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Assessing anthropogenic vulnerability of coastal regions: DEA-based index and rankings for the European Atlantic Area

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ABSTRACT

This paper aims to assess the vulnerability of coastal areas to sectoral pressures from maritime-related socio-economic activities. To do this, a DEA-based method is proposed to construct a synthetic index of anthropogenic vulnerability with which to rank European Atlantic Area countries and regions down to a regional scale below the national level. The set of indicators selected for this index focuses on five important vectors: marine spills, port activities, tourism, protection of natural areas, and water quality and waste management. The paper shows that, overall, the United Kingdom has the most vulnerable coast in Atlantic Europe, with Ireland showing the most resilient coast of all. Furthermore, the proposed method also allows one to identify peer groups with the same vulnerability pattern. Thus, policies aiming to reduce the vulnerability of a target region may be devised by focusing on the least vulnerable regions within the relevant group. The detailed analysis presented may help regional policy makers as a diagnostic tool to detect and assess vulnerability weaknesses so that they can design and carry out appropriate actions in line with integrated European coastal management policies.

1. Introduction

During the last decades, the European Union has experienced important increases in pressure on coastal resources, in coastal population, and in near-shore and on-shore infrastructures. Integrated European environmental management policies concerning marine strategies and the management of coastal zones in Europe try to respond to this by offering a comprehensive and integrated approach to the protection of all European coasts and marine waters [1–5]. In this respect, the relevant recommendations and directives recognize the great environmental, economic, social, cultural and recreational importance of coastal zones of Europe, while, in contrast, admitting to an increasing deterioration of conditions as regards both the coasts themselves and the quality of coastal water [6].

Besides, the EU identifies marine and maritime sectors as crucial drivers for growth and jobs. The so-called "blue" economy generates approximately 5.4 million jobs and a gross value added of almost 500 billion a year [7]. Consistent with the Europe 2020 targets, the Blue Growth Strategy recognizes that the European seas and oceans are central to the European economy with great potential for innovation, economic growth and job creation [8]. Moreover, within the new European Green Deal [9], the role of the oceans and the blue economy has become central to tackling climate change.

As a consequence, marine and coastal environments are under pressure from a wide range of activities in both traditional and emerging sectors that take place in these areas [10]. In response, the EU integrated marine policy aims to ensure the economic and environmental sustainability of European coastal zones while they control the deterioration of their natural, socio-economic and cultural resources by improving the coordination in the coastal development and protection plans.

The EU integrated marine and coastal policies require coordinated action at the regional level, guided and supported by an appropriate framework at the national level. In this regard, it is understood that generating information and knowledge about the coastal zones and their potential physical and social vulnerability risks is a key point [1] and EU funded research has been allocated to this end in recent years [*e.g.* 10–12, among others].

Therefore, the quantitative assessment of the effects of the increasing environmental challenges faced by our coasts and oceans and the growth in the maritime sectors is one of the priorities of the EU marine strategy framework. This requires member states to develop a strategy for its marine waters, including the analysis of the pressures and impacts of maritime activities, and an economic and social analysis of the use of the waters for these activities and the cost of degradation of the coastal environment [1,4].

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Within this framework, the EU Interreg Moses project [12] was created to examine the blue growth path for sustainable development of the major sectors operating in the Atlantic European regions. Interreg Atlantic Area supports transnational cooperation projects in the Atlantic regions of five countries: France, Ireland, Portugal, Spain and the United Kingdom. The Moses project builds upon the EU Interreg Marnet project [11,13] and focuses on examining the environmental pressures and impacts from the growing sectors and possible transition paths to sustainable blue growth. In fact, one of the main objectives of Moses consists in assessing the vulnerability of marine and coastal regions to sectoral pressures from a socio-economic point of view.

Some previous research on coastal vulnerability has tended to focus on the *impact of geophysical processes*, such as anticipated natural hazards, *on the territory* of the geographical area under study. That line of research uses different methodologies to assess those impacts, being the Coastal Vulnerability Index (CVI) the most common one [14]. The CVI considers physical variables such as the geomorphology of the coast or the erosion among others. Boruff et al. [15] are the first to propose a Coastal Social Vulnerability index (CSoVI) to measure social vulnerability, understood as the community's ability to respond to environmental hazards. CSoVI is calculated applying the same methodology as the CVI to socio-economic and demographic factors [16]. These indexes have been used to assess coastal vulnerability in different areas such as the Mediterranean coast [17,18], USA [19] or India [20], among others.

Another line of work in this area deals with the assessment of *human impacts on the ocean*, following the methodology developed by Halpern et al. [21], which is an ecosystem-based approach. The idea is to construct an index that measures the cumulative impact on the oceans by quantifying the sensitivity of certain ecosystem components to human pressures. This approach has been applied to regional studies in USA [22,23] and Canada [24] among others. At the European level, some assessments have been developed for the Baltic Sea [25] and the Eastern North Sea [26] using the latter approach.

In contrast, this paper aims to lay down the basis for the construction of an index of anthropogenic vulnerability measuring the *impact of human uses on the territory* of coastal regions and, secondly, offer a ranking of EU Atlantic coastal regions in accordance with it. In this respect, it will be implicitly assumed in what follows that coastal anthropogenic vulnerability is defined as the degree to which coastal areas are susceptible to damage or degradation due to impacts related to maritime transportation, port facilities and coastal socio-economic uses.

Accordingly, five vectors of interest with different basic indicators were contemplated. Namely, vector 1 (marine spill risk) that aims to identify spill locations in Atlantic European waters and construct a marine spill risk index for the coastal territories in the European Atlantic Area; vector 2 (port activities) that contemplates the assessment of vulnerability due to passengers and goods transportation and covers indicators related to sustainability awareness such as energy efficiency, land use, etc. vector 3 (tourism activities) that covers indicators related to tourism and recreation; vector 4 (protection of coastal areas) that is related to coastal Sites of Community Importance; and vector 5 (water quality and waste management) that assesses bathing water quality from indicators such as Atlantic European blue flag beaches, waste disposal and recovery, etc.

With this database of basic indicators, and using appropriate statistical tools [27–29], the paper constructs a synthetic index of vulnerability ranking European Atlantic Area countries down to the smallest regional level of each country. In the process, partial rankings are also obtained on each of the vulnerability vector subindices. Cross-efficiency Data Envelopment Analysis (DEA) is used for this purpose, because of its ability to compile all the information available for each region into a single score with non-parametric data-driven adjustable weights.

The results obtained can provide new insights into the impact of socio-economic activities on the coastal vulnerability in the European Atlantic Area. They can be used to compare the vulnerability of different regions which in turn can assist in the implementation of integrated European marine and coastal management policies.

The paper is organized as follows. Section 2 describes the vectors making up the overall index. Section 3 explains the statistical method used for the computation of vulnerability index scores. The results obtained for the relative vulnerability of the Atlantic European coastal regions as measured by each of the vectors are discussed in Section 4, while Section 5 interprets the ensuing overall synthetic index of vulnerability and the corresponding peer groups emerging from the analysis. Section 6 concludes with some implications of these results.

2. Vector design

Table B.1 lists the indicators used in the construction of each of the five vectors that make up the vulnerability index. (See Appendix A for a detailed explanation of the sources used).

2.1. Marine spill risk

Marine spill risk values for Atlantic European coastal regions were taken from [30]. Using recorded historical spills in European waters from 1970 to 2014 [31] that paper carried out an evaluation of marine spill risks for all European coastal territories following a method that "uses tools of geographic information systems and computer modeling to simulate the effect of spills at sea. The modeling considers the size of the spill, its distance from the coast, the shape and length of coast that would be affected and the direction and speed of the ocean currents" [32].

Therefore, in the construction of this vector, two of the marine spill risk indicators reported by [30] were used. Namely, the 'currents-free' marine spill risk scores R_{0i} and the final scores R_i that incorporate the effect of sea currents at the time and place of the spill.

2.2. Port activities

Maritime shipping is widely recognized as a very environmentally sustainable form of transport. Even so, given the large volume of maritime activity and its rapid growth, the maritime sector "is a major contributor to global environmental change through its local and cross-boundary air, water and land impacts. Addressing the environmental impacts of shipping is therefore an essential and pressing governance issue" [33]. Maritime shipping is also the backbone of international trade and accounts for more than 80% of international trade volume [34]. For the European Atlantic Area regions maritime transport and ports play a strategic role, not only for trade or passenger traffic but also in terms of development and territorial cohesion (75% of the EU imports and exports depend on maritime transport).

In order to identify the impacts of port activity on coastal vulnerability in the Atlantic regions we considered several raw indicators related to the number of ports in the region, their size and importance, as well as the concern of port authorities about the impact of their activities and operations on the environment. Most of these indicators measure the possible negative impact on both the maritime and terrestrial environment of port operations and activities. However, the last two indicators collect information on good environmental practices in ports and their concern for sustainable development [35]. Therefore, to incorporate these latter indicators into the vulnerability index their values are multiplied by -1. Finally, prior to starting the construction of the vulnerability index, all these indicators have been standardized using the length of the coastline for each region.

