View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Edge Hill University Research Information Repository

Assessment of coastal protection as an ecosystem service in Europe

Camino Liquete[a], Grazia Zulian[a], Irene Delgado-Fernandez[b], Adolf Stips[a], Joachim Maes[a]

[a]European Commission, Joint Research Centre, Institute for Environment and Sustainability, Via E. Fermi 2749, I-21027 Ispra, VA, Italy

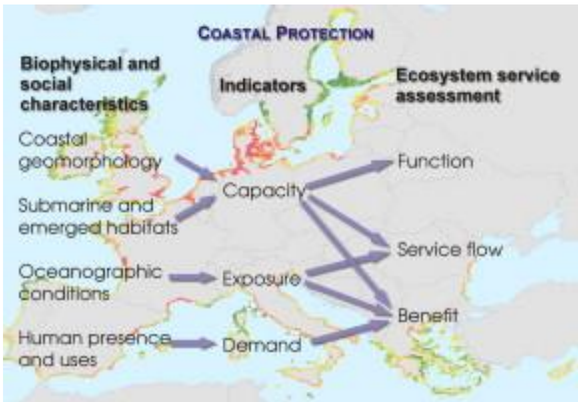
[b]Department of Natural, Geographical & Applied Sciences, Edge Hill University, St Helens Road, Ormskirk, Lancashire L39 4QP, UK

Abstract

Mapping and assessment of ecosystem services is essential to provide scientific support to global and EU biodiversity policy. Coastal protection has been mostly analysed in the frame of coastal vulnerability studies or in local, habitat-specific assessments. This paper provides a conceptual and methodological approach to assess coastal protection as an ecosystem service at different spatial–temporal scales, and applies it to the entire EU coastal zone. The assessment of coastal protection incorporates 14 biophysical and socio-economic variables from both terrestrial and marine datasets. Those variables define three indicators: coastal protection capacity, coastal exposure and human demand for protection. A questionnaire filled by coastal researchers helped assign ranks to categorical parameters and weights to the individual variables. The three indicators are then framed into the ecosystem services cascade model to estimate how coastal ecosystems provide protection, in particular describing the service function, flow and benefit. The results are comparative and aim to support integrated land and marine

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

Graphical abstract



Highlights

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

Keywords

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

1. Introduction

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

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

This study provides a practical example to assess the ecosystem service coastal protection (CP) at EU scale. Coastal ecosystems may contribute between 36% (Costanza, 1999) and 77% (Martínez et al., 2007) of global ecosystem services value. However, given the complexity of coastal systems and the lack of precise economic valuations, both land and marine spatial planning usually neglect natural CP and other important ecosystem services. The consequences of natural hazards on the coastal zone and their impacts on humans (coastal vulnerability) have been subject of much research for many years (e.g. Capobianco et al., 1999, Pethick and Crooks, 2000, Bryan et al., 2001, Adger et al., 2005, Green and McFadden, 2007, Harvey and Woodroffe, 2008, Nicholls et al., 2008 and McLaughlin and Cooper, 2010). The assessment of CP as an ecosystem service has been only recently addressed with a focus on the action of mangrove forests (Granek and Ruttenberg, 2007, Barbier et al., 2008 and Das and Vincent, 2009), seagrass meadows (Bos et al., 2007), coastal wetlands (Costanza et al., 2008 and Shepard et al., 2011), sand dunes (Everard et al., 2010), several of these habitats (Rönnbäck et al., 2007 and Koch et al., 2009), the specific case of coastal managed realignment policy in England (Turner et al., 2007 and Luisetti et al., 2008), or even the attempt to quantify bioshield protection against tsunamis (Cochard et al., 2008 and Sanford, 2009). Most studies focus on specific ecosystem types or local case studies, and provide useful examples of the application of the ecosystems service approach as a way to show the important role that particular natural environments play in coastal protection. However, none of these studies proposes a conceptual framework and specific metrics that can be replicated and compared across different areas or spatial–temporal scales. The only integrated and geographically explicit approach similar to the one proposed in this paper is the coastal vulnerability/protection model of InVEST (http://www.naturalcapitalproject.org/InVEST.html, Guerry et al., 2012), a decision support tool for mapping ecosystem services mostly at local scale.

This paper aims at assessing and mapping the CP ecosystem service at a continental (European) scale. The first part of the paper introduces the conceptual background and updates it with new, spatially explicit indicators that allow quantifying each step of the so called ecosystem services cascade model (Haines-Young and Potschin, 2010), namely protection capacity, coastal exposure and human demand for CP. Then we describe the study area, the main variables and the sources of information. The second part of the paper presents the distribution of the three novel CP indicators along European coastlines, and includes an analysis of the main anthropogenic pressures on the coastal zone. Finally, we map and assess the ecosystem service flow and the associated benefit, discuss the applicability of our approach, and propose future areas of improvement and lines of work.

2. Methods and data

2.1. Conceptual approach

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

Several approaches to map ecosystem services have been developed and their methodologies are reviewed in Burkhard et al. (2009) and Eigenbrod et al. (2010). In particular the ecosystem services cascade model, which links biodiversity and ecosystems to human wellbeing through the flow of ecosystem services (Haines-Young and Potschin, 2010 and De Groot et al., 2010), proves to be useful for framing spatial indicators of ecosystem services at multiple scales (e.g. Kienast et al., 2009, Haines-Young et al., 2012, Liquete et al., 2011, Maes et al., 2012 and van Oudenhoven et al., 2012).

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

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

(b) *Natural exposure* (CP_{exp}): The predicted need of CP based on the climatic and oceanographic conditions of each area. CP_{exp} together with CP_{cap} give an indication of the service flow (middle box in the cascade scheme) from a natural perspective, i.e. the use of the service will be higher where the coastal systems are exposed and do have protection capacity.

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

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

Another novel approach of this study is to consider all types of habitats and natural structures in the analysis. Usually, ecosystem services tend to be associated only to the main habitats able to provide that service (see the literature review in Section 1). In this study, based on the opinion of 20 experts in coastal research through the compilation of individual questionnaires, a long list of habitats and natural structures could be ordered in a meaningful sequence corresponding to their influence on coastal protection. The prioritisation of the main categories of the variables coastal geomorphology and habitats is shown in Table 1. This classification allows assigning ranks to qualitative variables, which is a relatively common practice in coastal studies (e.g. McLaughlin and Cooper, 2010, Özyurt and Ergin, 2010, Pendleton et al., 2010 and Tallis et al., 2011). In general terms, the feedback given by the group of experts agrees well with the ranking adopted by other researchers (e.g. Pendleton et al., 2010).

