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High risk water pollution hazards affecting Aveiro coastal lagoon (Portugal) – A habitat risk assessment using InVEST

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A R T I C L E I N F O

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InVEST
Habitat risk assessment
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A B S T R A C T

Anthropogenic pressures put at jeopardy ecosystem services (ES) provided by natural habitats. Ecosystem Based Management (EBM) approaches can support policymakers dealing with physical, chemical, and biological stresses caused by high-risk water pollution (HRWP) and sudden-accidental pollution (SAP). The objective of this study is to evaluate how alarming HRWP pressures might become in fragile marine, coastal, estuarine, and freshwater socio-ecological systems (MCEF-SES) surrounded by heavily industrialized and urbanized areas. To this end a spatially explicit analysis, using the InVEST-Habitat Risk Assessment (InVEST-HRA) model in combination with expert judgement from researchers from various fields, is performed. An application is provided for the case of the Ria de Aveiro (RdA) coastal lagoon in Portugal. Results show high spatial variance of HRWP hazards across RdA, with one major multi-layer risk hotspot at the center of the research area and a second patch of multiple risk hotspots towards the North of RdA. Salines emerge as the most threatened habitat followed by Intertidal flats and Saltmarshes. The most significant water pollution risk sources contributing to Salines cumulative risk are Fossil fuel processing, storage and sale units, Industrial units, Aquaculture, and the Marinas. Industries involving dangerous substances in the region threaten primarily Watercourses. This study confirms the InVEST-HRA model in combination with expert judgement is a transparent and easily replicable approach to build ES-based knowledge about habitat risks threatening MCEF-SES in a Natura 2000 site heavily pressured by HRWP hazards. After further valuation analysis, pondering gains and losses from regional development and environmental protection, this knowledge can support the planning and management of coastal areas and the prioritization of pollution abatement interventions. In particular, by estimating the loss that HRWP causes in the value of ecosystem services, defining HRWP abatement policies, assessing the effectiveness, costs and benefits of those abatement policies and, ultimately, evaluating the results for the well-being of local communities through global efficiency analysis, cost-benefit analysis or cost-effectiveness analysis. Hence, it bridges the gap between an informed EBM and the development policies of fragile regions.

1. Introduction

Marine, coastal, estuarine and freshwater socio-ecological systems (MCEF-SES) contamination is among the most deleterious events produced by economic development – in particular high-risk water pollution (HRWP) like sudden-accidental pollution (SAP). Furthermore, the

Abbreviations: ES, Ecosystem services; EBM, Ecosystem-based mmanagement; HRWP, High-risk water pollution; SAP, Sudden-accidental pollution; MCEF-SES, Marine, coastal, estuarine and freshwater socio-ecological systems; InVEST-HRA, Integrated Valuation of Ecosystem Services and Tradeoffs - Habitat Risk Assessment; RdA, Ria de Aveiro; PSP, Point-source pollution; ANPC, Civil National Protection Authority (in Portugal); CLC, Corine land cover; AIDA, Regional industrial association (in RdA region); FFPSSUs, ossil fuel processing, storage and sale unitsF; WWTP, Wastewater treatment plants; SRTP, Solid residues treatment plants; LSSEs, Landfills and sewage submarine emissaries; SEVESO industries, Industrial units dealing with dangerous substances as described to in Article 3 of the SEVESO Directive (Directive 2012/18/EU); Non-SEVESO Industries, Industrial units (operators, installations, or establishments) not covered by the SEVESO directive (European Parliament, 2012); CSV, Comma-separated values; GIS, Geographic information system.

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worsening of environmental contamination triggers major disruptions on habitats and calls for public policies aimed at remedying environmental hazards (Islam and Tanaka, 2004). Water pollution comprehends materials, substances and energy dumped by humans into marine and estuarine environments which lead to the decline of MCEF water resources, the jeopardizing of aquatic living resources and the impairment of water use-quality – with direct negative impact on human use of the sea and human welfare (UN, 2016). In this study, HRWP is defined as the water pollution that can be point-source pollution (PSP) and sudden-accidental pollution (SAP). PSP is all "pollution produced by a stationary site or fixed facility discharging pollutants into the environment that can be traced back to (points to) its origin, identifying its contamination source" (Aquarium of the Pacific, 2016); SAP is defined as abrupt pollution releases which are "fortuitous and arise unexpectedly or without warning" (Ballard and Manus, 1990: p. 617).

Risk assessment consists of determining how objects exposed to a hazard might be impacted and which is the probability corresponding to each potential damaging outcome (Azevedo et al., 2017). Hence, a hazard is the possibility (uncertainty) of an environmental impact produced by an event occurring within a given area and timeframe; risk is the estimated loss suffered by an object exposed to a hazardous occurrence within a given area and timeframe (Azevedo et al., 2017). To clearly distinguish between hazard and risk, one must integrate the concept of uncertainty. Also, other authors consider important to include the degree of exposure, including the typology of hazardous substances (such as density and type), and the time of exposure (Azevedo et al., 2017; Kumpulainen, 2006). The Prisma Project (2016), for example, define risk using two alternative – even if interrelated – expressions: (1) Risk = Probability * Impact, and (2) Risk = Hazard * Vulnerability (see Fig. 1).

As can be observed, the second definition indicates that a hazard is transformed into a risk by the degree of vulnerability of those objects under threat, suggesting that "any hazard implies only a potential negative result (a crisis or a disaster) which materialization (or not) depends on the vulnerability, the defenselessness, of those exposed to it. In turn, vulnerability is a composed concept which comprises exposure and susceptibility" (Prisma Project, 2016). In this study, following the Stanford University - Natural Capital Project (2014), risk is defined as the likelihood that anthropogenic pressures will reduce the quality of habitats to the point that their ability to deliver ecosystem services is impaired.

Different from hazards induced by natural events, hazards caused by industrial disasters are unexpected events induced by humans which cause great damages to populations and the environment (de Lemos, 2008). There is a multitude of hazardous industrial activities, which might give rise to pollution events, ranging from the emissions produced by industrial processes, the transportation, storage and use of hazardous substances and materials, to industrial disasters (Christensen et al., 2003; de Lemos, 2008). Often located close to sensitive MCEF-SES and in the proximity of urban areas, both ports and oil & gas infrastructures are good examples of hazardous activities, as they host a wide range of hazardous processes and materials, prone to explosions, blazes and toxic chemical releases (Depellegrin and Blazauskas, 2012; Ronza et al., 2006). Catastrophic disasters, such as fires, oil spills, explosions, spontaneous hull wrecks, cargo, traffic accidents, ship collisions, strandings and ship foundering may happen (de Lemos, 2008; Stam et al., 1998; Walker, 2000) and, together with other industrial activities on the rise, put a large pressure on MCEF-SES (Custódio et al., 2017; Nobre et al., 2009; Troell et al., 2014; Villasante et al., 2013). Together with shipping maintenance operations and industries involving dangerous substances as described in Article 3 of Directive 2012/18/EU (SEVESO industries), those events might release toxic chemicals that contaminate important natural ecosystems and affect them for extended periods of time (Christensen et al., 2003; Oliveira et al., 2014).

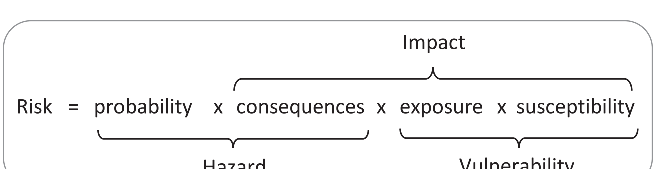

Fig. 1. Key components of risk (source: Prisma project, 2014).

Even if risk assessment is viewed as an important step in the process of managing environmental hazards, only few studies couple the assessment of habitat risks from HRWP hazards in MCEF-SES with environmental-economic approaches and almost all of them focus on oil spill accidents (Bastos et al., 2021). These studies aim to assess endured losses (Depellegrin and Blazauskas, 2012; García Negro et al., 2009; Garza-Gil et al., 2006), establish the factors having impact on oil spill costs (Ventikos and Sotiropoulos, 2014), estimate the costs of clean-up operations (Montewka et al., 2013), uncover the value of lost ecosystem services (ES) (Sajid et al., 2020), and determine the criteria and/or levels for compensation amounts (Kennedy and Cheong, 2013; Kontovas et al., 2010; Psarros et al., 2011).

Besides oil spill studies, some HRWP studies opt for focusing on land-use issues. Zhai et al. (2020) assess the ecological risk caused by human activities in coastal ecosystems for the case of northern Shandong and eastern Jiangsu (China); Zheng et al. (2020) study the change in ecological conditions (including the water body index) produced by urbanizing coastal ecosystems, for the case of China (the Chinese coastline); and Yan et al. (2020) analyze the change in the structure and the value of coastal ES caused by human activities and economic development (aquaculture, port and construction) in coastal areas, also for the case of China (the Chinese coastline). Finally, the two HRWP studies focusing on industrial hazards identify main risk-sources from a wide range of chemical companies located along the Yangtsé river in China (Peng et al., 2013) and assess the risk of accidental release of radioactive substances in Central Europe (Monte et al., 2009). Furthermore, the use of combined approaches to assess ecosystems and ES are sparse (Chung et al., 2015) and there are no studies that assess habitat risk resulting from the co-occurrence – at the same time and place – of a whole portfolio of HRWP hazards in MCEF-SES.

Hence, with the global goal of contributing to earlier studies by building knowledge about habitat risk assessment, this study aims to evaluate how alarming HRWP pressures might become in fragile MCEF-SES surrounded by heavily industrialized and urbanized areas. Hence, this study contributes to improving Ecosystem Based Management (EBM) in regional settings and the definition of areas for development and areas for conservation within specific MCEF sites. To this end a spatially explicit analysis, using the InVEST-Habitat Risk Assessment (InVEST-HRA) model in combination with expert judgement from researchers from various fields, is performed to investigate high-risk water pollution (HRWP) events threatening fragile lagoon ecosystems (namely marine, coastal, estuarine and freshwater) in a Natura 2000 site (Ria de Aveiro, Portugal).

