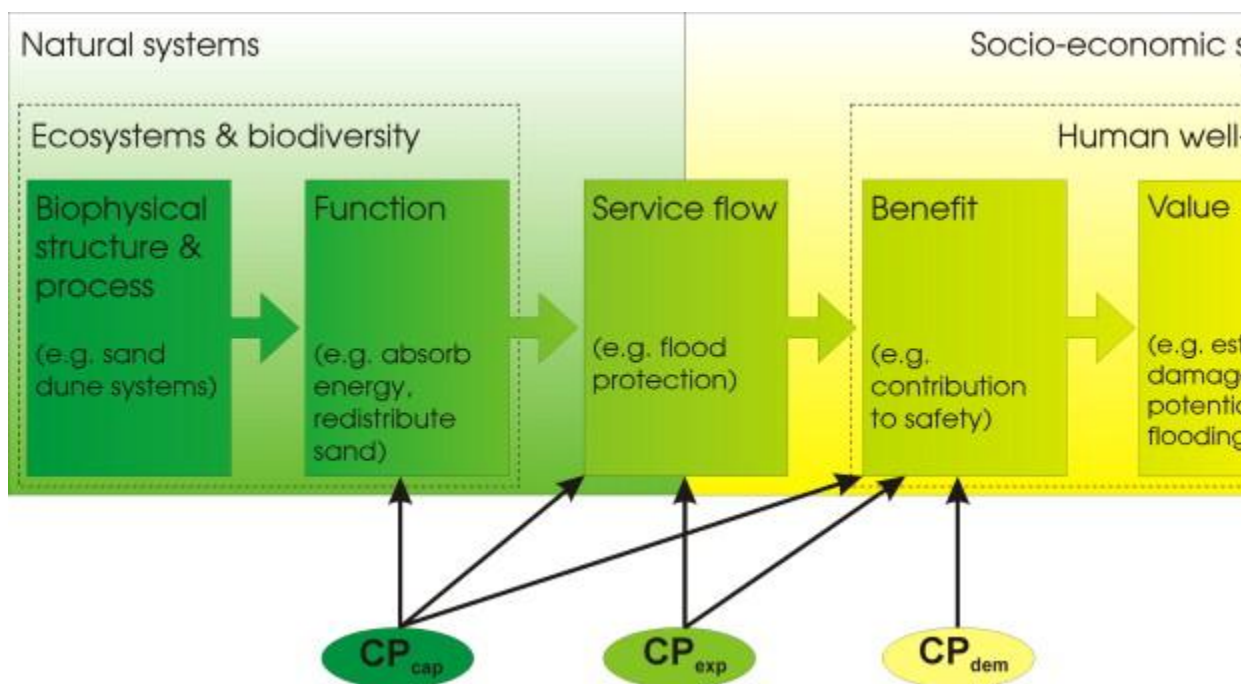


Fig. 1. Conceptual framework followed in this paper. The upper boxes show the basic structure of the cascade model framed within the natural and socio-economic context. The examples refer to the CP case study. The bottom shapes and arrows represent the indicators proposed in this paper that inform the different compartments of the cascade model.

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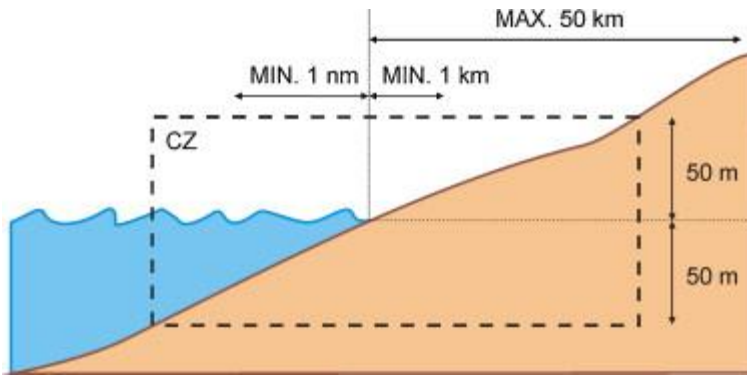


Fig. 2. Diagram showing the delimitation of the coastal zone (dashed box, CZ). Minimum and maximum distances from the shoreline (upper arrows) are always respected.