2.3. Tourism activities

This vector deals with vulnerability due to tourism focusing on the pressure that tourism activities exert on coastal territories. Tourism is an important sector for the countries in the European Atlantic Area with France and Spain as world leaders in international arrivals and the UK occupying fifth place.[1] However, in order to assess the impact of tourism in the Atlantic regions, we must take into account the fact that neither the weight of maritime and coastal tourism is homogeneous across these countries (79% in Spain vs. less than 10% in Ireland and in the UK [10]), nor is the Atlantic area the most important for France and Spain in terms of tourism (*e.g.* in Spain the Atlantic regions represent only about 15% of its total tourism [28]).

In order to measure the impact of tourism, several variables were considered from both the demand and the supply sides. These indicators have been standardized using local population in order to measure tourism intensity and using regional area to measure tourism density. The concepts of tourism intensity and tourism density are both relevant for this analysis since they capture two different aspects of tourism pressure. In this respect, this vector contemplates tourism intensity indicators that measure tourism demand/supply with respect to local population so they can be interpreted as social pressure indicators, and also tourism density indicators that measure tourism demand/supply with respect to the area so that they reflect tourism pressure on the territory of the region.

2.4. Protection of coastal areas

Natura 2000 has become “the largest coordinated network of protected areas in the world. The aim of the network is to ensure the long-term survival of Europe’s most valuable and threatened species and habitats, listed under both the Birds Directive and the Habitats Directive” [37,38]. This vector tries to capture the effect of the Natura 2000 network on maintaining the resilience of ecosystems, especially in the marine environment. In order to measure the effect of protected areas on the marine environment four indicators were chosen, weighted by the area of the region or in the case of marine sites, by the length of the coastline.

2.5. Water quality and waste management

This vector is based on coastal vulnerability due to human effects that influence the quality of water. In order to measure these pressures this vector uses information from two European directives, the Bathing Water Directive and the Waste Framework Directive. In total, eight indicators have been chosen to construct this vector. To measure bathing water quality, four indicators have been calculated with the percentage of marine bathing places with excellent, good, sufficient and poor water quality, respectively, for each region. Since the first two indicators can be interpreted as opposing vulnerability, their values have been multiplied by -1. The four indicators that measure the impact of waste generation and treatment operations have been standardized using the population of the region. Therefore, vulnerability is related to both bathing water quality and waste pressure.

3. Statistical method

The EU Moses database is made up of primary indicators collected down to NUTS3 Eurostat geographical level[2] from 2014 through 2017, the latter being the current base year with which the vulnerability index is constructed using all the indicators available for the five vectors mentioned above. When necessary, the imputation of missing values in the EU Moses database is done by extrapolating the last value recorded. On the other hand, if NUTS3 level values are not available over the past four years, the value imputed corresponds to the proportion of the respective NUTS2 area (or, alternatively, NUTS1 or NUTS0) relative to the relevant physical dimension of the NUTS3 region (say, population, surface, coast length, etc.). That is, the imputation process assumes either non-significant increase, or homogeneous distribution over nearest neighbors, or both in order to estimate non-available data at the required geographical level. For example, the 2017 *“Number of recovery recycling facilities”* value for Pontevedra, a Spanish province in the Galician region (or ES114 in Eurostat NUTS coding system), is missing from the database. Furthermore, that value is missing for the entire Galicia, the next higher regional level (NUTS2). Therefore, the first step in the imputation was to take the value recorded for the previous year at that higher level as a proxy for the base year and then redistribute that number among the Galician provinces, according to population in this case, which gave the estimate for Pontevedra.

In summary, we have 32 vulnerability indicators available, distributed across the five vectors of interest, for each of 100 Atlantic European NUTS3 coastal regions (14 in France, 7 in Ireland, 13 in Portugal, 16 in Spain and 50 in the UK).

3.1. DEA vulnerability scores

The aim of the statistical method is, for each vulnerability vector and for each of the $n = 100$ Atlantic European NUTS3 coastal regions (cases), to reduce the m values obtained from the different vulnerability indicators in the EU Moses database to a single vector score. For this, one may try a simple index with fixed weights, that is, the same weighted sum of the m vulnerability indicator values for all the regions. However, the choice of weights is often crucial in determining the scores obtained, even to the point of suspecting that the weights chosen may artificially be the cause of some cases being in front of others. A better choice, in contrast, is to use flexible weights obtained directly from the data and our purpose is to use Data Envelopment Analysis (DEA) to provide such weights [27–29,41,42]. DEA is a linear programming technique that, for each study case or unit, obtains a set of case-specific weights that maximize the corresponding weighted sum of values with the restriction that no case receives a score greater than unity [see 43–45, for a recent review of DEA methods].

In this study, more specifically, the ‘output-based’ DEA without-explicit-input formulation [46] means that, for each case or region R_k with indicator values z_{kj} ($j = 1, \ldots, m$), its relative vulnerability is maximized, that is

$$\max_{w} V_k = \sum_{j=1}^{m} w_j z_{kj}, \text{ subject to } V_k \leq 1 \; \forall k, \quad w_j \geq 0 \; \forall j, \quad k = 1, \ldots, n, \tag{1}$$

where $w_1, \ldots, w_m$ are the weights of the index, and k and j refer to the region and indicator respectively.

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[1] Figures for 2017 are as follows: 278 million tourists in France, 250 million in Spain, 158 million in the UK, and 34 million in Portugal and 20 million in Ireland [36].

[2] These regions are defined within the EU NUTS 2016 classification of territorial units for statistics (Nomenclature des Unités Territoriales Statistiques), a geographical system subdividing the EU territory into regions at four different levels: (i) NUTS0: member state level (e.g. Spain, France); (ii) NUTS1: major socio-economic regions; (iii) NUTS2: basic regions to apply EU regional policy; and (iv) NUTS3: smaller regions, such as “provinces” in Spain (*e.g.* Pontevedra) or “départements” in France (*e.g.* Finistère); [39,40].

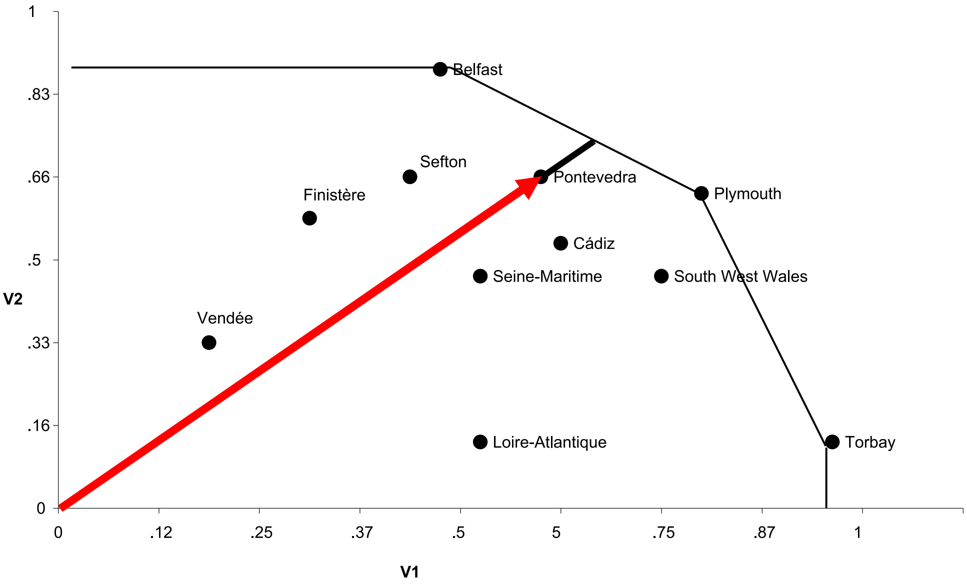


Fig. 1. Assigning vulnerability scores using DEA.

Fig. 1 illustrates a typical DEA vulnerability scoring example. Note how the outermost cases determine a vulnerability frontier that envelops the rest of the cases. In general, DEA gives those cases on the frontier a score of 1, while the scores allocated to less vulnerable regions within the envelop are equal to the radial distance to the vulnerability frontier. Thus, one important characteristic is that DEA models such as Eq. (1) are independent of the units of measurement of the individual indicators [47, p. 103].

For example, let us consider again the case of $\mathrm{R}_{\mathrm{ES114}}$ (Pontevedra) in vector 4 (protection of coastal areas). We have $m = 4$ vulnerability indicators (see Table B.1) whose values in the EU Moses database, relative to the region's surface and coast length respectively, are $z_{k,1} = 0.00378\,\mathrm{sites/km}^2$, $z_{k,2} = 8.88\%$, $z_{k,3} = 0.517\,\mathrm{sites/km}$, and $z_{k,4} = 0.722\,\mathrm{m}$, ($k = \mathrm{ES114}$). After applying the DEA model in Eq. (1) the optimal weights for this case were obtained and, with them, the maximum value for the vector 4 vulnerability DEA score for Pontevedra is $\widetilde{V}_k = 36.1\%$.