The results provide input and support in the exploration of pollution abatement strategies and, subsequently, cost-benefit assessment of these strategies.

The remainder of this paper is structured as follows. In Section 2 the employed methodology and the used data are explained. Next, in Section 3 obtained results are presented (starting with the results of the experts' survey and concluding with the InVEST-HRA risk outputs) and, subsequently, discussed in Section 4 (namely by identifying habitats at risk and major risk sources). Finally, Section 5 provides concluding remarks and recommendations for future research.

2. Materials and methods

Built on the basis of an ES approach, the InVEST Habitat Risk Assessment (InVEST-HRA) model (Stanford University - Natural Capital

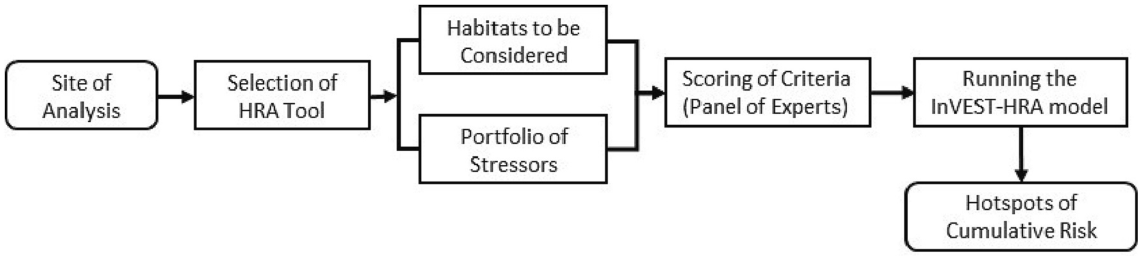

Fig. 2. Workflow stages of InVEST habitat risk assessment process.

Project, 2014) aims at measuring the cumulative risk produced by multiple anthropogenic activities on natural habitats, in a spatially explicit analysis (Arkema et al., 2014). The advantage of conducting a spatially explicit assessment is the fact that it provides a global (geographical) perspective of the biodiversity status and ES provided by a natural system in combination with the distribution of HRWP stressors, thus allowing for an adequate valuation and assessment of tradeoffs, both among ES and between ES and socioeconomic activities (Chung et al., 2015).

InVEST-HRA operates in conjunction with Geographic Information System (GIS) software. By ranking hazards threatening each specific habitat or specie, it computes habitats and species risk. If applied jointly with other socio-economic valuation models, such as the benefit transfer or meta-analytic models, InVEST-HRA helps assess tradeoffs between human action and benefits provided by habitats/species and, thus, supports policy decision-making (Arkema et al., 2014).

InVEST-HRA requires a clear definition of the geographical boundaries of the study area (Section 2.1), the definition of the habitats (Section 2.2), of the stressors to be considered (Section 2.3), and the characterization of the impact of anthropogenic activities over habitats (the scoring of the attributes), both exposure and consequence (Section 2.4 and Section 2.5. below) in order to, finally, perform the assessment of cumulative risk, including risk hotspots (Section 3.; see Fig. 2).

2.1. Study area

The geographical focus of this analysis is the Ria de Aveiro (RdA) coastal lagoon and its adjacent territory, on the central coast of Portugal. Following the European Statistical Units nomenclature, this is the statistical unit of "Aveiro region, Portugal", NUT level 3 (Fig. 3). The RdA is a shallow coastal lagoon belonging to the Vouga River system, which exhibits a single connection to the Atlantic Ocean. The RdA lagoon has a length of 45 km and a width of 10 km, with currents dominated by ocean tides. Fueled by an average of around 1,8E^6 m^3 fluvial water discharge and 137 E^6 m^3 tidal water influx in Spring, RdA waters cover an approximate 83 km^2 of total wetland area at high tide as opposed to only 66 km^2 at low tide (LAGOONS Project (University of Aveiro), 2014).

The RdA region is a very dynamic area, with numerous medium and small towns scattered along the lagoon borders, heavily industrialized, and served by a dense network of infrastructures (LAGOONS Project (University of Aveiro), 2014). Historically, RdA waters have been subjected to important pollution events – diffuse and point source – (de Lemos, 2008) and, even though currently it is closely monitored due to stronger environmental public awareness and tougher environmental regulations, its ecosystems remain under permanent threat. In fact, the Portuguese Civil National Protection Authority (ANPC) tags the transportation of hazardous materials in the region – by road, railway or ship – as prone to an "acute risk" of accident and classify the roads around and the railways passing through the RdA region as highly susceptible to hazardous accidents. Moreover, the ANPC classifies the Aveiro district within the top three Portuguese regions most exposed to disasters with many hazardous stationary installations. All of them are located close to the lagoon and mainly classified in the top risk class of "highly susceptible" to disasters (ANPC, 2015).

2.2. Defining the habitats to be considered

According to (AMBIECO/PLRA, 2011), RdA habitats comprise the marine area close to the coast, wooded dunes, lagoon/estuarine open waters, freshwater lagoons, intertidal banks, saltmarshes and reed beds, riparian woods and agrosystems. The focus of this analysis is the whole body of marine, coastal, estuarine and freshwater socioecological systems (MCEF-SES).

Following the Corine Land Cover (CLC) 2018 classification (Copernicus, 2012) and with reference to the Maritime Spatial Framework Directive (MSFD) lexicon, eight wetlands and water bodies habitats were defined (Fig. 3**)**: Inland marshes (CLC-411), Saltmarshes (CLC-421), Salines (CLC-422), Intertidal flats (CLC-423), Watercourses (CLC-511), Waterbodies (CLC-512), Coastal lagoons (CLC-521), and Sea and ocean (CLC-523). A 100 m × 100 m spatial resolution is used for the analysis.

2.3. Selecting the portfolio of stressors

Combining data supplied by the regional Industrial Association (AIDA) with the regional map of industrial risk (Secur - Ria, 2007), the APA River Basin Management Plans (APA, 2019), the ANPC information about RdA region (ANPC, 2015) and the MSFD (European Parliament, 2008), an initial selection of HRWP stressors threatening RdA MCEF-SES was defined upon a detailed examination of regional economic activities. In particular, the scheme for accident prevention published by the Portuguese Environmental Agency (APA, 2019) and the SEVESO Directive (European Parliament, 2012), allowed for the separation between SEVESO[1] industries and Non-SEVESO[2] Industries. Taking the inherent hazardousness of those economic activities, which might spark the occurrence of serious, high-impact disasters, a portfolio of key industrial activities and transport networks, was taken as the most critical stressors within and around the RdA coastal lagoon. Selected industrial activities are SEVESO industries, Ports (the Seaport, the Inshore fishing port, Marinas and recreational ports), Fossil fuel processing, storage and sale units (FFPSSUs), Wastewater treatment plants (WWTP), Solid residues treatment plants (SRTP), Landfills and sewage submarine emissaries (LSSEs), Aquaculture units and Non-SEVESO industries. Selected transport networks are Motorway traffic lanes, Road traffic lanes, Shipping lanes and Railways (Fig. 4).

Thus, the final portfolio of selected RdA habitats and stressors is composed of eight habitats – Ocean, Coastal lagoon, Intertidal flats, Salt

[1] SEVESO industries are industrial units (operators, installations, or establishments) dealing with dangerous substances as described to in Article 3 of the SEVESO Directive (Directive 2012/18/EU).

[2] Non-SEVESO Industries are the industrial units (operators, installations, or establishments) not covered by the SEVESO directive (European Parliament, 2012).