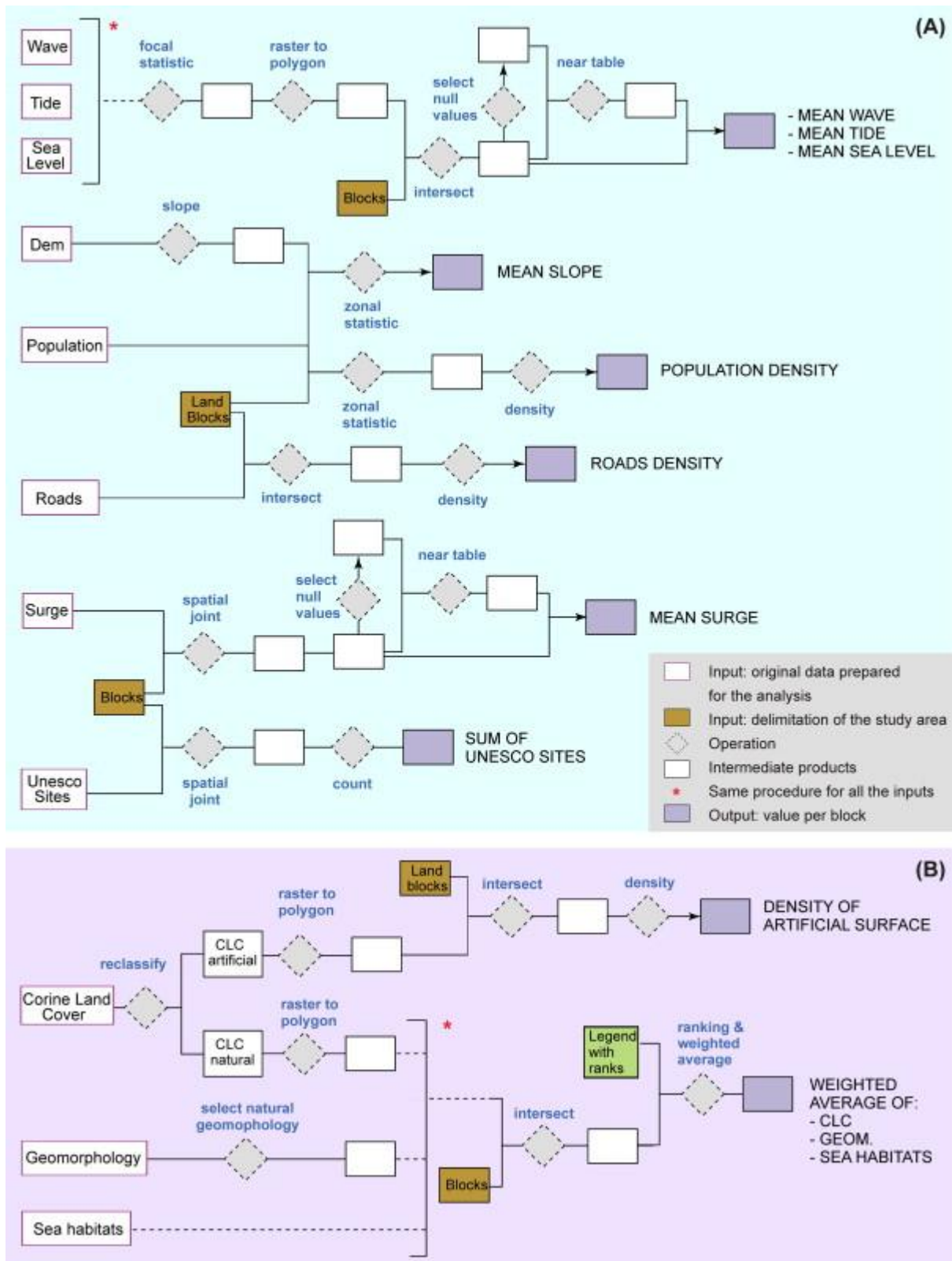


Fig. 3. Flow diagrams showing the simplified methodology used in this study to: (A) process the quantitative data, and (B) process the qualitative data.