Therefore, the DEA vulnerability score allocated to a particular region may be thought of as the outcome of a self-evaluation process with respect to the vulnerability frontier using flexible weights compatible with the region's own vulnerability pattern. However, we will still want to incorporate cross-evaluation using other vulnerability patterns in order to provide a more objective perspective for comparative purposes. In other terms, each region will not only be evaluated by its own weights but also by the weights selected for any other region in the database [*cf.* 48,49].

Let $\{\widetilde{w}_j(\ell); j = 1, \ldots, m, \ell \neq k\}$ be the set of optimal weights obtained from Eq. (1) by the rest of the regions $\mathrm{R}_{\ell \neq k}$ in their own self-evaluations. According to them, a target region R_k will obtain $n-1$ cross-evaluation scores as

$$\widetilde{V}_k(\ell) = \sum_{j=1}^{m} \widetilde{w}_j(\ell) z_{kj}, \quad \ell \neq k, \tag{2}$$

which, together with each own self-evaluation score, means that at the end of the complete evaluation process each region will receive a total of n scores that can be written into the columns of an $n \times n$ cross-efficiency matrix $\widetilde{V} = \left[\widetilde{V}_k(\ell)\right]$ [29,50,51]. Therefore, a summary score for the kth region in the vulnerability vector of interest can be obtained as the arithmetic mean of all its n self and cross evaluation scores, that is:

$$V(k) = \frac{1}{n} \sum_{\ell=1}^{n} \widetilde{V}_k(\ell), \quad k = 1, \ldots, n.$$

Following the example for $\mathrm{R}_{\mathrm{ES114}}$ (Pontevedra), we will end up with one self-evaluation score, obtained with its optimal weights as shown before, and 99 cross-evaluation scores obtained with the weights of the rest of the cases. The arithmetic mean is the 21.05% value used in the results for vector 4.

Finally, using the same method, we can also construct an overall index with which to combine all vulnerability vectors together. That is, for each region R_k, in Eq. (1) we have $m = 5$ vectors and the values $z_{k1}, \ldots, z_{k5}$ are the vector scores themselves.

For example, for $\mathrm{R}_{\mathrm{ES114}}$ (Pontevedra) we fed each of its vector scores $z_{k1} = 83.24\%$, $z_{k2} = 33.86\%$, $z_{k3} = 19.32\%$, $z_{k4} = 21.05\%$, $z_{k5} = 39.50\%$ into Eq. (1) and, with the appropriate weights, Pontevedra's self-evaluation obtained a maximum score of $\widetilde{V}_k = 91.41\%$, which is the value represented schematically in Fig. 1 (in the coordinate plane of its two main vectors for representation purposes). After averaging with the cross-evaluation scores, the overall vulnerability DEA score for Pontevedra was $V(\mathrm{ES114}) = 68.12\%$, or 6.81 on a scale of zero to ten as reported in what follows (see Fig. B.2).

3.2. DEA-based clusters

The optimization in Eq. (1) determines the degree of vulnerability of the target region R_k ($\min \widetilde{V}_\ell(k) \leq \widetilde{V}_k(k) \leq 1$). As a by-product, a set of optimal weights $\{\widetilde{w}_j(k)\}$ are obtained specifying a vulnerability function that may be approximately shared among a peer group of regions with a similar vulnerability pattern as R_k.

Therefore, this paper proposes the use of hierarchical cluster analysis [see *e.g.* 52] applied to the $n \times m$ matrix of optimal weights from Eq. (1) in order to group regions in such a way that regions within the same peer group have vulnerability patterns that are more similar to each other, in terms of a distance measure, than to those in other groups or clusters; [*cf.* 53,54].

This clustering may be useful from an environmental policy point of view. The design of policies aiming to reduce the vulnerability of a target region must take into account any information available about the drivers of its vulnerability pattern. However, for the target region, lowering the vulnerability score to the levels of any other less vulnerable region in a different peer group may be out of reach because this would involve a very difficult, if not impossible, change of pattern. Therefore, it is only natural to think that policies must be devised and implemented by looking at the least vulnerable regions within the same peer group, that is, with the same vulnerability pattern.

4. Results

In this section, we discuss the ranking of Atlantic European coastal regions based on the vulnerability scores, on a scale of zero to ten, obtained in the five vectors' subindices. For each vector, we first present the general results at the country level, and then analyze the results at the regional level emphasizing the findings about the peer groups that share a similar vulnerability pattern.

V1: marine spill risk

Aggregates in Table B.2 reveal how, on average, the UK and Portugal lead the vulnerability ranking of marine spill risk scores in the European Atlantic area, followed by Ireland and France. The actual ranking for all the coastal NUTS3 regions in Atlantic Europe is shown in Fig. B.1a. According to this, we observe that the coast of South West England and Wales (UK) register the highest levels of marine spill risk. For example, Torbay obtains the highest score (9.99/10), followed by South West Wales (9.46) Devon (9.31) and Swansea (9.06). In fact, there are only four non-British NUTS3 regions on the European Atlantic coast within the first 25 highest vulnerability scores in this vector; namely, Pontevedra (8.32) and A Coruña (7.49) in North West Spain, and Cávado (8.03) and Alto Minho (7.92) in Northern Portugal.

As discussed in Section 3.2, three peer groups with different marine spill vulnerability patterns can be obtained.

Direct marine spill effect. In particular, we note Dorset, and Bournemouth and Poole where the vulnerability risk is derived from marine spills directly, and sea currents appear not to have any effect.

Sea-currents effect. In contrast, West of England, Scotland, Northern Ireland and most of Canary Islands seem to derive their vulnerability to marine spills from the effect of sea currents only. More generally, the regions in Atlantic Spain, Atlantic France, Portugal, Cornwall and Wales are mostly affected from a direct spill risk (67%) but with a moderate effect from sea currents (33%). Similarly, Normandie and Ireland have a smaller direct spill risk but with slightly larger sea currents effect.

No marine spill risk. On the other hand, Lanzarote, Açores and Glasgow City appear not to have a significant vulnerability risk due to marine spills.

V2: port activities

The vulnerability subindex of port activity by country shows a homogeneous behavior across the Atlantic area (Table B.2): the UK and France are the most vulnerable countries with scores close to 2.5, Ireland and Spain are not far behind while Portugal is the least vulnerable country with a very low score, 1.28. These results are in line with the port activity observed in these countries. Ireland, the UK, France and Spain rely on shipping for conducting their trade. In the first two countries, being islands, around 95% of global trade by volume comes through its seaports; in France and Spain this volume exceeds 80%, while in Portugal it represents only 14% [55–57].

Results of the regional ranking on port activity vulnerability can be seen in Fig. B.1b. The subindex shows that even though its range goes from 0 for to 9.02, scores are below 3.09 for 75% of the regions. Thus, the distribution of the vulnerability is far from homogeneous: the majority of the regions have vulnerability indices below two, and only a few of them, those with the highest levels of port activity, show values above five. Belfast (and its neighbor Mid and East Antrim), Plymouth, Bristol and Seine-Maritime, home to four major ports, stand out as examples.

Analyzing the weights assigned to each indicator in the subindex, up to four groups with different port activity vulnerability patterns can be identified.

General port activity. A first group formed by regions with an important and diverse maritime activity related to freight volumes (39%), port area (24%) or passenger transport (20%). It includes the regions of Seine-Maritime, Cádiz, Sefton and Alentejo Litoral, home to the major ports of Le Havre, Algeciras, Liverpool and Sines, respectively.

Freight port activity. A second group is made up of regions with significant freight activity (92%), such as the Irish regions of Western and South-East, Bournemouth and Poole, Dumfries and Galloway and Newry, Mourne and Down in the UK, the French regions of Vendée, Ille-et-Vilaine and Pyrénées-Atlantiques and several regions in Northern Portugal and Northern Spain, as well as the Canary Islands of Fuerteventura and Lanzarote.

Passenger port activity. A third group of regions with a vulnerability pattern related to passenger transport, such as Dublin, Dorset, the Spanish regions of A Coruña and Cantabria, the Welsh regions of South West Wales and Flintshire and Wrexham or the Northern Irish regions of Derry City and Strabane and Belfast.

Low port activity. Finally, the largest group is characterized by a non-specific vulnerability profile, related mainly to the number of ports (62%) and their area (18%).

V3: tourism activities

The third column of Table B.2 presents the results on the tourism vulnerability subindex aggregated by country. On average, Spain appears as the most vulnerable country with an average score of 3.4, followed by Portugal and the UK, while France and Ireland score much smaller average values (1.5 and 1.3 respectively).