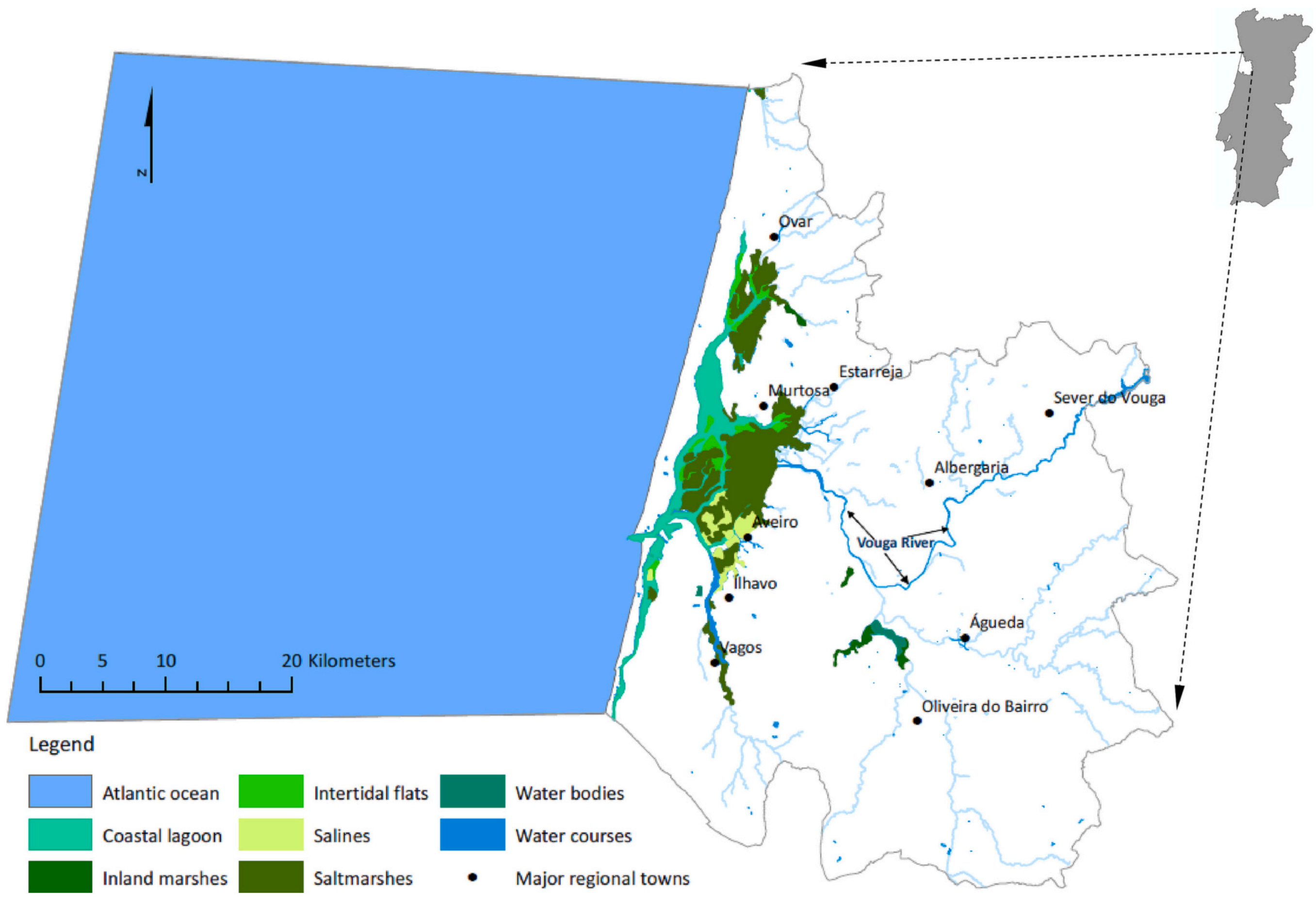

Fig. 3. The portfolio of marine, coastal, estuarine and freshwater habitats selected in the region of Aveiro.

marshes, Salines, Watercourses, Waterbodies and Inland flats – and twelve stressors – SEVESO industries, Seaport, Inshore fishing ports, Marinas & recreational ports, FFPSSUs, WWTPs-SRTPs-LSSEs, Aquaculture, Non-SEVESO industries, Motorways, Roads, Shipping lanes and Railways.

2.4. Calculating habitats' risk

Anthropogenic pressures (stressors) impact habitats both directly and indirectly. InVEST-HRA focuses on direct impacts only and computes risk by combining information about two key variables, namely exposure and consequence (Arkema et al., 2015; Ma et al., 2016). Exposure refers to the susceptibility of habitats to stressors, and is determined by the extent (probability) of spatial overlap between habitats and stressors, the duration (probability) that the stressors and habitats overlap, the intensity of the stressors, and the extent to which management practices mitigate impacts (Table 1-**A**) (Ma et al., 2016; Stanford University - Natural Capital Project, 2014). Consequence refers to the effect of this exposure (to stressors) on habitats, and is determined by the degree of habitat loss, the degree of change in habitat structure, frequency of natural disturbances, and recovery attributes of habitats (Table 1-**B**) (Ma et al., 2016; Stanford University - Natural Capital Project, 2014).

InVEST-HRA computes risk posed by anthropogenic stressors to habitats and species through four main stages (Stanford University - Natural Capital Project, 2014): (1) determination of the likelihood of exposure of habitats to stressors and the associated consequence of this exposure for habitats; (2) estimation of risk values for stressor-habitat combinations; (3) quantification of the cumulative risk produced by all stressors on all habitats; and (4) identification of "risk hotspot" areas.

Exposure (E) and consequence (C) are determined by rating exposure and consequence criteria and attributes (see Table 1). Following the Stanford University - Natural Capital Project (2014), all criteria are rated on a 0–3 scale (with 0 = no score), except for spatial overlap which assumes values of 0 (excludes the stressor from calculations) or 1 (includes the stressor in calculations). Overall exposure and consequence are computed as weighted averages of the exposure and consequence values:

$$E_{jkl} = \frac{\sum_{i=1}^{N} \frac{e_{ijkl}}{d_{ijkl} \times w_{ijkl}}}{\sum_{i=1}^{N} \frac{1}{d_{ijkl} \times w_{ijkl}}} \text{ and } C_{jkl} = \frac{\sum_{i=1}^{N} \frac{c_{ijkl}}{d_{ijkl} \times w_{ijkl}}}{\sum_{i=1}^{N} \frac{1}{d_{ijkl} \times w_{ijkl}}}, \quad (1)$$

where e_{ijkl} and c_{ijkl} are, respectively, the exposure and consequence values for criterion i, d_i refers to data quality rating for criterion i, w_i denotes the weight assigned to criterion i for habitat j, from stressor k in location l, and N is the number of criteria taken into account for each habitat (Arkema et al., 2015; Ma et al., 2016; Stanford University - Natural Capital Project, 2014).

Risk for stressor-habitat combinations is estimated combining exposure and consequence values using the Euclidean approach. Hence, risk (R) for habitat j from stressor k in location l is calculated based on the Euclidian distance from the origin in the exposure-consequence space:

$$R_{jkl} = \sqrt{(E_{jkl} - 1)^2 + (C_{jkl} - 1)^2} \quad (2)$$

The cumulative risk (R) on each habitat j over all locations l produced by all stressors k is given by the sum of all risk scores for each habitat:

$$R_j = \sum_{k=1}^{K} \sum_{l=1}^{L} R_{jkl} \quad (3)$$

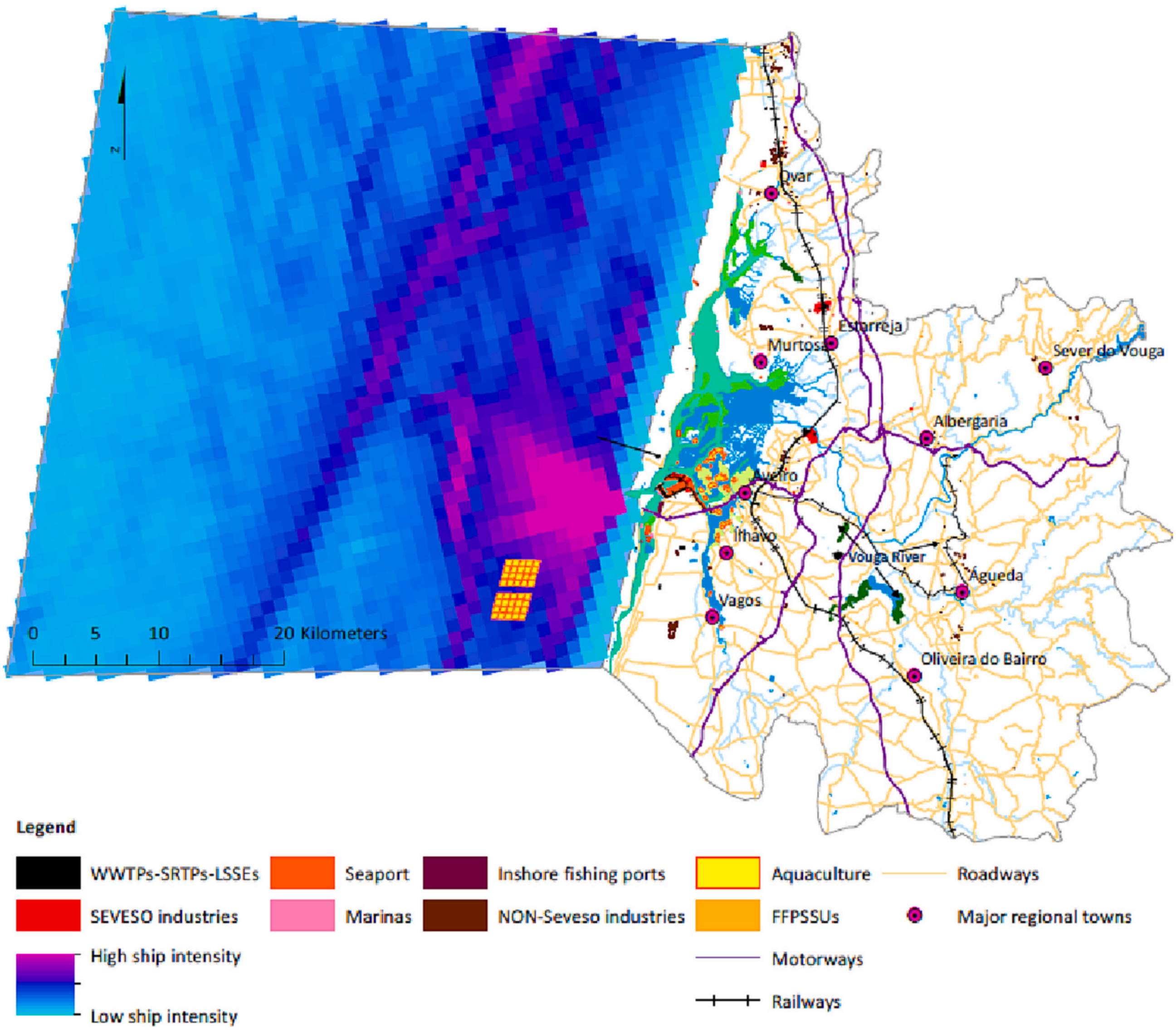

Fig. 4. The portfolio of high-risk water pollution stressors selected in the region of Aveiro.

Finally "risk hotspot" areas, i.e. areas where the influence of stressors is such that ecosystem structure and function may be severely compromised, are identified. Each habitat grid cell is classified as 'high', 'medium' or 'low' risk, based on the risk posed by, either, individual stressors, or, cumulative effects of multiple stressors. The classification 'high' is given to grid cells with a an individual or cumulative risk score of over 66% of the maximum possible risk score; the classification 'medium' is given to grid cells with a an individual or cumulative risk score of between 33% and 66% of the maximum possible risk score; and the classification 'low' is given to grid cells with a an individual or cumulative risk score of <33% of the maximum possible risk score.