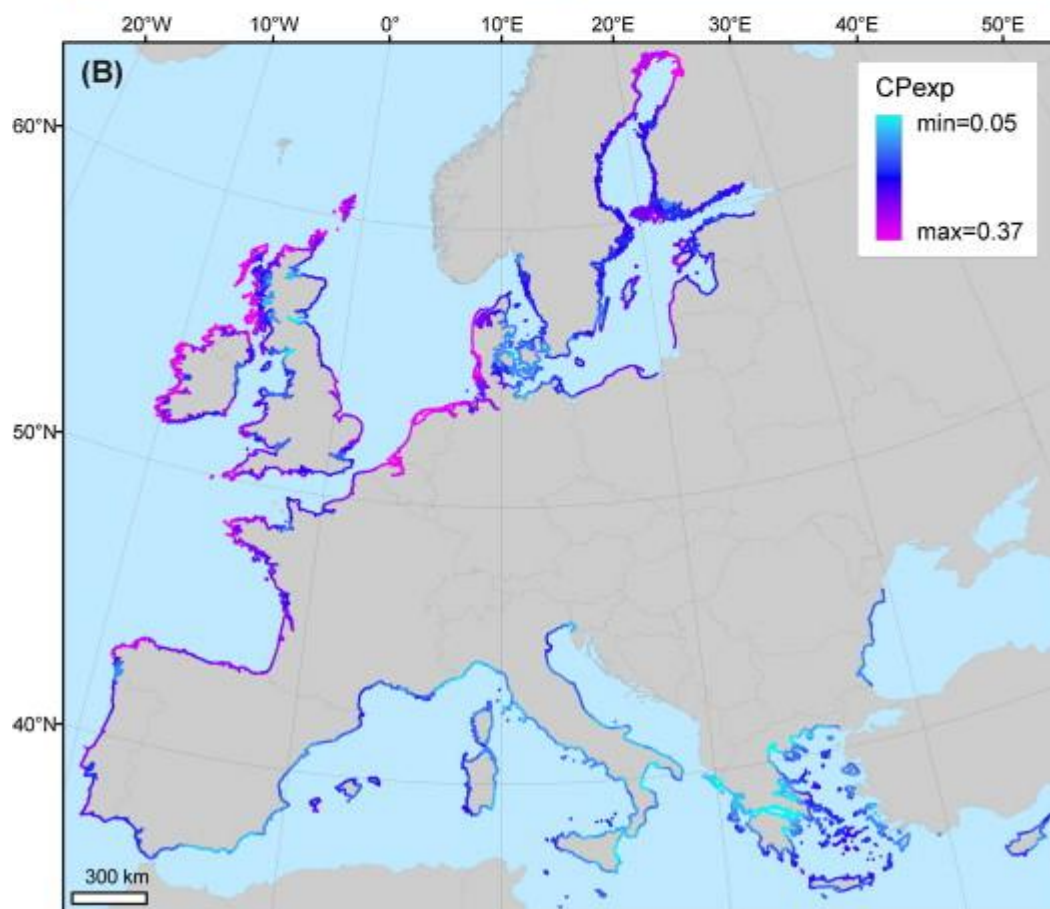