Table 1.
Main types of coastal geomorphology and coastal habitats ordered by their 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

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

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

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

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

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

Table 2.

List of variables and data sources considered in this study and their corresponding 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 fromWAMDI Group (1988) andKomen 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)		

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

2.2. Variables and data sources

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

2.3. Delimitation of the study area

The coastal zone is generally perceived as the land-sea interface. However, its geographical boundaries cannot be universally established; they depend directly on the problem posed, on the objective of the study, and on the scale of the analysis. The coastal zone considered in this study embraces the area potentially affected by extreme hydrodynamic conditions. This area is delimited in general by the 50 m depth isobath and the 50 m height contour line, although a minimum width of 1 nm offshore and 1 km inland from the coastline are also established (Fig. 2). These minimum limits avoid the total exclusion of some coastal areas due to relatively low data resolution (e.g. bathymetry) or due to the presence of very steep slopes (like the Irish cliffs or the Canarian continental shelf). Besides, a maximum extent of 50 km landwards from the shoreline is fixed to avoid identifying far inland habitats and populations (like Dusseldorf in Germany) as ‘coastal’. The same distance limits were used, for example, in the delimitation of coastal waters by the Water Framework Directive (Directive, 2000/60/EC) that established 1 nm offshore from the territorial baseline; in the immediate coastal strip up to 1 km inland defined by the EEA (2006) and McLaughlin and Cooper (2010); or in the coastal area extending up to 50 m height after the Millennium Ecosystem Assessment (MEA, 2005).

Once the coastal zone was delimited, operational units of a length of approximately 30 km were delineated perpendicular to the coast and the main topographic and bathymetry trends. This sums up a total of 1414 units or ‘blocks’ along the EU-27 coast (excluding Azores, Madeira and Canary Islands). Territorial borders inland and EEZ limits offshore were respected to allow for national aggregation.

2.4. Analysis and geoprocessing

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

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

3. Results

3.1. CP along European shorelines

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

Table 3.

Main statistical results of the quantitative variables analysed in this study along the 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

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

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

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

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

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

3.2. Anthropogenic pressure on the coastal zone

About 6.5% of the analysed European coast is artificial based on the data the Eurosion dataset. If we add the presence of coastal human-made structures or works, this percentage rise to 14%, although it is unevenly distributed across EU countries (Table 4and Fig. 5). From the total emerged coastal zone defined in this study (445,000 km^2), nearly 9% was covered by urban areas in 2000. Mean population density in the same coastal zone is estimated at 247 inhabitants per square kilometre, also with great variability between countries (Table 4 and Fig. 5), while mean road density is 1.5 km/km^2. As a result from human settlements and activities, key coastal habitats like European coastal wetlands, seagrass meadows or oyster reefs are threatened by the modification of their distribution, structure and function (Airoldi and Beck, 2007).

Table 4.

Main statistical results of the anthropogenic influence in the coastal area (as defined 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

a - Based on the CLC coastline.
b - Based on the coastal zone delimited in this study.
c - Based on the CLC 2000 classification.
d - Based on the Eurosion v2 dataset.
e - Based on Gallego (2010).

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

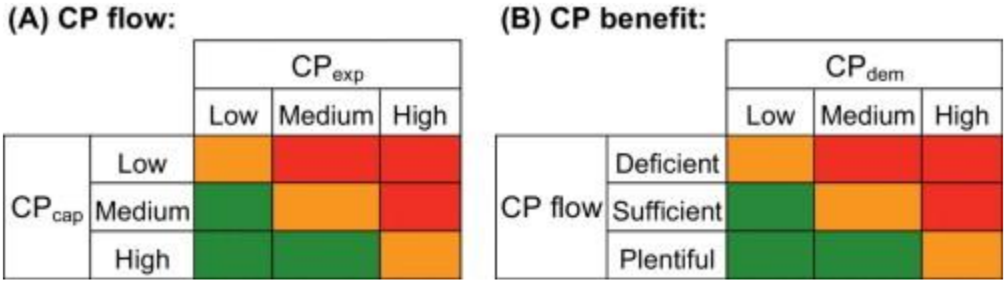
4. Discussion

4.1. Assessment of service flow and benefit

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

Table 5.

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



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

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

Fig. 6B shows that covered or plentiful CP benefit is mostly concentrated in Greece, around the Mediterranean islands, along the Eastern Scottish and Irish coasts, and in Scandinavian shores. On the contrary, the benefit seems deficient for human needs in the Southern Baltic, most of the EU Atlantic continental coast, England, Mediterranean Spain, and Italy. The sufficient category of CP benefit is scattered and widespread along the study area. The proportion of EU coastline classified as deficient, sufficient and plentiful for CP benefit is 31, 27 and 42%, respectively. This kind of assessment can be replicated in other study areas and used to highlight the most deficient coastal zones in terms of CP capacity, CP flow and CP benefit, as illustrated by the following examples. In general, a good conservation strategy aiming to increase the resilience of the coastal areas should focus in the restoration or improvement of the status of the low capacity coastal zones (CP_{cap} = low). Optimally, it should take into account other ecosystem services such as fish provision, water purification or recreation, together with their possible trade-offs and synergies, but this is out of the scope of this paper. If coastal inundation and erosion is a significant problem in the study area, special attention should be devoted to the deficient flow zones (CP flow = deficient). If the scope of the decision-making is to maximise the benefit that coastal communities could derived from the natural CP, then the focus should go to the deficient benefit zones (CP benefit = deficient). However, the 'sufficient' zones should also be monitored and controlled, since they stand at the borderline with degrading or unsustainable systems; a situation that is especially risky in highly exposed or highly populated coastal areas.

4.2. Data and methodological gaps

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

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

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

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

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

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

Based on the questionnaires described in Section 2.1, we could retrieve useful comments from experts on potential knowledge gaps of this study. In general, the present continental scale approach is seen as a rough analysis that may oversimplify the local coastal processes. Indeed, specific local coastal processes cannot be taken into account at this scale and resolution but the sound knowledge derived from them can be used to feed broader analyses aimed at supporting EU policy. In general, in coastal studies we lack the important step of the aggregation of data and knowledge transfer from local case studies to regional ones, as well as from complex scientific results to useful information for managers and policy makers.