Input data needed to run InVEST-HRA are: (1) area of analysis, (2) habitats/species at risk within the study area, and (3) HRWP stressors – all in a GIS compatible format (shapefile or raster files). Additionally, two CSV files are used to give directions to the software on: (1) the habitats/species and stressors to be considered, the buffers of stressors and the path to the respective GIS files, and (2) the scorings (rating, data quality and weights) to be applied to each criterion by the model.

2.5. Rating the exposure-consequence criteria

InVEST-HRA uses a range of criteria for rating exposure-consequence attributes per habitat and stressor (Stanford University (Natural Capital Project), 2014; see Table 2).

Following the most used methodology in cumulative impact mapping analysis (Arkema et al., 2014), expert opinion is chosen to rate exposure-consequence attributes per habitat for the RdA MCEF-SES. In this study, a semi-structured questionnaire was developed (see **Appendix A.1**), taking as a reference the output from running InVEST-HRA. The final structure of the questionnaire was composed of two main sections. The first set of questions aimed at characterizing each habitat. The second set of questions focused on ascertaining the spatial and temporal overlap between each stressor and each habitat, as well as the magnitude of related consequences. A last question was directed at determining buffer extensions for each stressor-habitat pairing. InVEST-HRA default rating criteria were used, that is, the 0–3 scale (1 = "low", 2 = "medium", 3 = "high" and 0 = "not applicable").

After pretesting the questionnaire (with seven environmental researchers, two biologists and one geographer), an expert survey was conducted (April to November 2019). The full procedure applied for the

Table 1
InVEST-HRA exposure (A) and consequence (B) criteria and attributes described.

Habitat risk: The risk of a habitat to be degraded by a stressor is related to the 'Exposure' of that habitat to a certain stressor (determined by the spatial and temporal overlap between habitat and the stressor), and the 'Consequence' of that exposure.	
A. The 'Exposure' criterium refers to the way habitats are put in danger by human activities, the degree of susceptibility a habitat shows when threatened by a stressor. Exposure to a stressor occurs whenever there is an overlap between habitats and human activities ('Spatial overlap' and 'Temporal overlap') and is determined by various attributes defined case-by-case. In this study the default 'Exposure attributes' put forward by InVEST-HRA are adopted, namely, the extent of overlap ('Spatial overlap'), the duration of the overlap ('temporal overlap'), the severity of the stressor ('Intensity'), and the capacity of management practices to effectively mitigate stressors' impact ('Management effectiveness').	
Exposure attributes:	
•Spatial overlap	Spatial overlap refers to the co-occurrence of habitats and stressors at the same location (grid cell). To assess spatial overlap in the study area, the model uses maps of the distribution of habitats and stressors, together with corresponding buffers to estimate spatial overlap between each habitat and each stressor at the grid cell and subregional scale. For each grid cell, if the habitat overlaps with a stressor, then spatial overlap = 1 and the model calculates exposure, consequence and risk using scores for the other criteria. If a habitat does not overlap with a stressor in a particular grid cell, then the model sets exposure, consequence and risk = 0 in that particular grid cell.
•Temporal overlap	Temporal overlap is the length of time over which the habitat is impacted by a stressor. Some stressors are present throughout the year (e.g., fixed industrial structures), while others are seasonal (e.g., some fishing practices or recreational activities) or sporadic (e.g., an oil spill). Similarly, some habitats exist all year-round (e.g., mangroves) while others are more ephemeral (some seagrass prairies).
•Intensity rating	Exposure of a habitat to a stressor depends not only on whether a habitat and a stressor occur simultaneously in space and time, but also on the intensity of that stressor. Two examples: (1) The intensity of nutrient loading associated with farmed salmon production cages depends on the number of fish per unit of production and on the waste-load discharged into the environment. (2) The destructive capacity of shellfish harvesting depends on the number of fishermen and on the type of practices used to harvest the shellfish. This criterion 'intensity of pressure' can be used to evaluate how fluctuations in the intensity of a stressor can change the risk to habitats. E.g., one might change the 'intensity score' to indicate that, in a future scenario, there will be changes in the density of the salmon stock in a production unit; or to represent relative differences in the intensity of one same stressor at different locations in the study area. For example, different types of shipping may be scored differently (a cruise ship may be a more intense stressor than a water cab, since one releases much more pollutants than the other).
•Management effectiveness	An effective management reduces and helps mitigate the impact of human stressors on habitats. For example, regulations that impose a minimum height for structures over water reduce the impact that excess shade might have on aquatic vegetation. The scoring of this criterion (by pressure) is done by comparison with other stressors in the region. That is, if one stressor is so well managed that it puts much less pressure on a habitat than another stressor (less well controlled) the management effectiveness is scored as "very effective". This criterion 'management effectiveness' can also be used to evaluate alternative management scenarios. Whenever the impact of human activities on habitats is high, 'management effectiveness' is scored as 'not effective', whenever the impact of human activities on habitats is low, 'management effectiveness' is scored as 'very effective'.
B. The 'Consequence' criterium refers to the vulnerability of habitats to a stressor (the 'Sensitivity') and the way these habitats are changed by the stressor, resist the negative events, and recover after the impact (the 'Resilience' of the habitat). Thus, the consequence criterium is organized into two classes of attributes: the consequence-sensitivity and the consequence-resilience attributes.	
B.1. The 'Consequence-sensitivity' of habitats is determined by various attributes, defined case-by-case. In this study the default 'Consequence-sensitivity attributes' put forward by InVEST-HRA are adopted, namely, the extent of loss suffered by a habitat due to being exposed to a specific stressor ('Change in area'), the changes in habitat structure induced by that impact ('Change in structure'), and the way the habitat has been put under stress previously by similar natural events (the 'Frequency of natural disturbance'),.	
•Change in area	'Change in area' is the percentual change that occurs in the extent of a habitat when it is exposed to a particular stressor, as a result of the 'sensitivity' of that habitat to the stressor. Habitats that lose a large percentage of their extent when they are exposed to a stressor are considered 'highly sensitive', while habitats that only lose a small extent are considered 'less sensitive'.
•Change in structure	For biotic habitats, 'change in structure' is the percentage change that occurs in the structural density of each habitat when it is exposed to a given stressor. An example of change in structure would be a change in the density of trees in a forest (or in its vertical or horizontal complexity) or a change in the density of polyps in corals. Habitats that lose a large percentage of their structure after being exposed to a given stressor are said to be "highly sensitive", while habitats that only lose a small proportion of their structure are said to be less sensitive. For abiotic habitats, 'change in structure' corresponds to the amount of structural destruction suffered by the habitat. Abiotic sensitive habitats may suffer total or partial destruction, while those that suffer only minor, or no destruction are considered more resilient. For example, trawling will produce total or partial destruction on muddy or gravel bottoms, while hard rock bottoms will suffer no or only slight destruction.
•Frequency of natural disturbance	A habitat can become more resilient to a stressor if it experiences frequent natural impacts of effect equivalent to the one produced by the human-induced stressor. For example, habitats in areas subject to receiving periodic supplements of nutrient produced by upwelling are adapted to greater variability in nutrient inputs and may resist better to increases in nutrient loading generated by aquaculture. Similarly, forests habituated to high winds may better resist selective deforestation. Or a coastal habitat accustomed to frequent storms may better resist the impact of destructive fishing practices. High frequency of natural disturbances of equivalent effect induces greater resilience in habitats and is therefore scored lower (as high scores mean greater habitat exposure/sensitivity and result in greater risk).
B.2. The 'consequence-resilience attributes' refers to the recovery potential of the habitat, determined by its regeneration patterns, which profile is built on life history characteristics of habitats, defined case-by-case. In this study the default 'Consequence-resilience attributes' put forward by InVEST-HRA are adopted, namely 'Natural mortality', 'Recruitment rates', 'Recovery time' and 'Connectivity'.	
•Natural mortality rate (biotic habitats only)	Habitats having high natural mortality rates are usually more productive and able to recover faster; as such, they are scored as being less impacted by stressors (i.e., high mortality rates are assigned a low score). Like with any other attribute, greater consequence of the impact from a stressor receives a high score number.
•Recruitment rate (biotic habitats only)	Frequent recruitment increases resilience because the more new-recruits the habitat can attract, the more likely and faster the species population of an area affected by a negative impact can be restored. In other words, high recruitment confers greater resilience to the habitat and, as such, is scored lower. Like with any other attribute, greater consequence of the impact from a stressor receives a high score number.
•Recovery time (age at maturity)	Biotic habitats that achieve maturity earlier are more likely to recover quickly from a disturbance than habitats that take longer to mature. This maturity refers to the maturity of a habitat as a whole (e.g., a mature alga or a mature forest), not to the reproductive maturity of an individual of a certain species. In the case of abiotic habitats (e.g., mudflats), shorter recovery times decrease the consequences of exposure to human activities. In contrast, bedrock habitats will recover only at geological time scales, significantly increasing the negative consequences of exposure/impact.
•Connectivity rate (biotic habitats only)	Greater proximity between habitat patches increases the recovery potential of a habitat by enhancing the capacity (and the probability) of new recruits re-establishing populations of affected species in an area that has been disturbed. Connectivity refers to the relative distance a recruit can travel. For example, patches of habitat that are 10 km apart from each other are considered poorly connected if we are talking about species whose larvae or seeds are able to travel a few hundred meters only, but well connected if we are talking about species whose larvae or seeds can travel hundreds of kilometers. Like with any other attribute, greater consequence of the impact from a stressor receives a high score number.

Sources: https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/habitat_risk_assessment.html, as retrieved in 01 February 2023; Ma et al. (2016); Stanford University - Natural Capital Project (2014).