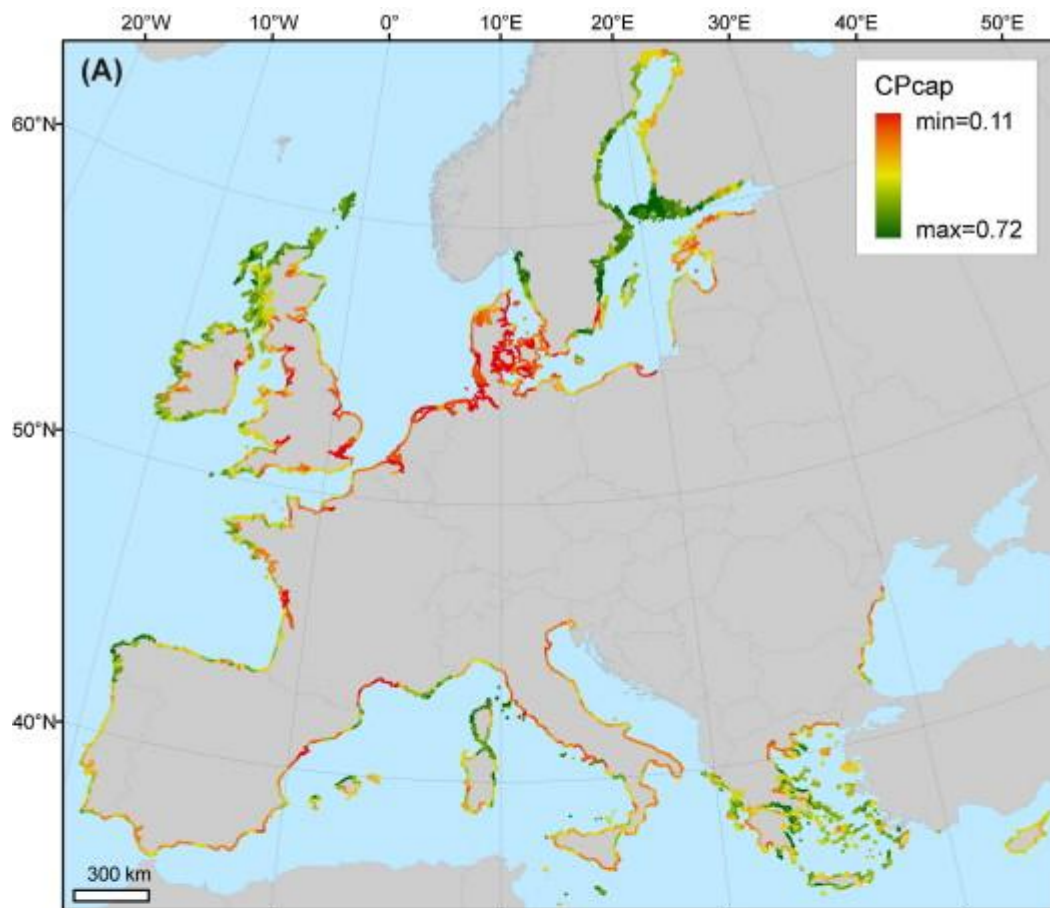