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

4.3. Application of the assessment of CP

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

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

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

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

5. Conclusions

Natural hazard regulation services, like coastal protection (CP), show a declining trend due to the rapid loss of natural buffers such as coastal wetlands, while at the same time the value of those regulation services keeps rising given the increase in human vulnerability to natural hazards (Elmqvist et al., 2010). Still, the role of ecosystems on the moderation of extreme events is poorly understood and it is rarely taken into account in management or land/marine spatial planning decisions. This paper proposes a conceptual framework and spatially explicit indicators of CP from an ecosystem service perspective, that is, it assesses the natural capacity, the service flow and the demand of that service. We apply the proposed methodology on the European continent. This work may support, amongst others, the implementation of the EU Biodiversity Strategy and the EU Floods Directive. The analysis can be replicated at different spatial and temporal scales. Specific data and knowledge gaps for this continental scale assessment have been highlighted, as well as further variables to improve the resolution at smaller scales. Next steps in this research could include the monetary valuation of natural CP in Europe, and a series of climatic and policy scenarios to visualise the evolution of the service capacity, flow and benefit. This approach could be also used to assess how different pressures can deteriorate the ability of coastal ecosystems to provide protection, leading to large negative social and economic consequences.

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

Acknowledgements

Authors appreciate the contribution, time dedication and constructive comments from the experts that agreed to fill our questionnaire: M.T. Abogado Rios (Venezuelan Ministry of Environment), L. Airoldi (University of Bologna), G. Anfuso, N.G. Rangel-Buitrago and other colleagues from the University of Cádiz, R. Certain (Université de Perpignan), A. de Groot (Wageningen University), O. Ferreira and A. Matias (Universidade do Algarve), J. Guillén (Institute of Marine Sciences, Barcelona), J.A. Jimenez (Universitat Politecnica de Catalunya), M. Phillips (Swansea Metropolitan University), E. Pranzini (University of Florence), M. Sedrati (University of South Brittany), A. Vila Concejo (University of Sydney) and, especially, A. Cooper (University of Ulster).

The research leading to these results has received funding from the European Community's Seventh Framework Programme under Grant Agreement No. 244170 (PEGASO project).

The views expressed in this document are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

References

Adger, W.N., Hughes, T.P., Folke, C., Carpenter, S.R., Rockstrom, J., 2005. Socio-ecological resilience to coastal disasters. Science, 309 (2005), pp. 1036–1039

Airoldi, L. Abbiati, M., Beck, M.W., Hawkins, S.J., Jonsson, P.R., Martin, D., Moschella, P.S., Sundelof, A., Thompson, R.C., Aberg, P., 2005. An ecological perspective on the deployment and design of low-crested and other hard coastal defence structures. Coast. Eng., 52 (2005), pp. 1073–1087

Airoldi, L., Beck, M.W., 2007. Loss, status and trends for coastal marine habitats of Europe. R.N. Gibson, R.J.A. Atkinson, J.D.M. Gordon (Eds.), Oceanography and Marine Biology: An Annual Review, vol. 45 (2007), pp. 345–405

Barbier, E.B., Sally, D.H., Chris, K., Evamaria, W.K., Adrian, C.S., Brian R.S., 2011. The value of estuarine and coastal eco-system services. Ecol. Monogr., 81 (2) (2011), pp. 169–193

Barbier, E.B., Koch, E.W., Silliman, B.R., Hacker, S.D., Wolanski, E., Primavera, J., Granek, E.F., Polasky, S., Aswani, S., Cramer, L.A., Stoms, D.M., Kennedy, C.J., Bael, D., Kappel, C.V., Perillo, G.M.E., Reed, D.J., 2008. Coastal ecosystem-based management with nonlinear ecological functions and values. Science, 319 (2008), pp. 321–323

BODC (British Oceanographic Data Centre), 2009. The GEBCO_08 Grid, Version 20091120, Resolution of 30 arc-seconds (2009) Available at: http://www.gebco.net

Bos, A.R., Bouma, T.J., de Kort, G.L.J., van Katwijk, M.M., 2007. Ecosystem engineering by annual intertidal seagrass beds: sediment accretion and modification. Estuar. Coast. Shelf Sci., 74 (1-2) (2007), pp. 344–348

Bryan, B., Harvey, N., Belperio, T., Bourpan, B., 2001. Distributed process modeling for regional assessment of vulnerability to sea-level rise. Environ. Model. Assess., 6 (2001), pp. 57–65

Burkhard, B., Kroll, F., Müller, F., Windhorst, W., 2009. Landscapes’ capacity to provide ecosystem services: a concept for land cover based assessments. Landsc. Online, 15 (2009), pp. 1–22

Capobianco, M., DeVriend, H.J., Nicholls, R.J., Stive, M.J.F., 1999. Coastal area impact and vulnerability assessment: the point of view of a morphodynamic modeller. J. Coast Res., 15 (3) (1999), pp. 701–716

CNES (Centre National d'Etudes Spatials), 2010. AVISO Products: Map of Regional Patterns of Observed Sea Level (2010) Available at: http://www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/

Cochard, R., Ranamukhaarachchi, S.L., Shivakoti, G.P., Shipin, O.V., Edwards, P.J., Seeland K.T., 2008. The 2004 tsunami in Aceh and Southern Thailand: a review on coastal ecosystems, wave hazards and vulnerability. Perspect. Plant Ecol. Evol. Syst., 10 (1) (2008), pp. 3–40

Cooper, J.A.G., Mckenna, J., 2008. Working with natural processes: the challenge for coastal protection strategies. Geogr. J., 174 (4) (2008), pp. 315–331

Costanza, R., 1999. The ecological, economic, and social importance of the oceans. Ecol. Econ., 31 (2) (1999), pp. 199–213

Costanza, R., Pérez-Maqueo, O., Martinez, M.L., Sutton, P., Anderson, S.J., Mulder, K., 2008. The value of coastal wetlands for hurricane protection. Ambio, 37 (4) (2008), pp. 241–248

Das, S., Vincent, J.R., 2009. Mangroves protected villages and reduced death toll during Indian super cyclone. Proc. Natl. Acad. Sci. U.S.A., 106 (18) (2009), pp. 7357–7360

De Ferranti, J., 2009. Tiles of topographic maps covering North Eurasia between 6–30°E and 60–68°N. Sources: Russian 100k and 200k; 50k topos of Norwegian Jotunheimen and More og Romsdal; Other Topographic Maps (2009). Available at: http://www.viewfinderpanoramas.org/dem3.html

De Groot, R.S., Alkemade, R., Braat, L., Hein, L., Willemen L., 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecol. Complex., 7 (2010), pp. 260–272

Directive, 2000/60/EC. Directive, 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. OJ L 327, 22.12.2000, p. 1.