Table 2
Scoring criteria applied to rate exposure and consequence attributes.

Habitat-stressors overlap attributes / Scoring			
Exposure attributes (1)	**1**	**2**	**3**
•temporal overlap rating (2)	0–4 months of the year	4–8 months of the year	8–12 months of the year
•management effectiveness	Very effective	Somewhat effective	Not effective, poorly managed
•intensity rating	Low intensity	Medium intensity	High intensity
Consequence-sensitivity attributes (1)	**1**	**2**	**3**
•frequency of disturbance	Frequent (daily to weekly)	Intermediate (several times/Yr)	Rare (annually or less)
•change in area	Low loss in area (0–20%)	Medium loss in area (20–50%)	High loss in area (50–100%)
•change in structure (3)	Low loss (0–20%)	Medium loss (20–50%)	High loss (50–100%)
Habitats' resilience attributes / Scoring			
Consequence-resilience attributes (1)	**1**	**2**	**3**
•recruitment rate	Annual or more	Every 1–2 years	Every 2+ year
•natural mortality rate	High mortality (80% or higher)	Moderate mortality (20–50%)	Low mortality (0–20%)
•connectivity rate	Highly connected (dispersion >100 km)	Medium connectivity (10-100 km)	Low connectivity (<10 km)
•recovery time	<1 Year	1–10 Years	> 10 Years

Comments: (1) A "zero" score would mean that the criterion is excluded from the analysis. (2) Temporal overlap refers to habitat/stressor co-occurrence in time/space. (3) Low loss in structure means 0–20% loss in density (biotic habitats) or little to no structural damage (abiotic habitats); Medium loss in structure means 20–50% loss in density (biotic habitats) or a partial structural damage (abiotic habitats); High loss in structure means 50–100% loss in density (biotic habitats) or a total structural damage (abiotic habitats).

questionnaire inquiry is presented in **Appendix A.2**. The chosen profile for the interviewees involved researchers from the University of Aveiro that hold a Ph.D. degree and that have published research related to RdA MCEF-SES (namely water pollution, metal and chemical contamination of ecosystems, impacts resulting from interactions between habitats/species and humans). Out of the 81 approached researchers (52 biologists/ecologists, 14 environmental scientists, 11 chemists, and 4 physicists/geoscientists), 21 researchers were interviewed (in person) to answer the questionnaire (13 biologists/ecologists, 5 environmental scientists, 1 chemists, and 2 physicists/geoscientists). Each interview lasted about one hour, and consisted of a brief introduction to the study, the objective and the approach, followed by detailed questions on and rating of exposure and consequence criteria and attributes. Interviewees selected those habitats and stressors that best aligned with their area of expertise. After data treatment, the survey results were debated in a final group discussion involving researchers having participated in the pre-test stage.

3. Results

After processing the results of the experts' survey, InVEST-HRA habitats' risk outputs are presented hereafter. First, the exposure degree of RdA habitats to HRWP stressors, then the sensitivity of RdA habitats to HRWP events and, finally, the resulting "single" risk (non-cumulative), by habitat and stressor. The final point of this session offers an overall view of cumulative impact of HRWP pressure on the whole of RdA habitats.

3.1. RdA marine, coastal, estuarine and freshwater habitats' risk - survey results

Results from the survey show that most RdA habitats are identified by researchers as moderately resilient to pollution impacts (**Table A.3.1, in Appendix A.3**). Their most significant feature of resilience is the recruitment rate, where all habitats except for the Ocean were rated 1 (meaning a high capacity of recruiting new species' individuals and an optimal recovery potential after a negative impact). RdA habitats exhibiting the weakest resilience attribute are Salines and Inland marshes, with a "recovery time" rated 3 (indicating a slow recovery capacity from a negative impact suggesting they are more sensitive to HRWP stressors' impact).

With respect to Habitat-Stressor overlap attributes, respondents did not provide information for distinguishing exposure-consequence stressors **by habitat**. The only discrimination the survey allows is between Waterbodies (5, CLC level I) and Wetlands (4, CLC level I). Thus, the same exposure-consequence rating by attribute (an average rating) is applied throughout all Waterbodies and Wetlands habitats.

Overall, the exposure to HRWP stressors is perceived as having a medium/intermediate impact on RdA habitats (**Table A.3.2, in Appendix A.3**). The exceptions are the *temporal overlap* of stressors with habitats (rated with "3", meaning that they co-occur all year round, except for Marinas) and the pollution caused by Road and Rail traffic, which is perceived as less intense and rated with "1".

Except for the attribute *frequency of disturbance* (which is considered high), the other two consequence-sensitivity stressors were rated with "1" or "2" (**Table A.3.3, in Appendix A.3**).

Buffer extents by stressor, range from 3675 m for Aquaculture industrial units to 21,144 m for Shipping lanes (Table 3).

Finally, referring to *data quality* scoring, all ratings coming from the experts' questionnaire were scored as "best data" on data quality. In addition, by applying the possibilities offered by the *weight* criteria, some stressors' criteria were upgraded (e.g. the frequency of disturbance produced by pollution resulting from SEVESO industries, WWTPs-SRTPs-LSSEs, FFPSSUs and Aveiro seaport) and others were downgraded (**Table A.3.4, in Appendix A.3**).

Regarding *intensity* rating criteria, due to their prevalence in the region, SEVESO industries and Aquaculture are subjected to a spatially explicit analysis and, instead of giving them the score produced by the experts' survey, a path to each corresponding shapefile was given. No criterium was excluded from the analysis, meaning that no criterium was given a zero score.

Table 3
Pollution buffers (reach) specified by experts to each stressor within Ria de Aveiro habitats.

Stressors	HRWP Buffers (in meters)	
	Mean Median	Std. Dev.
SEVESO industries	4900	7706
WWTPs-SRTPs-LSSEs	4448	6285
Non-SEVESO industries	7172	4129
FFPSSUs	7667	4046
Seaport	6538	3187
Inshore fishing port	6663	3169
Marinas & recreational ports	6471	3515
Aquaculture units	3675	2822
Shipping lanes	21,144	36,287
Road traffic lanes	8111	8768
Railways	6311	4203

3.2. Habitats' risk level of RdA MCEF-SES – InVEST-HRA output results

In this section the results obtained from running the InVEST-HRA tool are presented. First, the obtained exposure degree of RdA habitats to HRWP pressures, then the sensitivity (consequence) for each RdA habitat due to exposure to each HRWP pressure, followed by the resulting habitat-by-habitat specific risk. Finally, RdA areas facing most risk are presented, per habitat, and the presentation of results is concluded with the presentation of global (cumulative) risk, both by habitat and for the RdA as a whole.

3.2.1. Exposure of RdA marine, coastal, estuarine and freshwater habitats to high-risk water pollution (HRWP) stressors

Risk management practices in the region of Aveiro have improved over the years and, in general, the quality of surface water and sediments comply with official parameters set-out by law (AMBIECO/PLRA, 2011). Still, apart from the ocean (that is impacted by maritime traffic only), RdA MCEF-SES habitats remain widely exposed to HRWP stressors (Fig. 5).

Focusing on the maximum exposure rates and the most harmful stressors, it can be observed that the strongest HRWP single (non-

Fig. 5. Exposure of Ria de Aveiro habitats to high-risk water pollution stressors.

cumulative) pressures are exerted by SEVESO industries (affecting primarily the Watercourses; 2.667), WWTPs-SRTPs-LSSEs (on the Ocean and the Watercourses; 2.333), the Seaport (on the Coastal lagoon and Watercourses; 2.333), the Inshore fishing port (on the Coastal lagoon; 2.333), FFPSSUs (on Salines and Saltmarshes; 2.333) and Non-SEVESO Industries (on the Salines, Saltmarshes, Waterbodies and Watercourses; 2.333). Beyond the pressure exerted on Watercourses, SEVESO industries remain a fairly transversal stressor at all RdA habitats, even if more moderately. Critical to the Ocean (exhibiting an exposure rating of 2.000), the Shipping lanes also impact the Coastal lagoon (1.981), Intertidal flats (1.835), Salines (1.829) and Saltmashes (1.755).

If we consider all the investigated stressors combined, the most exposed habitats to HRWP are Salines (global exposure to the whole of stressors ranging from a minimum 0.949 to a maximum 1.669), Saltmarshes (0.377–1.675), Coastal lagoon (0.286–1.652), Intertidal flats (0.386–1.612) and Watercourses (0.548–1.476). Habitats exposed relatively less to HRWP are Waterbodies (0.5–1.077) and Inland marshes (0.472–0.816). The Ocean appears to be the habitat least exposed to HRWP pressures (0.0–1.399).

3.2.2. *Sensitivity (Consequence) of RdA marine, coastal, estuarine and freshwater habitats to high-risk water pollution (HRWP) stressors*

The degree of loss endured by each RdA MCEF-SES habitat (sensitivity of each habitat) varies with the type of stressor and among habitats, depending on their characteristics (Fig. 6). Looking at the pressure exerted by each individual HRWP stressor and keeping our focus on the maximum sensitivity rates, RdA habitats are highly sensitive to all the investigated HRWRP stressors, except for Railways (whose highest

Fig. 6. Sensitivity of Ria de Aveiro habitats to high-risk water pollution stressors.

maximum consequence remains below 2; with 1.875 for both Inland marshes and the Salines) and Motorways (rating highest 2.000 for Salines). With maximum consequence rates above 2, all HRWP proved to be strong stressors for some of RdA habitats, which revealed the following highest sensitivity peaks: FFPSSUs (ranging from 2.625 for Salines to 2.042 for Watercourses), Aquaculture (from 2.429 for Salines to 2.000 for Saltmarshes), Marinas (from 2.400 for Salines to 2.200 for Intertidal flats), Non-SEVESO industries (from 2.385 for Salines to 2.041 for Ocean), SEVESO industries (from 2.367 for Salines to 2.100 for Watercourses), WWTPs-SRTPs-LSSEs (from 2.316 for Intertidal flats to 2.077 for Salines), Inshore fishing port (from 2.313 for Salines to 2.194 for Intertidal flats), Shipping lanes (from 2.226 for Salines to 2.087 for Coastal lagoon), Roadways (2.222 for Inland marshes and Salines) and Seaport (from 2.102 for Salines to 2.100 for Coastal lagoon and Watercourses).