The regional distribution of the subindex scores in Fig. B.1c helps explain these results. First of all, seven Spanish regions and four Portuguese ones are among the 25 most vulnerable regions, while none of the French regions are in this most vulnerable group. On the other hand, all Irish regions except Dublin are among the 25 least vulnerable ones.

A more detailed analysis of the NUTS3 regions with the highest scores reveal that they are representative of two main types of tourism: traditional tourist resorts and urban tourism. The first positions are occupied by Portuguese and Spanish regions representative of what is called the "sun and sand" tourism model. Thus, the first one is Algarve, followed closely by two Canary Islands regions, Lanzarote and Fuerteventura. Other clear examples of this tourism model are Gran Canaria, Tenerife and Madeira (11–13th positions). We find as well in this group some of the most important seaside resorts in the UK such as Bournemouth and Poole (2nd), Blackpool (6th) and Plymouth and Torbay in the so called English Riviera (7th and 8th), along with areas like the Lake District (East Cumbria, 18th). Next, the main urban concentrations in the European Atlantic Area follow an urban tourism model. In the UK, Belfast (5th), Bristol (9th), Glasgow and Liverpool (13-14th) and Cardiff (25th); in Portugal, Lisboa and Porto (17th and 21th); and in Ireland, Dublin (22nd). In contrast, other comparatively large Atlantic European urban areas like Bordeaux in France and Bilbao and Vigo in Spain have a low score.

As explained in Section 2, the pressure indicators used to compute the tourism vulnerability subindex have a dual facet: either they come from the supply/demand side or they put pressure on society/territory. The analysis of the DEA weights allows us to identify some peer groups with similar vulnerability profiles.

Supply-driven vulnerability. Supply indicators determine the tourism vulnerability pattern of a good number of regions. One group consists of Algarve, Linconshire (including Blackpool), Dorset and Somerset where tourism pressure comes exclusively from the supply side, specifically the hotel accommodation indicators (75%). The Spanish, Portuguese and French regions (except Canary Islands, Algarve, Madeira and Baisse Normandie) and the British regions of Belfast, Wales, Cornwall, Plymouth and Bournemouth form another peer group. In these 45 regions, supply indicators account for 97% of the pressure, 64% from the food and beverage sector and 29% from the accommodation sector. Last, the Northern Ireland group (excluding Belfast) presents a profile where the supply indicators have the highest scores, but the accommodation sector is the dominant one (40%), while the food and beverage sector comes second (25%). The vulnerability pattern in these groups puts pressure mainly on the region's territory with the exception of Blackpool where the pressure is a social one.

Demand-driven vulnerability. Vulnerability risk derives mainly from demand indicators in the rest of the regions, with slight differences in their vulnerability pattern. We identify a first group (Basse Normandie, the Scottish regions, Cumbria, Merseyside, Bristol, Bath, Devon and Torbay) where the vulnerability comes mostly from the total number of arrivals at any type of tourist accommodation (60%); while arrivals only at hotels account for 62% of the vulnerability in a second group formed by the Irish regions (except Dublin) and Cheshire. On the other hand, the pattern of a third group formed by the smallest Canary Islands (Hierro, La Palma, Gomera) depends 100% on overnights in hotel establishments. In these three groups, the pressure is mostly on the region's territory (except for Glasgow and Liverpool). In the last group, formed by Dublin, Madeira and the biggest Canary Islands, the pressure is split between arrivals at hotels (35%) and overnights in hotels (31%) and is mainly a social pressure.

V4: protection of coastal areas

In this case, we note that since the more protected areas, or larger surface area, a region has the less vulnerable it is, the interpretation of this subindex is that the higher the score, the less vulnerable the region is.

Ireland is the country with the highest number of protected areas, followed by Spain, mainly thanks to the protected areas of the Canary Islands, while the UK is the country with the lowest protection level. The results by country in Table B.2 reflect this fact: the UK holds the first place with an average score of 0.6, followed closely by Portugal, France and Spain while Ireland is the least vulnerable country with a subindex score much higher than the rest (4.1).

Subindex scores in Fig. B.1d show that the most vulnerable regions are those without protected areas, neither terrestrial nor marine: eighteen in the European Atlantic Area, mostly in the UK and Portugal. In contrast, the least vulnerable regions include most of the Irish regions, the Spanish and Portuguese islands and the French regions of Pyrénées-Atlantiques, Manche and Finistere as well as the British regions of Bristol and Antrim.

The indicators used in this vector refer either to the protected areas in general or to the marine areas in particular. Analyzing the weights of these indicators in the subindex, four groups have been identified according to their vulnerability pattern.

Marine protection. A first group of regions that are determined mainly by the indicators related to marine protected areas includes all the French regions except Eure and Pyrénées-Atlantiques, all the Irish regions except Dublin, A Coruña, Pontevedra, and the two largest Canary Islands (Tenerife, Gran Canaria) in Spain, Oeste in Portugal and finally Dorset, the Northern Irish regions of Newry, Mourne and Down and Antrim and Newtownabbey, the Welsh regions of Gwynedd, South West Wales, and Bridgend and Neath Port Talbot and the Scottish Highlands in the UK.

Terrestrial protection. A second group with a vulnerability profile related to land-based protected areas includes most of the Spanish and Portuguese regions along with many of the Welsh and South-West England regions.

Terrestrial and marine protection. A third group characterized by a balance between the influence of land and marine sites is formed by the Spanish regions of Lugo, Cadiz and Huelva, the French region of Pyrénées-Atlantiques and the Portuguese regions of Aveiro, Alentejo Litoral and Madeira.

No protection. A last group comprising the most vulnerable regions, those without protected areas, consists of two Portuguese regions (Cávado and Lezíria do Tejo) and most of the regions of Northern Ireland, the North West of England and the Scottish Lowlands.

V5: water quality and waste management

The last column of Table B.2 presents the results on this subindex aggregated by country. On average, the UK occupies the first place followed by France, Portugal and Spain while Ireland is the least vulnerable country.

Subindex scores in Fig. B.1e show the regional ranking on water quality and waste management. It may be observed that the group of the least vulnerable regions is made up of all the Irish regions but Dublin and almost half of the Spanish ones. On the other hand, twenty two British regions are located within the group of twenty five most vulnerable ones.

The indicators that conform the vulnerability subindex of this vector are related to the quality of the water in the bathing places and to waste generation and treatment. Analyzing the weights assigned to each indicator, up to three groups of regions with similar vulnerability patterns can be identified.

Water quality. A first group of regions is influenced by water quality indicators. Within it, a subgroup characterized by the good quality indicators (74%) is formed by the regions of South-West France, the regions of South Ireland, the Algarve and the regions of North Portugal, West Cumbria, Plymouth, Isle of Anglesey and Cardiff and Vale of Glamorgan in the UK along with all the Spanish regions except the Canary Islands and the Basque Country. In contrast, a second subgroup determined by poor quality indicators (77%) comprises Dublin, the Northern Ireland region of Ards and North Down, and the Scottish Lowlands.

Waste management. A second group with a vulnerability pattern determined by all the indicators related to waste generation and treatment includes Brittany and Normandy in France and the Portuguese Azores. To these, a subgroup can be added that is mainly determined by the recovery recycling indicator (60%) and formed by the French regions of Loire-Atlantique, Seine-maritime and Pyrenees-Atlantiques, Border and West in Ireland, the southern English regions of Torbay and Devon, the Scottish Highlands except the islands, Newry, Mourne and Down, and Causeway Coast and Glens in Northern Ireland, the Basque Country in Spain and Alentejo Litoral, Coimbra, Lisboa and Madeira in Portugal.

Water and waste. The last group, the most numerous and made up of the Canary Islands and the majority of the UK regions, is determined by both water quality (55%) and energy recovery indicators (44%).