Directive, 2007/60/EC. Directive, 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks. OJ L 288, 6.11.2007, p. 27.

EEA (European Environment Agency), 2010. 10 Messages for 2010 – Coastal Ecosystems. European Environment Agency, Office for Official Publications of the European Union, Luxembourg (2010) 17 pp.

EEA (European Environment Agency), 2006. Changing Faces of Europe's Coastal Areas, EEA Report No. 6/2006. EEA, Copenhagen (2006). Available at: http://reports.eea.eu/eea_report_2006_6/en

EEA (European Environment Agency), 2011. Corine Land Cover 2000 Raster Data – Version 15 (08/2011). Processed by The European Topic Centre on Land Use and Spatial Information (2011). Available at: http://www.eea.europa.eu/data-and-maps

Eigenbrod, F., Armsworth, P.R., Anderson, B.J., Heinemeyer, A., Gillings, S., Roy, D.B., Thomas, C.D., Gaston, K.J., 2010. The impact of proxy-based methods on mapping the distribution of ecosystem services. Journal of Applied Ecology, 47 (2010), pp. 377–385

Elmqvist, T., Maltby, E., Barker, T., Mortimer, M., Perrings, C., Aronson, J., De Groot, R., Fitter, A., Mace, G., Norberg, J., Sousa Pinto, I., Ring, I., 2010. Biodiversity, ecosystems and ecosystem services. P. Kumar (Ed.), The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations, Earthscan, London (2010)

European Commission, 2009. Report from the Commission to the Council and the European Parliament: Composite Report on the Conservation Status of Habitat Types and Species as Required under Article 17 of the Habitats Directive. COM(2009) 358 Final. European Commission, Brussels (2009) 13.7.2009

European Commission, 2010. Communication from the Commission to the European Parliament and the Council on Marine Knowledge 2020: Marine Data and Observation for Smart and Sustainable Growth. COM(2010) 461 Final. European Commission, Brussels (2010) 8.9.2010

European Commission, 2011. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Our life Insurance. Our Natural Capital: An EU Biodiversity Strategy to 2020. COM(2011) 244 Final. European Commission, Brussels (2011) 3.5.2011

Eurosion, 2005. Geomorphology, geology, erosion trends and coastal defence works, Version 2, 1:100 000. Dataset available at http://www.eea.europa.eu/data-and-maps. More information at http://www.eurosion.org/.

Eurostat, 2011. Coastal region statistics–Statistics Explained (2011). Available at: http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Main_Page

Everard, M., Jones,L., Watts.B., 2010. Have we neglected the societal importance of sand dunes? An ecosystem services perspective. Aquat. Conserv. Mar. Freshw. Ecosyst., 20 (4) (2010), pp. 476–487.

Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada., Umland,J., Werner,M., Oskin, M., Burbank, D., Alsdorf, D. (2007) The shuttle radar topography mission. Rev. Geophys., 45 (2007), p. RG2004

F.J. Gallego, F.J. 2010. A population density grid of the European Union. Popul. Environ., 31 (2010), pp. 460–473 Data available at: http://www.eea.europa.eu/data-and-maps/data/population-density-disaggregated-with-corine-land-cover-2000-2

Granek.E.F., Ruttenberg, B.I. 2007. Protective capacity of mangroves during tropical storms: a case study from Wilma and Gamma in Belize. Mar. Ecol. Prog. Ser., 343 (2007), pp. 101–105

Green. C., McFadden. L. 2007. Coastal vulnerability as discourse about meanings and values. J. Risk Res., 10 (8) (2007), pp. 1027–1045

Guerry, A.D., Ruckelshaus, M.H., Arkema, K.K., Bernhardt, J.R., Guannel, G., Kim, C.-K., Marsik, M., Papenfus, M., Toft, J.E., Verutes, G., Wood, S.A., Beck, M., Chan, F., Chan, K.M.A., Gelfenbaum, G., Gold, B.D., Halpern, B.S., Labiosa, W.B., Lester, S.E., Levin, P.S., McField, M., Pinsky, M.L., Plummer, Polasky, M.S., Ruggiero, P., Sutherland, D.A., Tallis, H., Day, A., Spencer, J. 2012. Modeling benefits from nature: using ecosystem services to inform coastal and marine spatial planning. Int. J. Biodivers. Sci. Ecosyst. Serv. Manage., 8 (1-2) (2012), pp. 1–15

Haines-Young, R.H., Potschin, M. 2010. The links between biodiversity, ecosystem services and human well-being. D. Raffaelli, C. Frid (Eds.), Ecosystem Ecology: A New Synthesis, BES Ecological Reviews Series, Cambridge University Press, Cambridge (2010), pp. 110–139

R. Haines-Young, R.H., Potschin, M., Kienast, F. 2012. Indicators of ecosystem service potential at European scales: mapping marginal changes and trade-offs. Ecol. Indic., 21 (2012), pp. 39–53

Harvey, N., Woodroffe, C. 2008. Australian approaches to coastal vulnerability assessment. Sustain. Sci., 3 (1) (2008), pp. 67–87

Jarvis, A., Reuter, H.I., Nelson, A., Guevara. E. 2008. Hole-filled SRTM for the globe Version 4.1. CGIAR-CSI SRTM 90m Database (2008) Available at: http://srtm.csi.cgiar.org

Kienast, F., Bolliger, J., Potschin, M., de Groot, R., Verburg, P.H., Heller, I., Wascher, D., Haines-Young, R. Assessing landscape functions with broad-scale environmental data: insights gained from a prototype development for Europe. Environ. Manage., 44 (2009), pp. 1099–1120

Koch, E.W., Barbier, E.B., Silliman, B.R., Reed, D.J., Perillo, G.M.E., Hacker ,S.D., Granek, E.F., Primavera, J.H., Muthiga, N., Polasky, S., Halpern, B.S., Kennedy, C.J., Kappel, C.V., Wolanski, E. 2009. Non-linearity in ecosystem services: temporal and spatial variability in coastal protection. Front. Ecol. Environ., 7 (1) (2009), pp. 29–37

Komen, G.J., Cavaleri, L., Doneland, M., Hasselmann, K., Hasselmann, S., P.A.E.M. Janssen. 1994. Dynamics and Modelling of Ocean Waves. Cambridge University Press, Cambridge (1994) 532 pp.