Considering all HRWP stressors combined, the most vulnerable RdA habitats remain the Salines (global sensitivity[3] ranging from 0.985 to 1.734), Saltmarshes (0.492–1.715), Coastal lagoon (0.427–1.713), and Intertidal flats (0.467–1.648). Less vulnerable RdA habitats are the Ocean (0.148–1.432), Inland marshes (0.550–0.872), Waterbodies (0.546–1.109) and Watercourses (0.581–1.416).

3.2.3. *Habitat-by-habitat specific risk*

In a detailed analysis – stressor-by-stressor (single) and habitat-by-habitat –, the risk resulting from the abovementioned exposure-consequence conditions for each of the RdA habitats, shows the highest risk values for Salines (global risk rate ranging from 0.568 to 1.256) (Fig. 7).

At some distance, follow RdA Intertidal flats (0.158–1.103), Saltmarshes (0.162–1.052) and the Coastal lagoon (0.173–1.041). Lowest risk rates are observed for the Ocean (0.000–0.904), Watercourses (0.348–0.892), Inland marshes (0.327–0.583) and Waterbodies (0.184–0.574). Overall, HRWP stressors exerting maximum risk over RdA habitats – risk scores close or exceeding 2 - are FFPSSUs (ranging from 2.230 for Salines to 1.975 for Saltmarshes), SEVESO industries (2.118 for Watercourses), Non-SEVESO industries (2.039 for Salines) and Aquaculture (2.013 for Salines). Also with relatively high maximum risk scores, even if remaining below 2.000, emerge the Marinas (1.991 for Salines) and WWTPs-SRTPs-LSSEs (1.948 for Intertidal flats; 1.946 for Ocean).

The spatial analysis shows that Salines, Intertidal flats, Saltmarshes and the Coastal lagoon are the habitats subjected to higher risks (maximum risk scores of 1.256, 1.103, 1.052 and 1.041, respectively), the Ocean and Watercourses suffer medium risks (maximum risk scores of 0.904313 and 0.892) and Waterbodies and Inland marshes stay at low risk levels (maximum risk scores of 0.583 and 0.574). Driven by a complex combination of HRWP stressors (a myriad of Aquaculture units, the Seaport, the Railway, the Motorway, the regional Roadways, the Marinas, Inshore fishing ports and some Fossil fuel sale units), RdA Salines risk hotspots are located at the mouth of Ílhavo Channel, around the Paraíso Lake and at the North of Mira Channel (Fig. 8**, (e))**, while RdA Intertidal flats risk hotspots are located in front of Costa Nova beach, associated with Aquaculture units and the Marinas located at this spot **(**Fig. 8**, (c))**, Saltmarshes risk hotspots are located around the salines, at the mouth of Ílhavo Channel, at the Paraíso Lake and at the North of Mira Channel **(**Fig. 8 **(f)),** and RdA Coastal lagoon risk hotspots are located at the North of Mira Channel, the Paraíso Lake and the North of Ílhavo Channel, driven mainly by Aveiro Seaport (associated with the handling of hazardous substances), the Railway and Motorways (and associated transport of hazardous substances to Aveiro Seaport), Aquaculture units, Marinas and the Inshore fishing port **(**Fig. 8**, (b))**.

In turn, RdA Ocean risk hotspots are medium to low and located at the mouth of the Aveiro Seaport (the biggest risk hotspot), with smaller risk hotspots at the Northern shore of Torreira Beach, off the coast of Ovar village (at Furadouro Beach), off the coast of Esmoriz village (at Barrinha de Esmoriz Beach) and off the coast of Vagueira Beach (Fig. 8**, (a)**). Note that the extremely pressuring international Shipping lanes passing off the coast of Aveiro are located at >100 km off the Portuguese mainland coast and, hence, its impacts on RdA MCEF-SES remain marginal. Also, RdA Watercourses risk hotspots are low and mostly located at the North of Ílhavo Channel (related to Aveiro Seaport) and at Rio Príncipe Channel, at the mouth of Vouga River (related to one big SEVESO industry located there in combination with the major national Railway passing through the area **(**Fig. 8**, (d))**.

Finally, RdA Waterbodies and RdA Inland marshes risk hotspots are low and located at Pateira do Carregal, to the West of Pateira de Fermentelos and towards the North of RdA, at Monte de Baixo Inland marsh (Fig. 8**, (g)** and **(h)**).

3.2.4. *RdA marine, coastal, estuarine and freshwater areas at risk*

None of the RdA habitat have areas facing a “high risk”, from an overall perspective (that is, considering all stressors). However, part of them have some portion of their areas facing a “medium risk” considering all stressors combined (namely RdA Salines, 49.6%; Intertidal flats, 4.2%; Coastal lagoon, 2.1%; Saltmarshes, 0.2%) (Fig. 9).

Still, on a one-by-one analysis, it can be observed that some HRWP stressors keep some RdA habitats under a “high risk” pressure. Indeed, some portion of the Salines area face high risk, threatened by Aquaculture (33.7% of the area), by FFPSSUs (1.8%), by Non-SEVESO industries (0.4%), and a small percentage of Watercourses’ area face high risk threatened by SEVESO industries (0.5%). All remaining RdA habitat’s areas stay at a medium to low risk. Salines persist being the one having the biggest part of their area facing a medium risk (100.0% threatened by Roadways, 76.6% threatened by FFPSSUs, 71.7% threatened by Non-SEVESO industries, 65.7% by Aquaculture and 62.3% by Motorways). Inland marshes also have a significant part of their area facing a medium risk (100.0% threatened by Roadways and 62.8% by FFPSSUs). Even though most part of the areas of the RdA Ocean, Watercourses, Waterbodies, Saltmarshes and Inland marshes remain, overall, at low risk, there are already significant parcels of their areas facing a medium risk induced by some anthropogenic activities which threaten their integrity. In fact, (1) Non-SEVESO industries, FFPSSUs and Aquaculture menace RdA Watercourses and each of these stressors put >50.0% of habitats’ area at a medium risk; (2) Shipping lanes loom over RdA Ocean and put already 54.0% of it at a medium risk; (3) Roadways put the whole of RdA Inland marshes and RdA Salines at a medium risk; (4) FFPSSUs, Non-SEVESO industries, Aquaculture, Motorways and Roadways also represent a significant threat to different RdA habitats; (5) a minimum of 31.0% Saltmarshes area have to deal with a medium risk induced from diverse stressors (aquaculture, FFPSSUs, Roadways or Industrial units); (6) at least 55.0% of the RdA Watercourses area are put at a medium risk by various stressors, namely FFPSSUs and Industrial units (both threatening 55.0% of the habitats’ area), Aquaculture (53.0%), WWTPs-SRTPs-LSSEs (24.0%), Seaport and SEVESO industries (17.0% each).

3.2.5. *Total risk to RdA marine, coastal, estuarine and freshwater habitats*

Upon successful completion of INVEST-HRA running, a comprehensive picture of the RdA MCEF-SES cumulative risk (all habitats and all stressors, taken simultaneously) is obtained, ranging from 0 to 1.217 (Fig. 10). Given that 0 means “No Risk” and 3 means “High Risk”, this result shows that, all over RdA lagoon region, the global risk (all HRWP pressures and all habitats) ranges from “No-Risk” areas to a highest – albeit moderate – risk of 1.217.

Habitats with highest risk are those in the areas between Aveiro (the regional capital), Ílhavo town and the Ocean, including the Northern portions of Mira Channel and of Ílhavo Channel. Some other smaller risk hotspots are located at Rio Príncipe, at the Northern shore of Torreira

[3] Global sensitivity is the average sensitivity to all the HRWP analyzed stressors, combined together.

Fig. 7. Risk to Ria de Aveiro marine, coastal, estuarine and freshwater habitats from high-risk water pollution stressors.

Beach, off the coast of Ovar village (at Furadouro Beach), at Monte de Baixo Inland marsh, at Barrinha de Esmoriz Beach and off the coast of Vagueira Beach.

3.3. Reflections about results

At RdA, a rather diverse mosaic of risk hotspots was obtained. The SEVESO industries in the area around Estarreja (chemical complex) and the area around Aveiro Seaport are reflected in the RdA quality of superficial waters and sediments (AMBIECO/PLRA, 2011), and are confirmed by our results. However, if one looks at the co-occurrence of HRWP hazards, even with sizable point sources of pollution (Cerqueira et al., 2008), Estarreja does not emerge as a pollution hotspot while Aveiro Seaport does appear as a major risk hotspot. This is due to the limited variety of HRWP hazards affecting the vicinity of Estarreja (limited to SEVESO industries and one Railway), while risk estimates from InVEST-HRA are particularly based on multiple stressors overlapping each other at the same time and space. In fact, a higher ecosystem risk is located at the center of our area of interest (**hotspot H1** at Fig. 10), around the regional capital (Aveiro) and the Seaport, where multiple stressors overlap.