Fig. 4. Estimation of the set of indicators proposed in this study along the European shoreline: (A) coastal protection capacity (CP_{cap}); (B) coastal exposure (CP_{exp}); and (C) demand for coastal protection (CP_{dem}).

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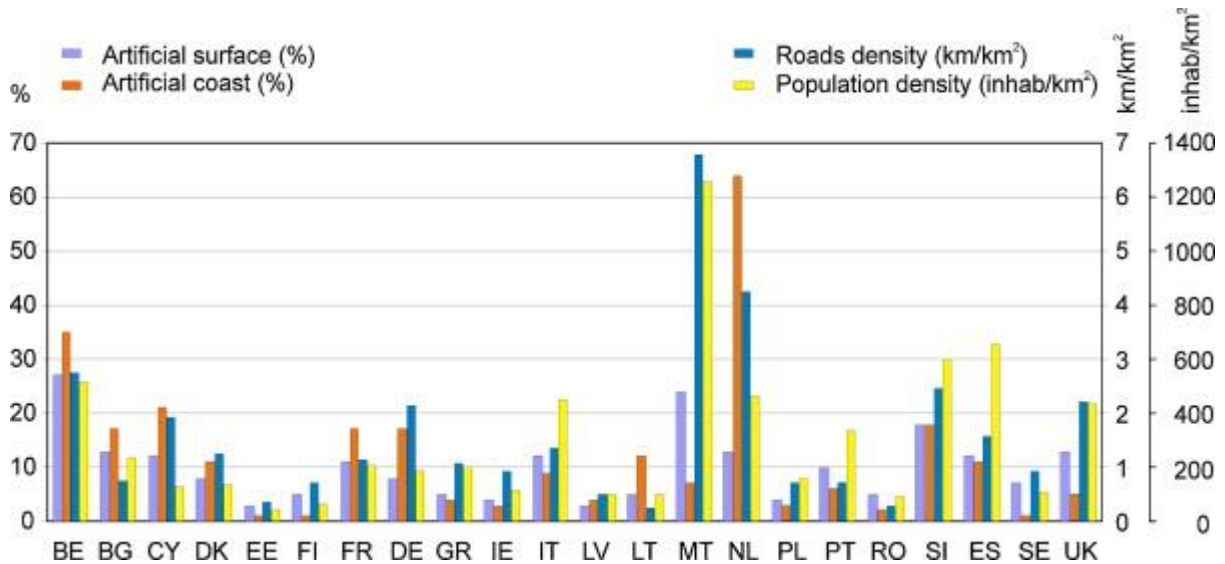


Fig. 5. Main anthropogenic pressures present in the coastal zone per EU Member State (coastal zone as defined in this study). Artificial surface and artificial coast are shown in the left vertical axis, while roads density and population density refer to the corresponding right vertical axes.