Liquete, C., Maes, J., La Notte, A., Bidoglio . G. 2011. Securing water as a resource for society: an ecosystem services' perspective. Ecohydrol. Hydrobiol., 11 (3-4) (2011), pp. 247–259

Luisetti, T., Turner, K., Bateman, I., 2008. An ecosystem services approach to assess managed realignment coastal policy in England. Centre for Social and Economic Research on the Global Environment, Working Paper ECM 08-04, 22 pp.

Lyard, F., Lefevre, F., Letellier, T., Francis. O. 2006. Modelling the global ocean tides: modern insights from FES2004. Ocean Dynam., 56 (2006), pp. 394–415

Maes, J., Egoh, B., Willemen, L., Liquete, C., Vihervaara, P., Schägner, J.P., Grizzetti, B., Drakou, E.G., La Notte, A., Zulian, G., F. Bouraoui, F., Paracchini, M.L., Braat, L., Bidoglio. G. 2012. Mapping ecosystem services for policy support and decision making in the European Union. Ecosyst. Serv., 1 (1) (2012), pp. 31–39

MapCruzin, 2011. Free European Continent ArcGIS Shapefile Map Layers. Data derived from the OpenStreetMap community, The Free Wiki World Map. Available at: http://www.mapcruzin.com and http://www.openstreetmap.org.

Martínez . M.L., Intralawan, A., Vázquez, G., Pérez-Maqueo, O., Sutton, P., Landgrave, R. 2007. The coasts of our world: ecological, economic and social importance. Ecol. Econ., 63 (2-3) (2007), pp. 254–272

S. McLaughlin, S., Cooper, J.A.G. 2010. A multi-scale coastal vulnerability index: a tool for coastal managers. Environ. Hazards, 9 (3) (2010), pp. 233–248

MEA (Millennium Ecosystem Assessment) 2005. Our human planet: summary for decision makers. Millennium Ecosystem Assessment, Island Press (2005) 109 pp.

MESH (Mapping European Seabed Habitats), 2010. Combined EUNIS Habitats v3.2. Information derived from MESH Consortium webGIS data (http://www.searchmesh.net) which received funding from the INTERREG IIIB NEW programme (http://www.nweurope.org/).

Nicholls, R.J., Wong, P.P., Burkett, V., Woodroffe, C.D., Hay, J. 2008. Climate change and coastal vulnerability assessment: scenarios for integrated assessment. Sust. Sci., 3 (2008), pp. 89–102

Özyurt, G., Ergin, A. 2010. Improving coastal vulnerability assessments to sea-level rise: a new indicator-based methodology for decision makers. J. Coast. Res., 26 (2) (2010), pp. 265–273

Pendleton, E.A., Thieler, E.R., Williams S.J. 2010. Importance of coastal change variables in determining vulnerability to sea- and lake-level change. J. Coast. Res., 26 (1) (2010), pp. 176–183

Pérez-Maqueo, O., Intralawan, A., Martínez, M.L. 2007. Coastal disasters from the perspective of ecological economics. Ecol. Econ., 63 (2-3) (2007), pp. 273–284

Pethick, J., Crooks, S. 2000. Development of a coastal vulnerability index: a geomorphological perspective. Environ. Conserv., 27 (4) (2000), pp. 359–367

Rönnbäck, P., Kautsky, N., Pihl ,L., Troell, M., Söderqvist, T., Wennhage, H. 2007. Ecosystem goods and services from Swedish coastal habitats: identification, valuation, and implications of ecosystem shifts. Ambio, 36 (7) (2007), pp. 534–544

Sanford, M.P. 2009. Valuating mangrove ecosystems as coastal protection in post-tsunami South Asia. Nat. Areas J., 29 (1) (2009), pp. 91–95

Shepard, C.C., Crain, C.M., Beck, M.W. 2011. The protective role of coastal marshes: a systematic review and meta-analysis. PLoS ONE, 6 (11) (2011), p. e27374

Small, C., Nicholls, R.J. 2003. A global analysis of human settlement in coastal zones. J. Coast. Res., 19 (3) (2003), pp. 584–599

Tallis, H.T., Ricketts, T., Guerry, A.D.,. Wood, S.A., Sharp, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, D., Cameron, K., Arkema, E., Lonsdorf, E., Kennedy, C., Verutes, G., Kim, C.K., Guannel, G., Papenfus, M., Toft, J., Marsik, M., Bernhardt ,J. 2011. InVEST 2.2.2 User's Guide. The Natural Capital Project, Stanford (2011)

Turner, R.K., Burgess, D., Hadley, D., Coombes, E., Jackson, N. 2007. A cost-benefit appraisal of coastal managed realignment policy. Glob. Environ. Change, 17 (3–4) (2007), pp. 397–407.

UNESCO-WHC, 2011. Official World Heritage List from the UNESCO World Heritage Convention (2011) Available online at http://whc.unesco.org

Vafeidis, A.T., Nicholls ,R.J., McFadden, L., Tol, R.S.J., Hinkel, J., Spencer, T., Grashoff, P.S., Boot, G., Klein R.J.T. 2008. A new global coastal database for impact and vulnerability analysis to sea-level rise. J. Coast. Res., 24 (4) (2008), pp. 917–924

Van Oudenhoven, A.P.E., Petz, K., Alkemade, R., Hein, L., de Groot. R.S. 2012. Framework for systematic indicator selection to assess effects of land management on ecosystem services. Ecol. Indic., 21 (2012), pp. 110–122

WAMDI Group, 1988. The WAM model: a third generation ocean wave prediction model. J. Phys. Oceanogr., 18 (1988), pp. 1775–1810