This kernel of HRWP hazards at RdA covers the strip between Aveiro (the regional capital) and the Seaport, the Northern sections of Mira Channel and Ílhavo Channel, the Paraíso Lake and the Ocean strip between S. Jacinto Nature Reserve and the South of Costa Nova Beach. A second layer of HRWP risk (**hotspot H2,** at Fig. 10) is a wider ring having the same epicenter and covering the Rio Príncipe Channel, slightly North of Aveiro town, the Southern sections of Ílhavo Channel

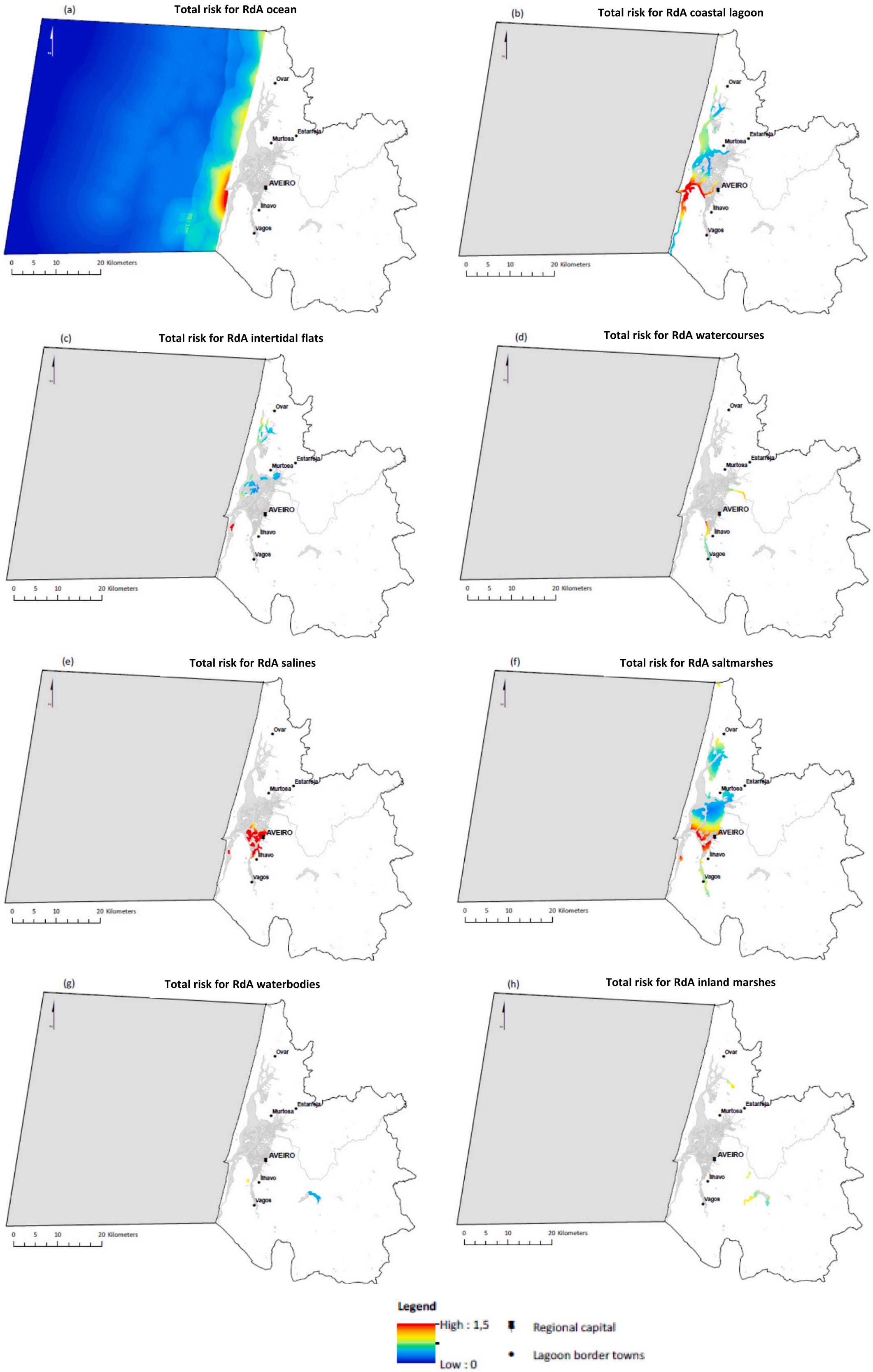

Fig. 8. Total risk for each of the Ria de Aveiro marine, coastal, estuarine and freshwater habitats.

Fig. 9. Area at risk for each of the Ria de Aveiro marine, coastal, estuarine and freshwater habitats, by stressor.

and Mira Channel, and the North belt of hotspot H1, between the Ocean and the regional capital, Aveiro, passing through S. Jacinto Nature Reserve.

Finally, a third layer of HRWP reveals a big stain having H1 and H2 as epicenter (**hotspot H3.1.**, at Fig. 10), covering the Wetlands of Pateira de Fermentelos, towards the Southeast, the Southern sections of Ílhavo Channel and Mira Channel, and the Ocean strip off the coast of Vagueira Beach, where an offshore Aquaculture compound is located; this third stain comprises five additional smaller stains of risk hotspots scattered towards the North of RdA (**hotspots H3.2., H3.3., H3.4., H3.5., H3.6.,** at Fig. 10), around Torreira Beach (**h.3.2.**) and Furadouro Beach (**h.3.3.**), covering the whole of Ovar Channels (**h.3.4.**) and two smaller patches of risk at Monte de Baixo Inland marsh (**h.3.5.**) and at the far North around Barrinha de Esmoriz (**h.3.6.**). When taking decisions about the development of new activities in the region, areas of high risk such as hotspot H1 should be viewed as clogged up with anthropogenic activities, while hotspot H2 should be considered as vulnerable ones, also overloaded with anthropogenic activities; H3 areas might yet be viewed as nature restoration areas.

3.3.1. RdA marine, coastal, estuarine and freshwater habitats at risk

Plotting the InVEST-HRA results onto exposure*consequence matrix

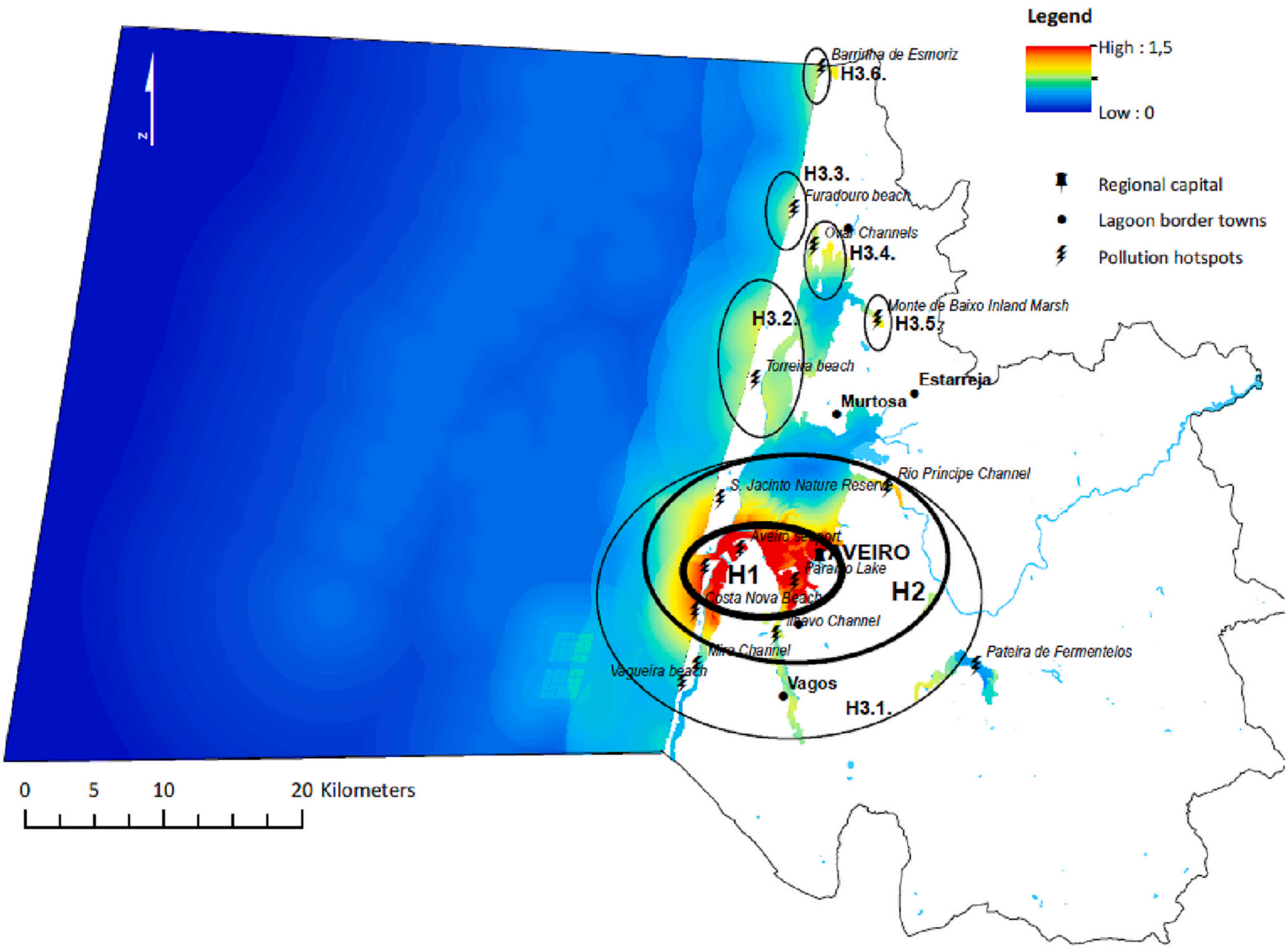

Fig. 10. Pollution hotspots at region of Aveiro marine, coastal, estuarine and freshwater habitats.

risk plots helps to identify habitats most at risk, provides guidance on which activities impact most the habitats of RdA, and assists policy makers in determining which management choices are better for the region to mitigate HRWP risk pressures more efficiently (Teck et al., 2010). Habitats exhibiting high exposure and high consequence (sensitivity) to a stressor are considered to be at risk. This is the case of RdA Salines that prove to be the most sensitive and most exposed habitat to HRWP stressors followed, at some distance, by Watercourses, the Coastal lagoon and Saltmarshes (Fig. 11). Ocean is at lowest risk, being the least sensitive and the least exposed of all RdA habitats.