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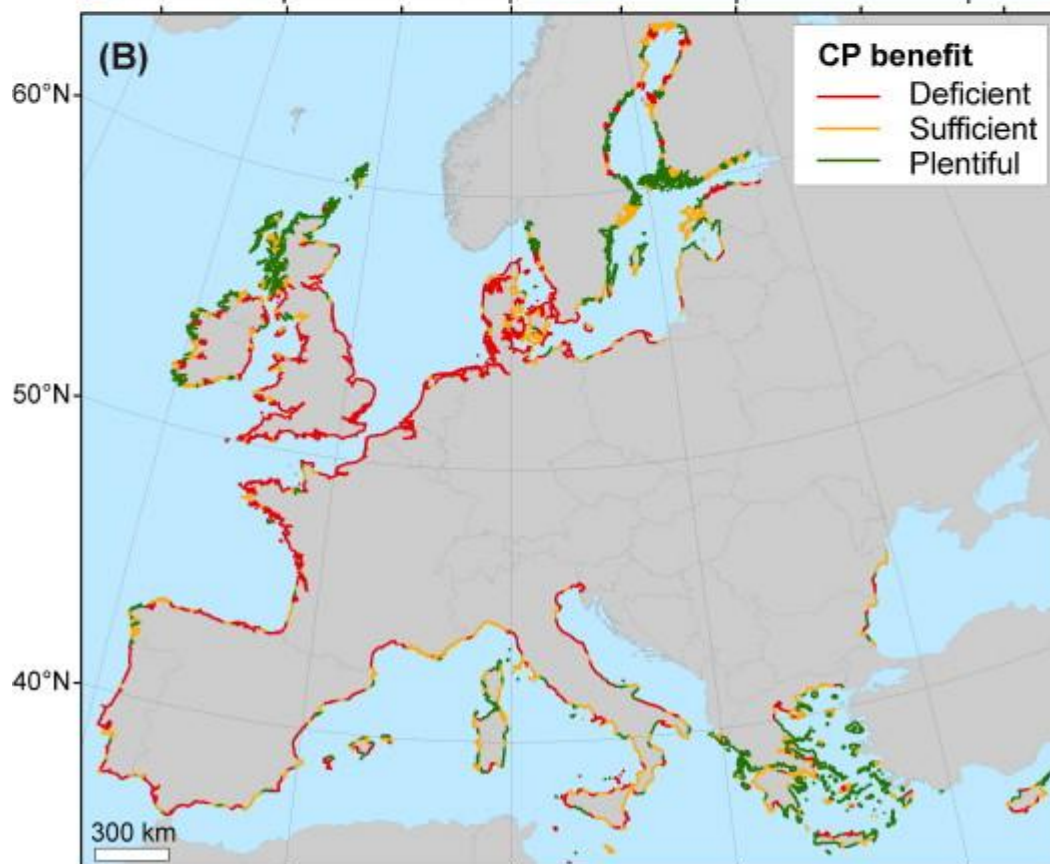
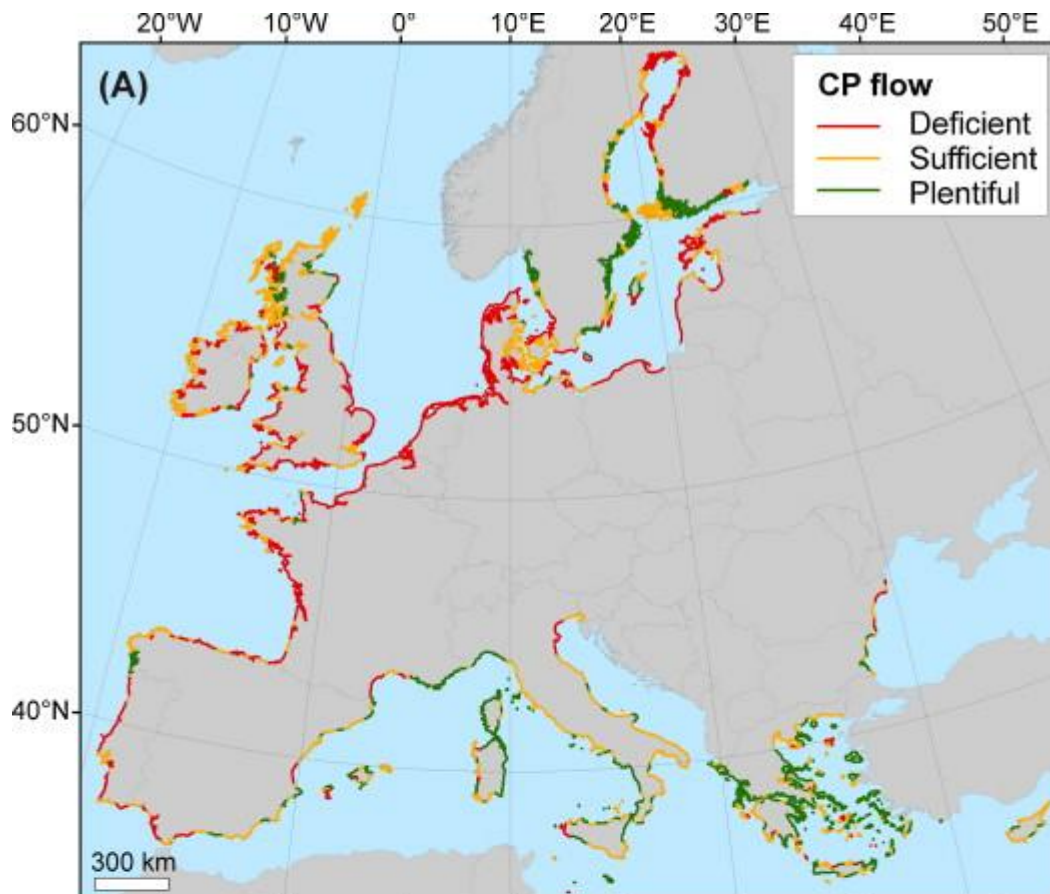


Fig. 6. (A) Coastal protection service flow (CP flow) estimated as a cross-tabulation of CP capacity and exposure (see Table 5A). (B) Coastal protection service benefit (CP benefit) estimated as a cross-tabulation of service flow and CP demand (see Table 5B).