List of figures

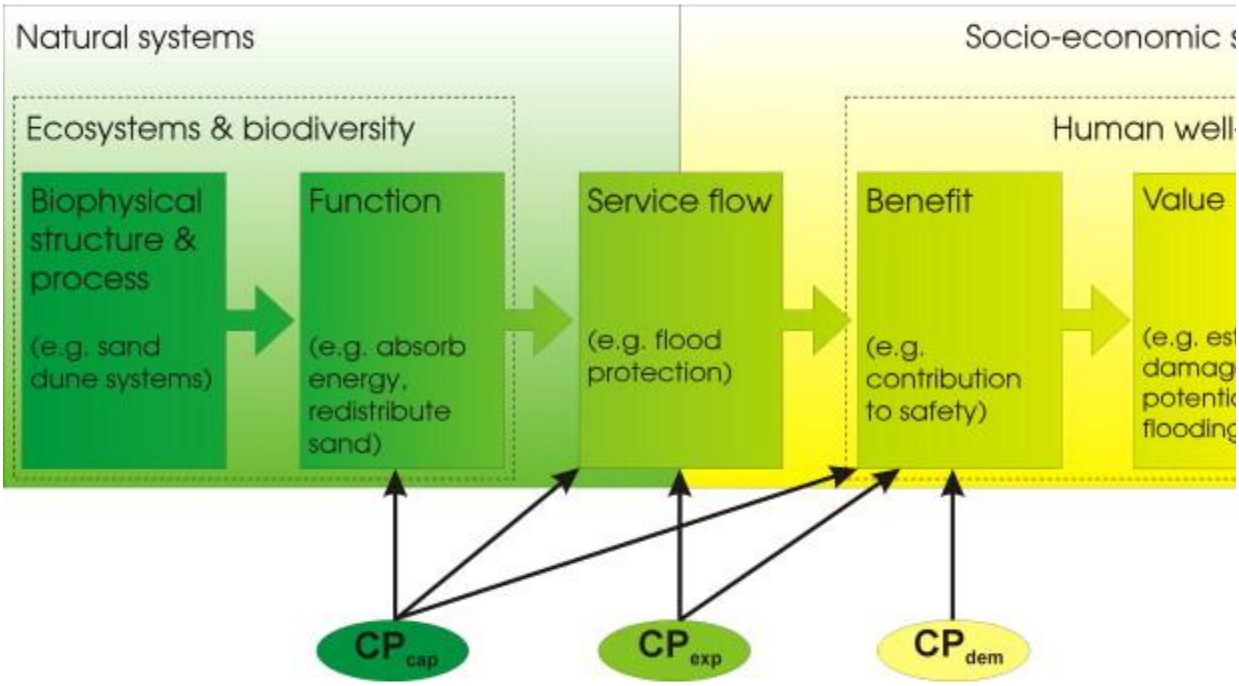


Fig. 1. Conceptual framework followed in this paper. The upper boxes show the basic structure of the cascade model framed within the natural and socio-economic context. The examples refer to the CP case study. The bottom shapes and arrows represent the indicators proposed in this paper that inform the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

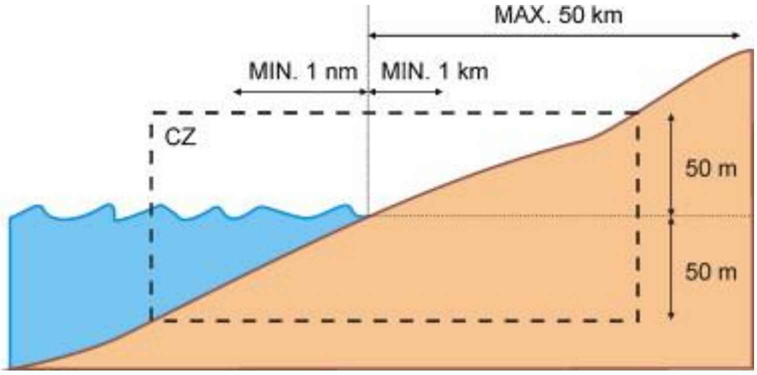


Fig. 2. Diagram showing the delimitation of the coastal zone (dashed box, CZ). Minimum and maximum distances from the shoreline (upper arrows) are always respected.