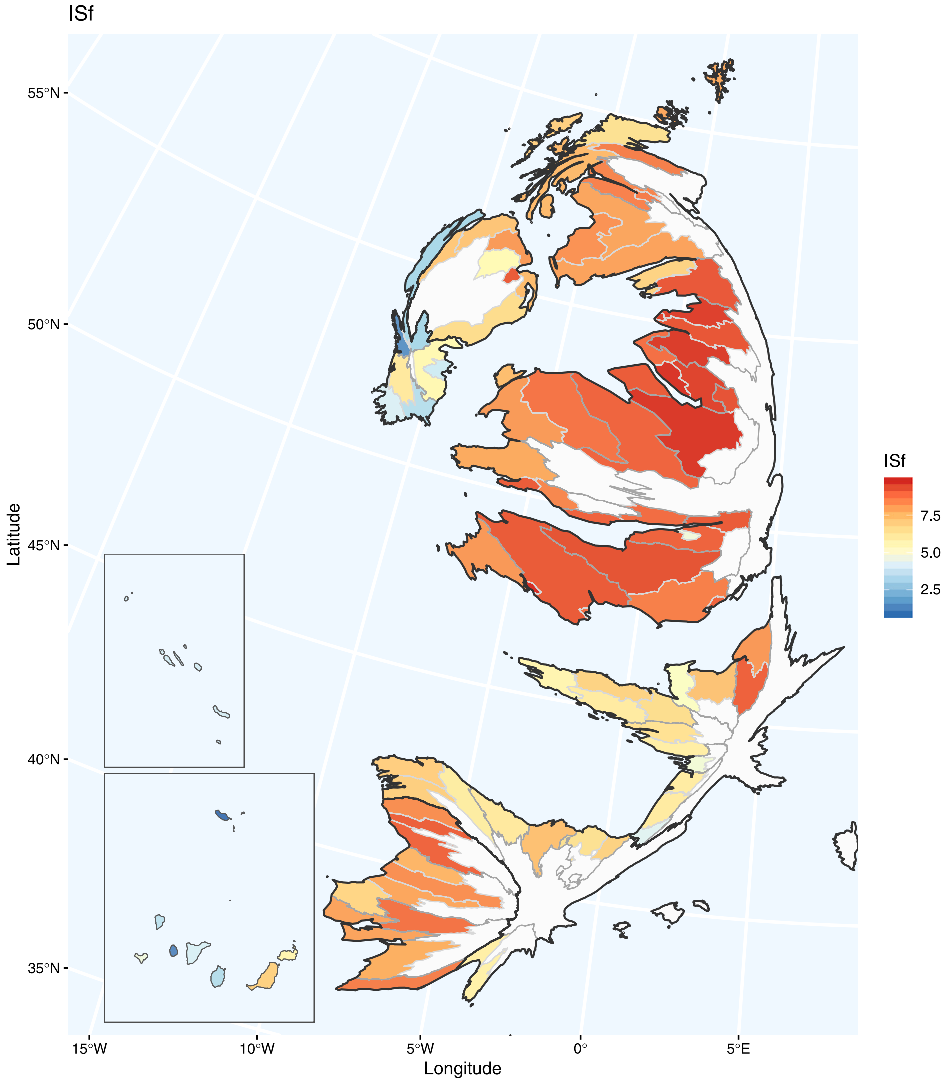


Fig. 2. European Atlantic coastal vulnerability index: cartogram with surfaces proportional to overall scores.

5. Overall synthetic index of vulnerability

A final aggregated vulnerability index was obtained by combining all the partial indices belonging to each of the five vectors (with V4 scores multiplied by −1 since vector 4 indicators are of "resilience" rather than of "vulnerability"). The cartogram shown in Fig. 2 illustrates the relative vulnerability of the Atlantic European coast, where every NUTS3 region's surface area has been scaled proportionally to its vulnerability index score. As we can see, except for most of Ireland and the Atlantic islands, the Atlantic European coast appears in reddish colors corresponding to higher values of vulnerability.

The regions with the greatest vulnerability (10% quantile) belong exclusively to the UK (see the overall ranking in Fig. B.2). In fact, in the first quarter all but three, Cávado (17th) and Porto (22nd) in Portugal and Eure in France (18th), are on the British coast.

More specifically, on the same scale of zero to ten as for the vectors' subindices before, the UK regions of Plymouth, Liverpool (9.8), Cheshire West and Chester (9.7), Chorley and West Lancashire (9.6), Lancaster and Wyre, Blackpool, East Merseyside (9.5), Warrington, Somerset and Mid Lancashire (9.2) lead the overall coastal vulnerability ranking, with six more with a score greater than 9.0. In contrast, the rest of Atlantic European countries have no regions with such high scores. For example, the highest scores in Portugal belong to Cávado (just below 9.0) and Porto (8.9), in France to Eure (8.9) and Seine-Maritime (7.9), in Spain to Cantabria (7.1) on the Bay of Biscay coast, A Coruña and Pontevedra (6.8) on the Galician coast and Fuerteventura (6.8) in the Canary Islands, and in Ireland the highest score corresponds to Mid-West (6.1) in the 72nd position.

By countries, the average scores are UK 8.2, Portugal 7.1, France 6.2, Spain 5.4 and Ireland 4.0 (see the country-level values in Table B.2), with an overall Atlantic European average of 7.1. A more complete comparison showing the heterogeneity of each country can be visualized using so-called violin plots, a combination of a mirrored kernel density plot and a box-and-whisker plot showing the interquartile range and 1.5 times that range (see Fig. 3).

In this respect, the UK shows a fairly compact vulnerability score distribution although biased towards high values, while Portugal, in spite of having an average score just marginally higher than for the whole European Atlantic Area, is the country with the highest regional heterogeneity with a substantial proportion of regions above average, but with a large variation due to the lowest vulnerabilities shown in Madeira (0.8) and Açores (4.0). Similarly Spain shows a large variation due to the relatively low vulnerabilities of all the Canary Islands — although most Spanish regions, except marginally the aforementioned Cantabria region, are below the Atlantic European average.

The map in Fig. 4 shows the different vulnerability peer groups identified from the analysis of the DEA weights. They can be described as follows.

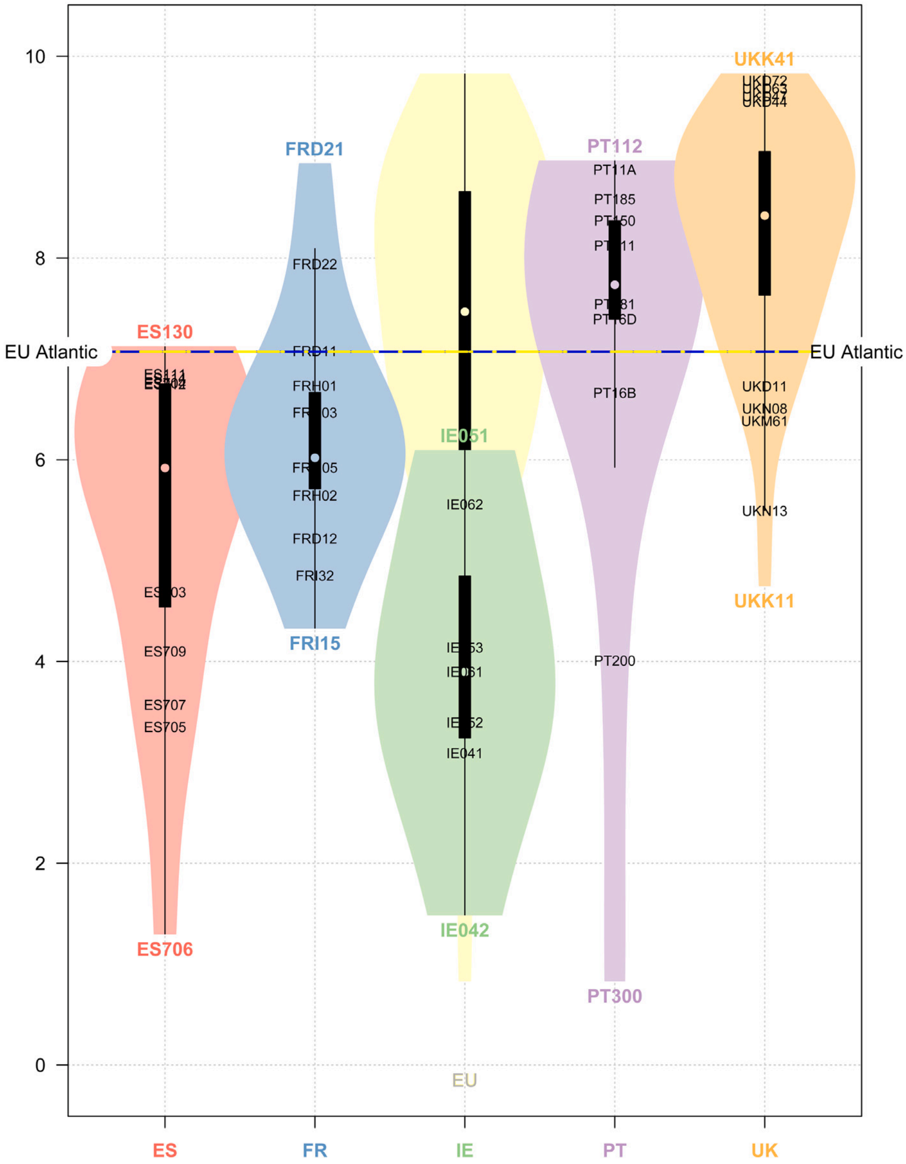


Fig. 3. European Atlantic coastal vulnerability index: country-wise distribution. The codes refer to the top/bottom five NUTS3 regions in each country; see Eurostat [40] for code reference.

Coastal protection pattern. The largest group is made up of 58 NUTS3 regions, 27 of them in the UK, that show a vulnerability pattern linked almost exclusively to indicators of coastal protection or lack thereof. Within this group, regions experiencing high vulnerability values, such as East Merseyside, Somerset and East Cumbria, could devise policies aiming to reduce their vulnerability by looking, for example, at Ireland's Border region, which is the least vulnerable region within this peer group.