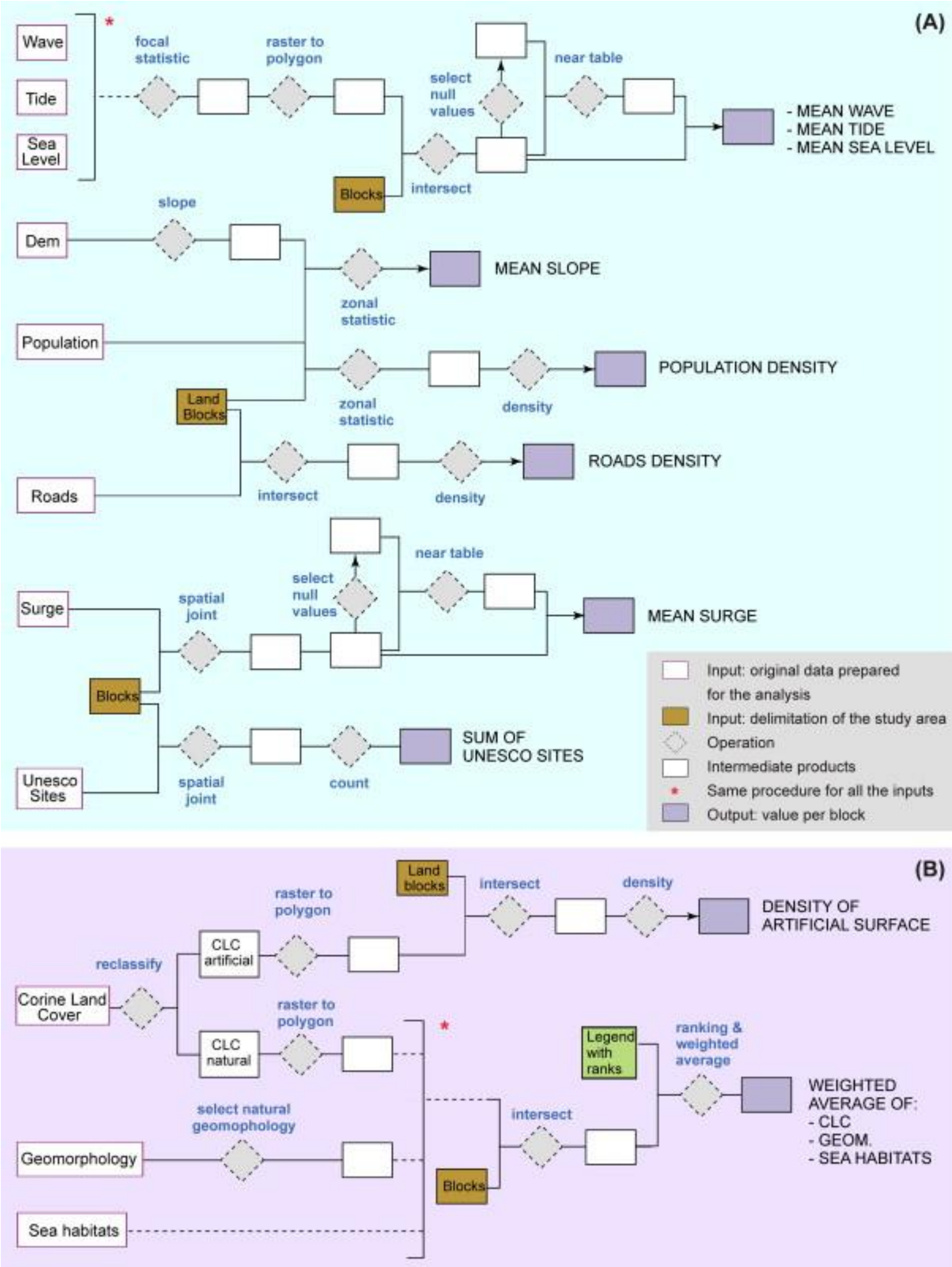
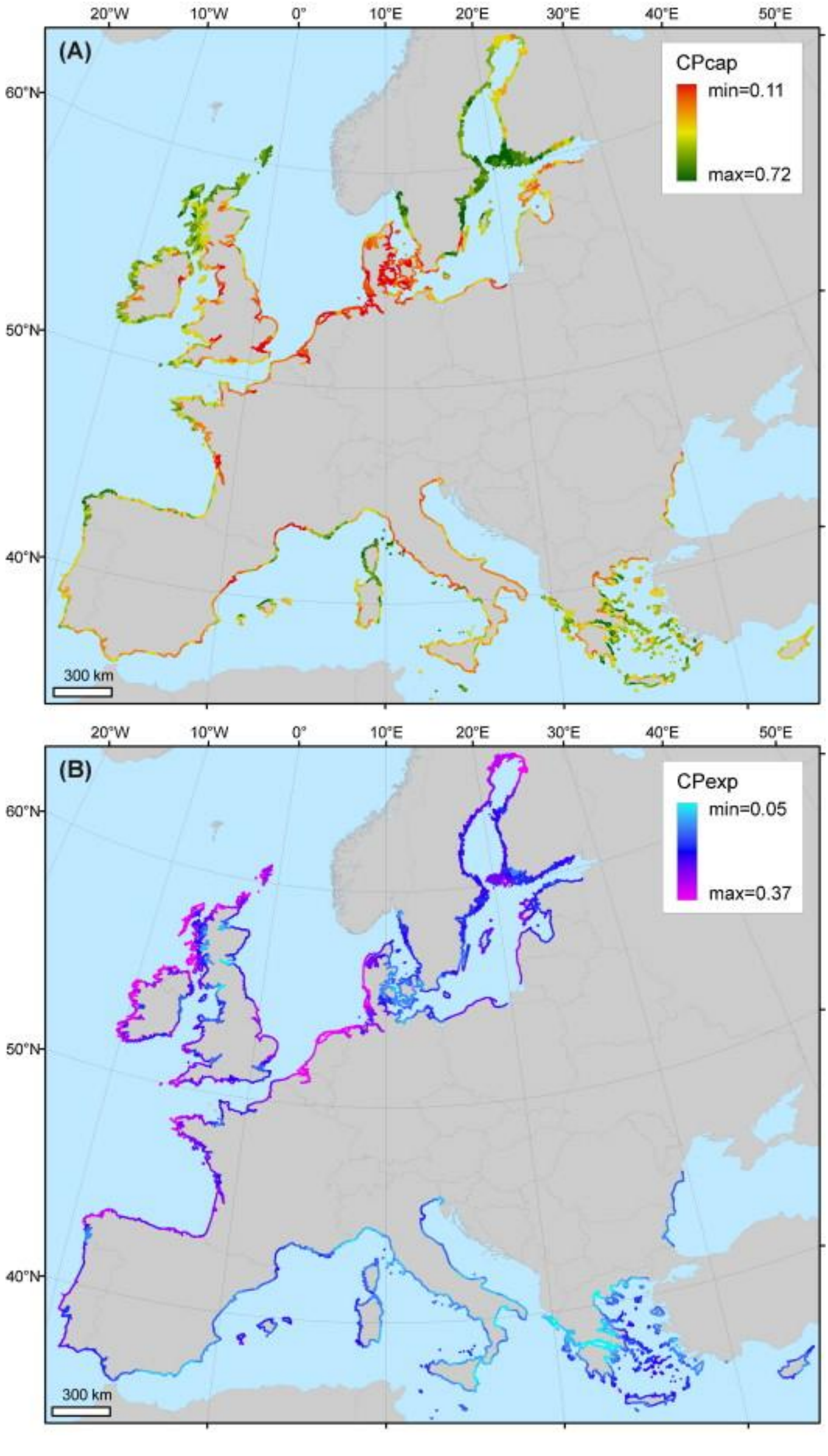


Fig. 3. Flow diagrams showing the simplified methodology used in this study to: (A) process the quantitative data, and (B) process the qualitative data.



(A)
CPcap
min=0.11
max=0.72
300 km
(B)
CPexp
min=0.05
max=0.37
300 km
20°W
10°W
0°
10°E
20°E
30°E
40°E
50°E
60°N
50°N
40°N

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}).

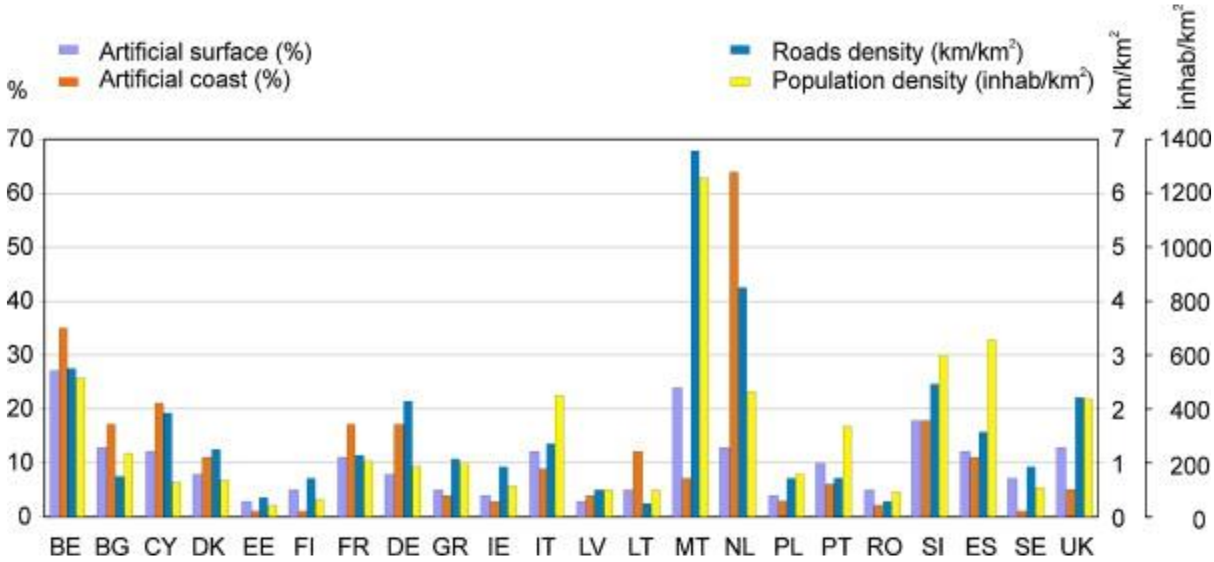


Fig. 5. Main anthropogenic pressures present in the coastal zone per EU Member State (coastal zone as defined in this study). Artificial surface and artificial coast are shown in the left vertical axis, while roads density and population density refer to the corresponding right vertical axes.

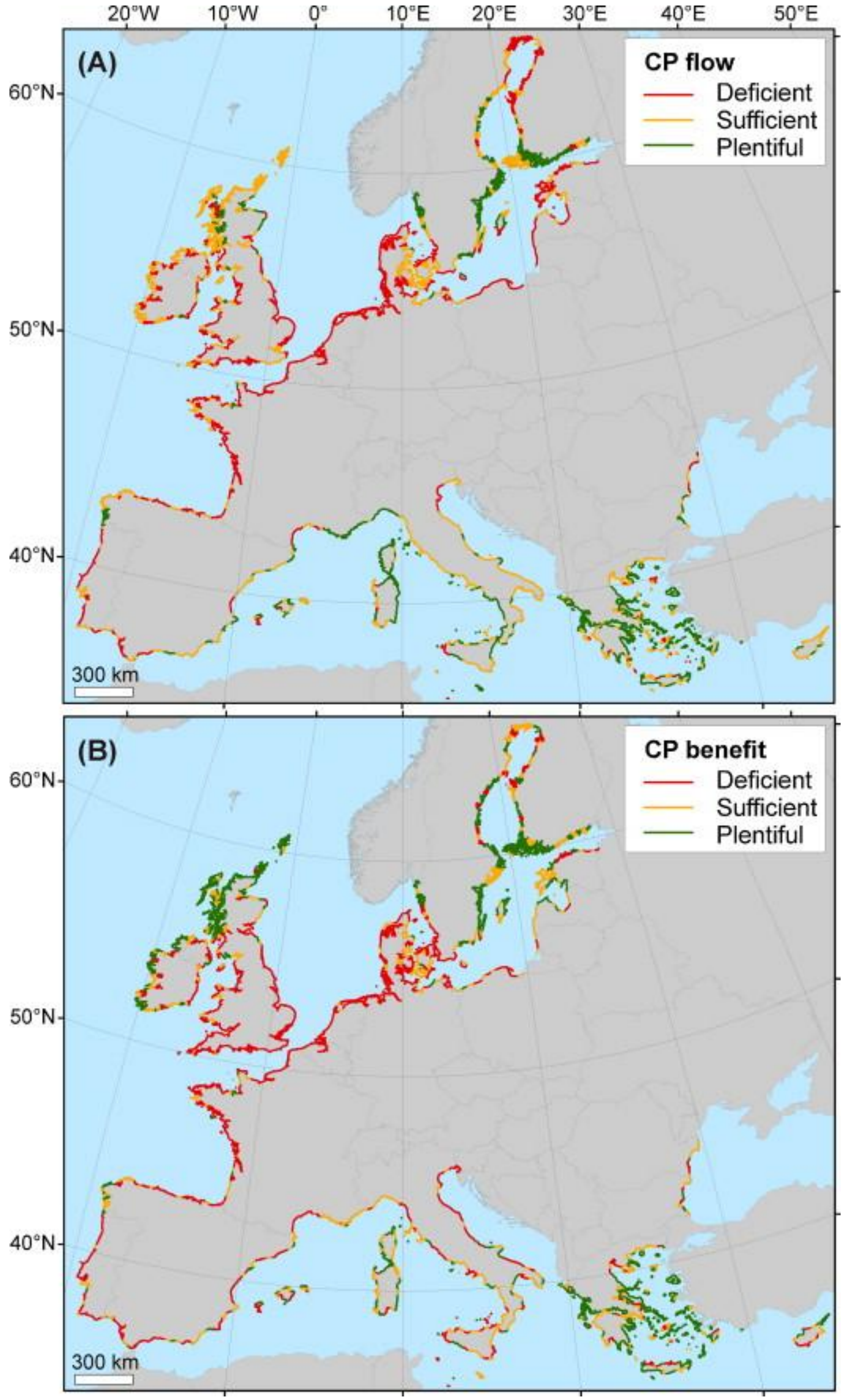

20°W
10°W
0°
10°E
20°E
30°E
40°E
50°E
60°N
50°N
40°N
(A)
CP flow
Deficient
Sufficient
Plentiful
300 km
(B)
CP benefit
Deficient
Sufficient
Plentiful
300 km

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).