Marine spills pattern. A second and relatively large group emerges from a vulnerability pattern mostly determined from exposure to marine spill risks (68%), in combination either with a significant effect (33%) from coastal protection indicators (7 regions, all except Alto Minho in Wales and West England, including Lancashire and Devon as the most vulnerable within this subgroup), or with a moderate impact (20%) from port activities (16 regions in Atlantic Spain, Ireland, Wales and West England, including Plymouth and Liverpool which score the highest). In this respect, the least vulnerable peer in the former subgroup is Wales' Gwynedd, while in the latter the least vulnerable peer is South-East Ireland.

Tourism pattern. A third group of 11 regions, all typical tourist resorts in Spanish Canaries and Portuguese and British destinations, have their vulnerability mostly due to tourism related indicators (57%) combined with a significant concern with water quality (30%). This notwithstanding, we note that Blackpool, and Bournemouth and Poole stand out from the rest in this group due also to their vulnerability to marine spills. On the other hand, the least vulnerable peer in this group appears to be Madeira.

Water and waste pattern. With respect to water quality and waste management, a fourth group emerges from regions whose main vulnerability concerns relate to these indicators (71%), They are 7 regions mostly in North West England and Scotland plus Manche and Western Ireland, the latter being the least vulnerable peer in this group.

Port activities pattern. Finally, Belfast stands out from all the others, since it is the only NUTS3 region in the European Atlantic Area that derives its vulnerability exclusively from the impact of activities related to its port. However, it may also be linked to

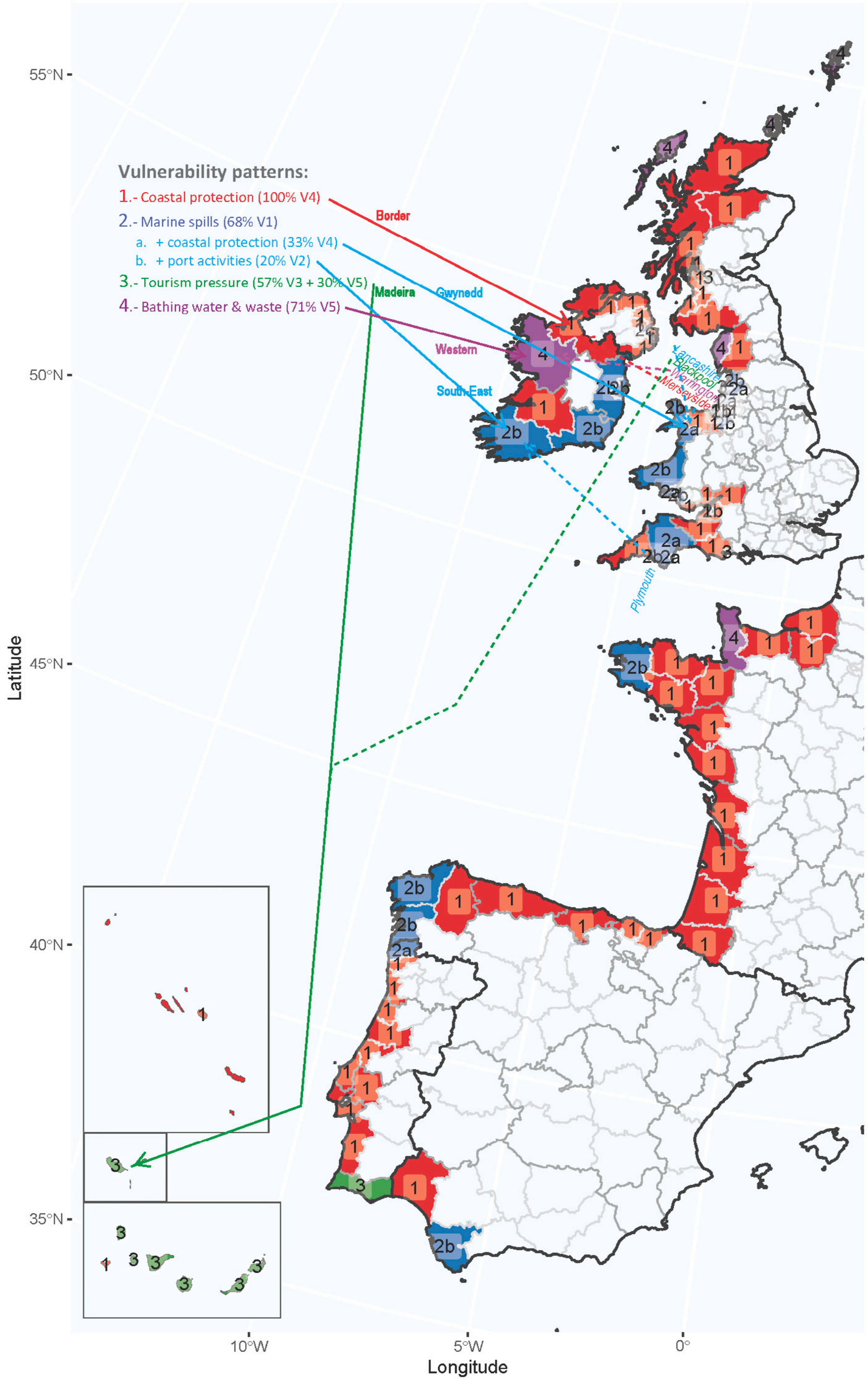


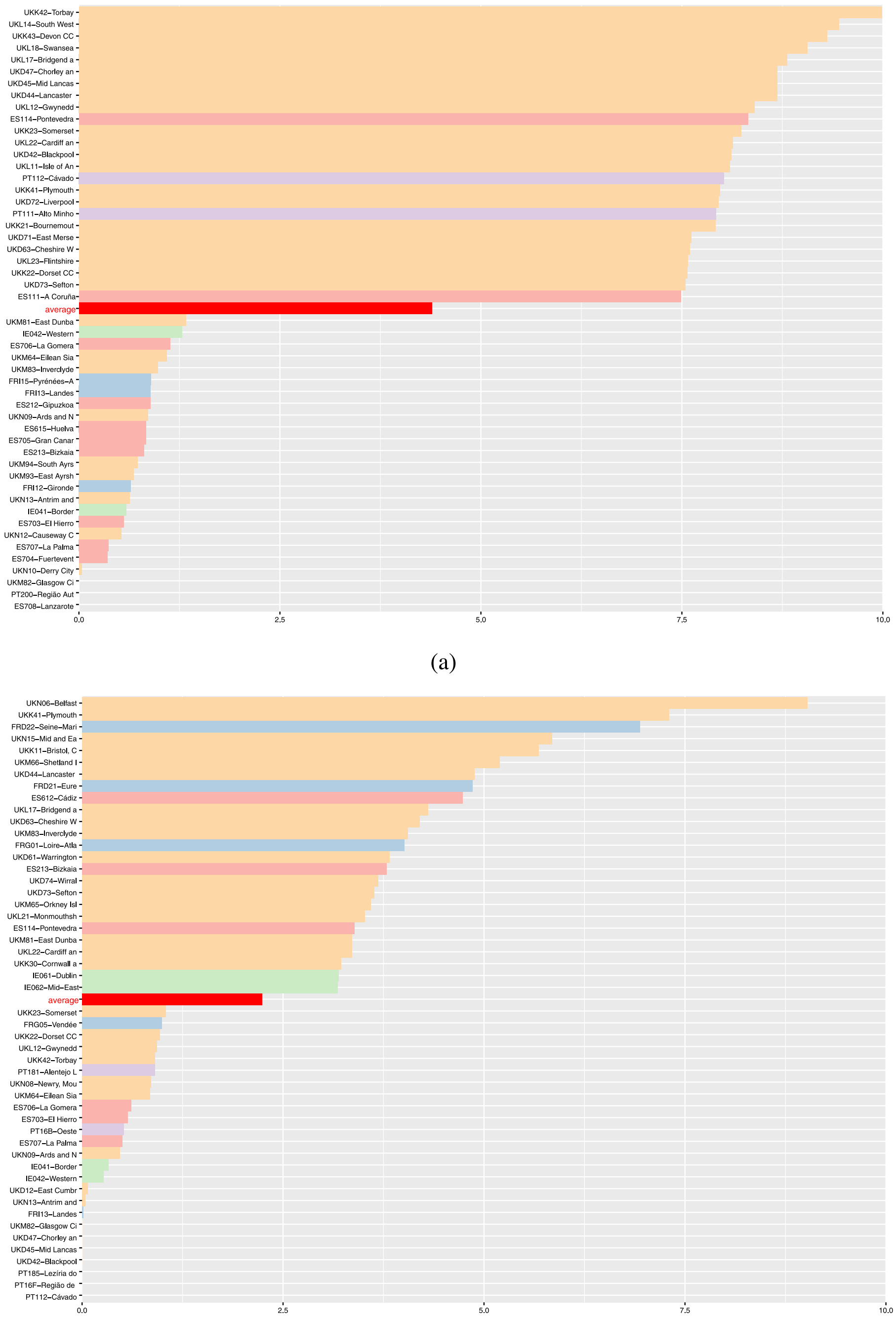
Fig. 4. European Atlantic DEA-based coastal vulnerability peer groups. Solid arrows point to the least vulnerable peer within each group; dashed arrows stem from regions in the vulnerability frontier (see text).

the subgroup mentioned above of 16 regions in Atlantic Spain, Ireland, Wales and West England that, although its main vulnerability concern is due to marine spills, also shows a moderate vulnerability impact from port activities.

6. Conclusions

The implementation of any marine policy aimed to protect the European coasts and to ensure their environmentally sustainable development will benefit from a detailed analysis of their degree of vulnerability with respect to a range of human uses taking place in these areas. In particular, the EU Marine Strategy Framework recommends member states to assess the level of human impacts on marine waters and coasts and the degradation of the coastal environment. This paper seeks to respond to this need for assessment and proposes a metric to measure and compare the degree of anthropogenic vulnerability of the Atlantic European coasts in order to make it a tool for marine and coastal management.

In order to summarize all the available information in an overall measure of vulnerability, the proposed method was used to construct a



(a)

(b)

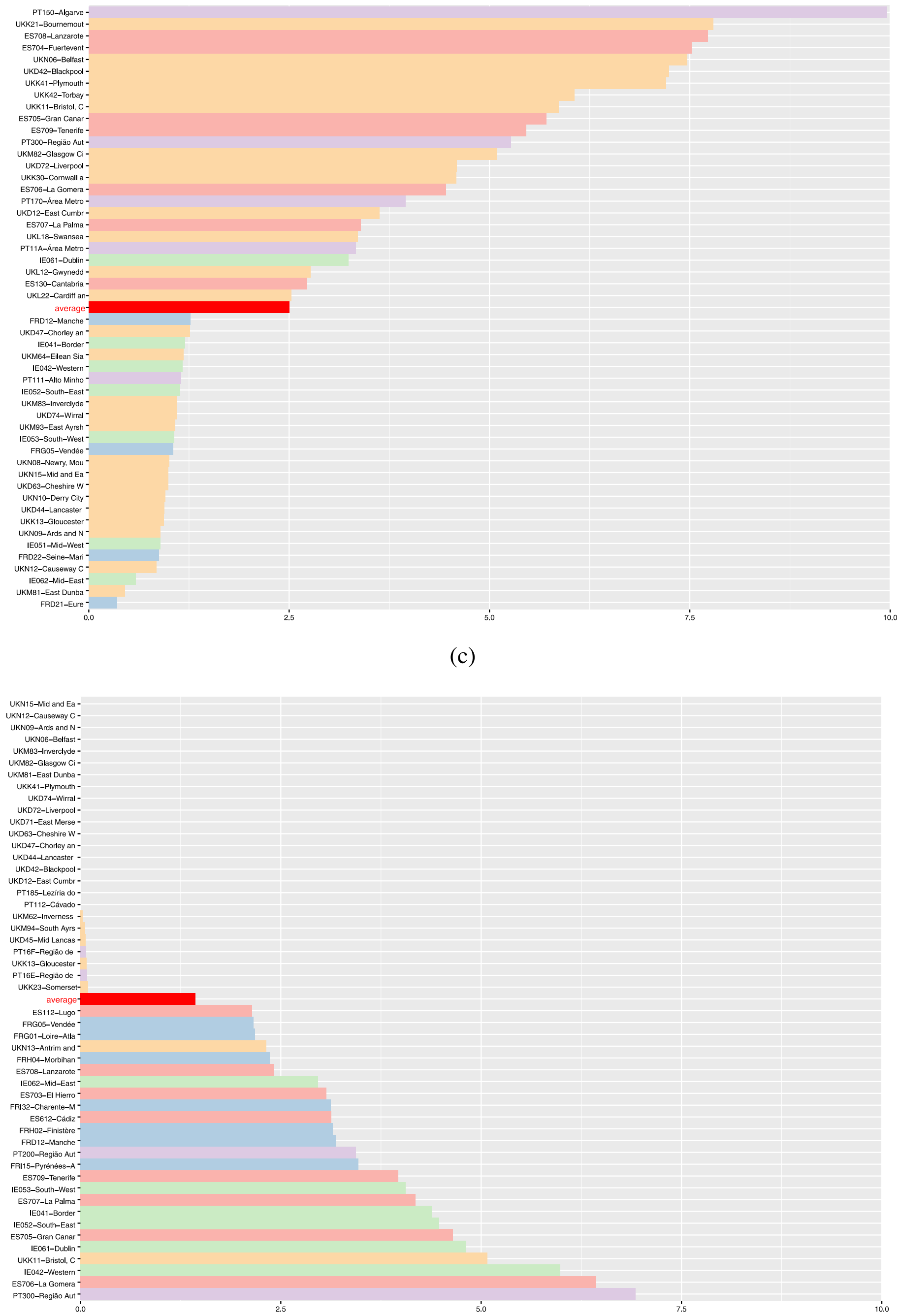
Fig. B.1. NUTS3-level vulnerability rankings (top/bottom 25; country colors as in Fig. 3; EU average in red).

synthetic index based on five vectors related to specific human uses that affect our coasts. The index provides a relative score for each Eurostat NUTS3 region that can be useful to assess its degree of coastal vulnerability in comparison to other regions in the European Atlantic Area.

Apart from this ranking, the proposed method allows us to identify peer groups of regions with similar vulnerability patterns. The analysis of the vulnerability patterns of those regions with better performance within each peer group can provide advice on how to design environmental policies and actions aiming to protect the European coasts and reduce the vulnerability of target regions.

In summary, we may conclude that the UK, with most coastal regions above the Atlantic European average, is the country with the highest vulnerability, while Ireland has the least vulnerable coast, with a quite compact distribution of all its regions well below average. Nevertheless, looking at the overall picture, most of the Atlantic European coast appears to be relatively vulnerable.

As regards further research, the vulnerability index proposed could be extended to cover different geographical areas or to compare different time periods. In the latter case, it could serve to assess the evolution of coastal vulnerability over time in order to help evaluate the degree of success of coastal strategies in a particular area. There are also some obvious limitations of the index which, in its present form, does not cover other kind of vulnerability vectors. In particular, it may be difficult to take into account some important influences that are not systematically measured at a regional scale below the



(c)

(d)

Fig. B.1. (*continued*).

national level, such as climate change, or even qualitative influences such as socio-cultural variables, etc. To allow for these, some statistical proxies could be incorporated to the analysis in the future. But, in general, the approach is valid as long as statistical information about the vulnerability vectors of interest is available.

The results obtained may offer new insights into the impact of human uses on the coastal vulnerability in the European Atlantic Area. As primary beneficiaries, local and regional policy makers may use these results as diagnostic tools to assess the coastal vulnerability of their region, and to detect its strengths and weaknesses so that they can design and carry out appropriate actions in line with integrated European coastal management policies.

CRediT authorship contribution statement

Javier Fernández-Macho: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Pilar González:** Investigation, Data curation, Writing - review & editing. **Jorge Virto:** Software, Validation, Investigation, Data curation, Writing - review & editing.

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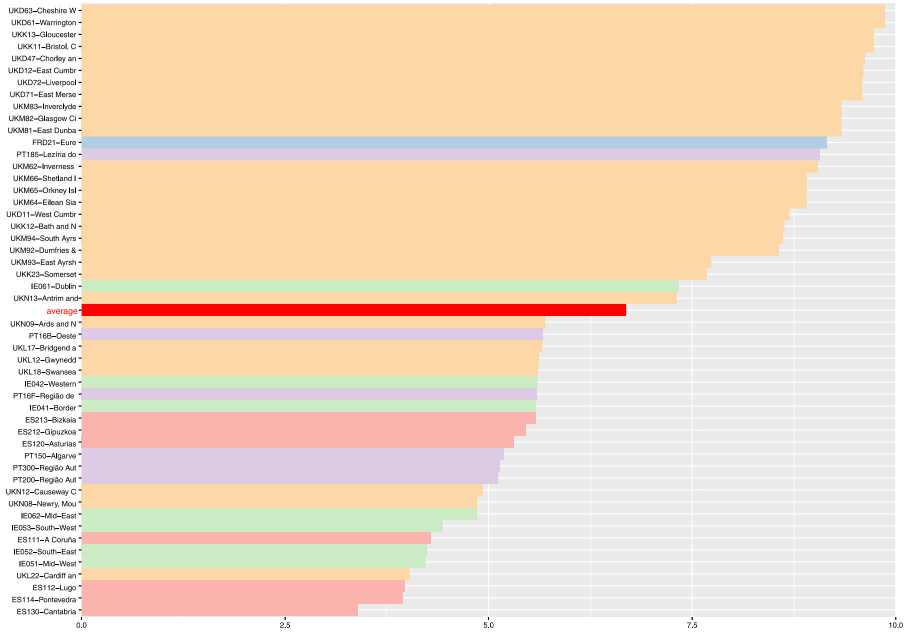

(e)

Fig. B.1. (*continued*).

Table B.1
Main indicators by vector.

V1. Marine spill risk		.
	'Currents-free' marine spill risk scores.	
	Spill risk scores with sea currents effect.	
V2. Port activities		.
	Number of ports.	
	Number of main passenger ports (> 200 000 passengers per year).	
	Number of main goods ports (> 1 million tonnes of goods per year).	
	Total port area.	
	Gross weight of goods handled in all ports.	
	Cruise passengers embarked and disembarked in all ports.	
	Passengers, excluding cruise passengers, embarked and disembarked in all ports.	
	Number of EcoPorts members.	
	Number of Port Environmental Review System (PERS) certified ports.	
V3. Tourism activities		.
Demand	Total arrivals at all types of tourist establishments.	
	Arrivals only at hotels and similar accommodation.	
	Total overnights in all types of tourist establishments.	
	Overnights only in hotels and similar accommodation.	
Supply	Total bed places in the accommodation sector.	
	Bed places in hotels and similar accommodations.	
	Total establishments in the accommodation sector.	
	Establishments in hotels and similar accommodations.	
	Establishments in the food and beverage sector.	
V4. Protection of coastal areas		.
	Number of Sites of Community Importance (SCI).	
	Total area of SCI.	
	Number of marine SCI.	
	Total marine area of SCI.	
V5. Water quality and waste management		.
Marine Bathing Places (MBP)		.
	MBP with excellent water quality.	
	MBP with good water quality.	
	MBP with sufficient water quality.	
	MBP with poor water quality.	
Waste management	Number of incineration disposal facilities.	
	Number of landfill disposal facilities.	
	Number of energy recovery facilities.	
	Number of recovery recycling facilities.	

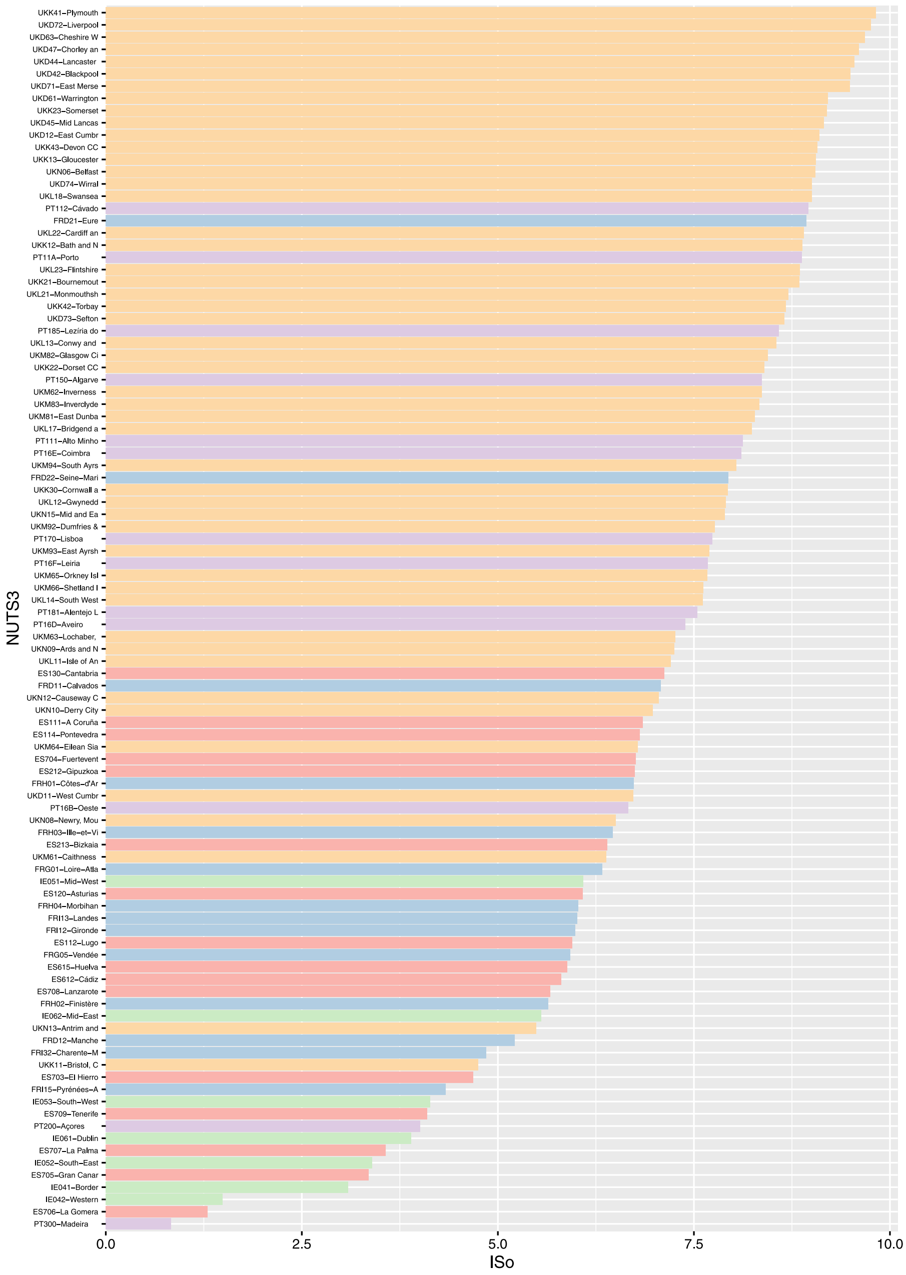

Fig. B.2. Overall synthetic index ranking (country colors as in Fig. 3).

Table B.2
Country-level aggregated vulnerability index.

Country	Vector 1 marine spill risk	Vector 2 port activities	Vector 3 tourism activities	Vector 4 protection of coastal areas	Vector 5 water quality & waste	Overall Index
France	3.61 (0.64 ; 6.83)	2.54 (0.01 ; 6.94)	1.51 (0.36 ; 2.41)	2.02 (0.17 ; 3.47)	6.57 (6.03 ; 9.15)	6.25 (4.33 ; 8.93)
Ireland	3.59 (0.59 ; 6.07)	1.98 (0.27 ; 3.19)	1.33 (0.58 ; 3.24)	4.09 (1.96 ; 5.99)	5.18 (4.23 ; 7.34)	3.95 (1.49 ; 6.09)
Portugal	4.15 (0.00 ; 8.03)	1.29 (0.00;2.75)	3.09 (1.15 ; 9.97)	1.14 (0.00 ; 6.93)	5.99 (5.11 ; 9.07)	7.14 (0.83 ; 8.96)
Spain	2.59 (0.00 ; 8.32)	2.06 (0.50 ; 4.74)	3.37 (1.34 ; 7.73)	2.59 (0.32 ; 6.44)	5.63 (3.40 ; 6.74)	5.44 (1.30 ; 7.12)
UK	5.36 (0.00 ; 9.99)	2.50 (0.00 ; 9.02)	2.51 (0.45 ; 7.79)	0.60 (0.00 ; 5.08)	7.45 (4.03 ; 9.86)	8.24 (4.75 ; 9.82)

Aggregation method: unweighted average of NUTS3 index values.
The range of the NUTS3 index values within each country is shown in brackets.

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Appendix A

The construction of the EU Moses database has involved the use of several sources:

1. Eurostat regional statistics.
    (a) Maritime transport statistics;
        - Passengers embarked and disembarked in all ports by direction.
        - Gross weight of goods handled in all ports by direction.
        - GISCO Ports dataset.

    (b) Regional Tourism statistics;
        - Arrivals at tourist accommodation establishments by NUTS2 regions.
        - Nights spent at tourist accommodation establishments by NUTS2 regions.
        - Number of establishments, bedrooms and bed-places by NUTS2 regions.

    (c) Waste management
        - Number and capacity of recovery and disposal facilities by NUTS2 regions.

2. European Sea Ports Organisation (ESPO), EcoPorts data.
    - Ports that are EcoPorts members.
    - Port Environmental Review System (PERS) certified ports.

3. European database on Natura 2000 sites and the Official Journal of the European Union: update of the list of sites of Community importance for the Atlantic biogeographical region, 2015 to 2017, to compute the total and marine area of each site of Community importance (SCI).
4. Bathing Water Directive: Status of bathing water (European Environment Agency) to compute the number of Marine Bathing Places with excellent, good, sufficient and poor water quality.

Appendix B

See Tables B.1 and B.2, and Figs. B.1–B.2.

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