3.3.2. *RdA most critical risk sources*

Within hotspot H1 the most severe HRWP risk pressures converge, namely Aquaculture, Roadways, FFPSSUs, Non-SEVESO industries, Motorways, Marinas, Seaport, Railways and Shipping lanes. This co-occurrence of HRWP stressors put at jeopardy RdA most vulnerable habitats located in this area, namely: RdA Salines, Coastal lagoon and Saltmarshes. The HRWP stressors pressing least in hotspot H1 are Inshore fishing port, SEVESO industries and WWTPs-SRTPs-LSSEs. The type of HRWP stressors that most compromise RdA MCEF-SES structures and functions vary widely, depending on the location of each specific habitat. Looking at the most fragile habitats, it can be observed that RdA Salines are mostly subject to HRWP pressures from Aquaculture, FFPSSUs, Non-SEVESO industries and Roadways (Fig. 12).

Moreover, it can be observed that all these HRWP stressors may hit quite high upper limits, both on exposure and on consequence (Fig. 12, **a.2.)**. Major sources of risk among RdA Watercourses are Non-SEVESO industries and FFPSSUs (Fig. 12, **b.1.** and **b.2.**), while all the stressors seem to contribute to HRWP risk pressure on RdA Coastal lagoon and RdA Saltmarshes (Fig. 12, **c.2.** and **d.2.**), even if exerting a lower pressure than in the case of Salines and Watercourses.

Major sources of risk among the least endangered habitats (Ocean, Waterbodies, Inland marshes and Intertidal flats) also depend on the location of each habitat (Fig. 13).

The most significant risk sources impacting those RdA are the Shipping lanes (coercing the Ocean and Intertidal flats), Roadways, FFPSSUs, Railways and Motorways (pressuring Waterbodies, Inland marshes and Intertidal flats). Non-SEVESO industrial units also take some prominence as a stressor to Intertidal flats.

4. Discussion

The good status of ecosystems, fragile natural areas and the preservation of their functions are critical to the quality of life in coastal areas and can be enhanced by ecosystem-based management (EBM) and risk control at sub regional scales aimed at minimizing ecosystem risk and optimizing regional welfare. Moreover, taken comprehensively and completely, the costs of preserving fragile coastal ecosystems are generally substantially smaller than the value they provide to society, while the costs of rehabilitating damaged ecosystems tend to be much higher than the costs of simply preserving them (Elliff and Kikuchi, 2017). Thus, it is crucial to identify all HRWP risk-sources and to adequately assess the risks they pose to ecosystems, so that adequate pollution abatement measures can be identified and implemented (Peng et al., 2013).

The implementation of effective and consequent EBM requires risk

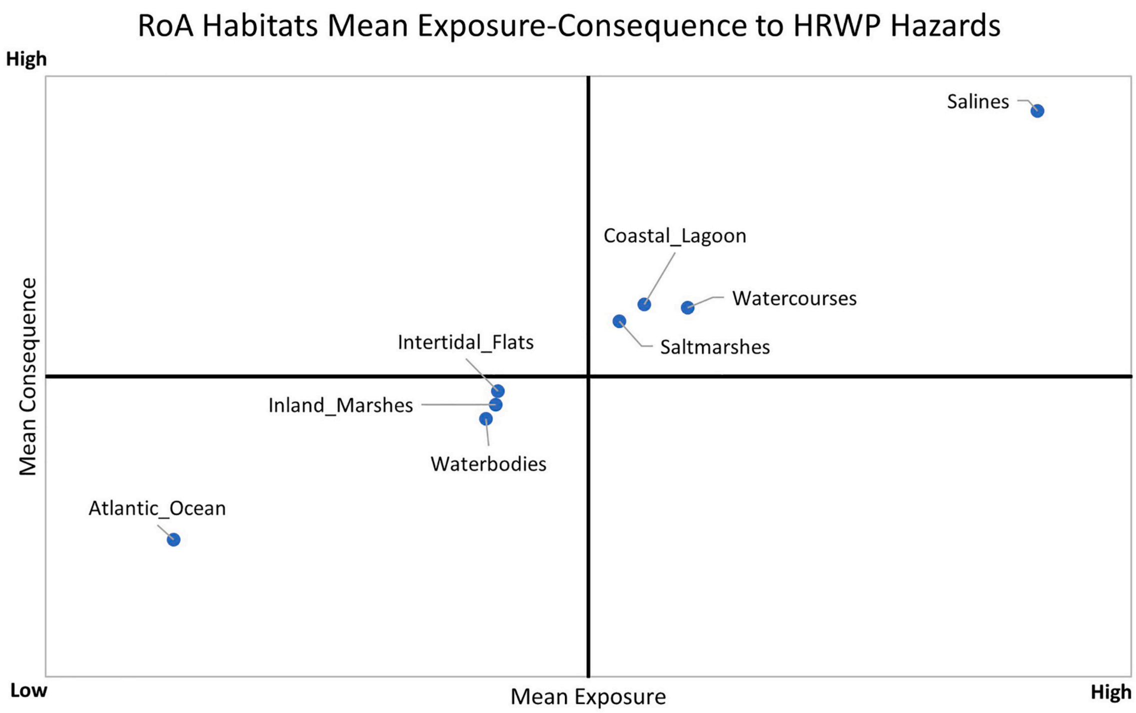

Fig. 11. Risk matrix of Ria de Aveiro habitats exposed to high-risk water pollution hazards.

assessment, based on sound and accurate data about the current condition of ecosystems, and the pressure human activities impose on them and the vulnerability of these habitats to those stressors (Teck et al., 2010). Quantitative and rigorous data is a crucial step in risk assessment, essential to formulate sound mitigation/adaptation policies – especially in contexts where resources are limited and policymakers are forced to set priorities (Duggan et al., 2015; Samhouri and Levin, 2012). Thus, in line with Samhouri and Levin (2012), Duggan et al. (2015) and Teck et al. (2010), we chose to score exposure and sensitivity-resilience attributes of habitats, required to run the InVEST-HRA model, by using expert judgement. Expert knowledge makes the model results more robust and, thus, provides a better basis for natural resources managers and policymakers to respond to potential environmental problems. As Teck et al. (2010) put it, researchers having investigated the habitats (or the species) under analysis are best placed to score both the exposure and the consequence criteria as to help identify which areas, habitats or species are under most stress. Furthermore, in our study, we go beyond Duggan et al. (2015) recommendation of getting involved Biologists – bringing-in researchers from a wider array of scientific areas, namely Biologists, Ecologists, Physicists and Chemists and, thus, providing enhanced security to the scorings and adding extra confidence to obtained results.

Building on this expert knowledge, we observe that results from this study align with those from previous studies on water pollution in the RdA coastal lagoon (Marta Lobão Lopes et al., 2014) and the water column (de Freire, 2007; M. L. Lopes et al., 2017). Despite the higher water velocity (shorter residence times) at the mouth of RdA lagoon (J. F. Lopes and Dias, 2007), which could indicate a lower concentration of pollution in the area, the highest HRWP hotspots (H1 and H2) are identified at this location, between the regional capital and the open ocean, due to the high concentration of HRWP pressures at this location. This is the location where we also find the most fragile habitats (Salines, Intertidal flats, Coastal lagoon and Saltmarshes), as a result of the very high concentration of risk factor. Here, management options have to be envisioned and prioritized to alleviate stressors' effects.

In line with Halpern et al. (2015) and Duggan et al. (2015), this study confirms that InVEST-HRA can be a powerful tool to assess habitat risks and to support national and regional stakeholders defining and prioritizing areas for development and conservation. Specially if combined with Geographic Information System tools, the InVEST-HRA model can be a strong support in the building and configuration of spatial management plans (Duggan et al., 2015; Halpern et al., 2015; Samhouri and Levin, 2012), namely by enabling decision-makers to (1) detect hotspot areas of risk within the area of interest, (2) identify which and where the natural habitats face higher risk, (3) establish which are the most critical risk sources for each habitat and location, and (4) understand how this risk might change in the future and influence the provision of ES (Stanford University (Natural Capital Project), 2014).

As Duggan et al. (2015) put it, the InVEST-HRA spatially explicit outputs improve understanding on how different human activities interact with each other and with ecosystems and allow for an easy identification of hotspots and the comparison of their relative seriousness. Moreover, this study also confirms the notion by Samhouri and Levin (2012) that the use of very fine-grained spatialized data in InVEST enhances risk assessment at the sub-regional scale. In fact, by using InVEST-HRA coupled with ArcGIS it was rather immediate to identify the key HRWP hotspots, their relative seriousness and, thus, decide which habitats and/or stressors are worst and need to be addressed first. This way, managers and decision-makers get a perspective on how regional policies and actions can act to improve local conditions while contributing to moderate risk at macro scales (Samhouri and Levin, 2012). The InVEST-HRA spatially explicit assessment of HRWP risk enhances flexible strategies and allows for the design of location-specific policies aimed at reducing the risk identified in certain habitats and/or spatial areas.

This study also confirms Teck et al. (2010) conclusion that InVEST-HRA is a fairly transparent approach, easy to replicate and appropriate to apply to fragile lagoon systems – delivering sound quantitative data to inform decision making. In accordance with Samhouri and Levin (2012), we consider that to evolve towards corrective action (or to adapt this approach to other regions or level of analysis) other questions have to be asked and answered, such as: To reduce the risk in a relevant way

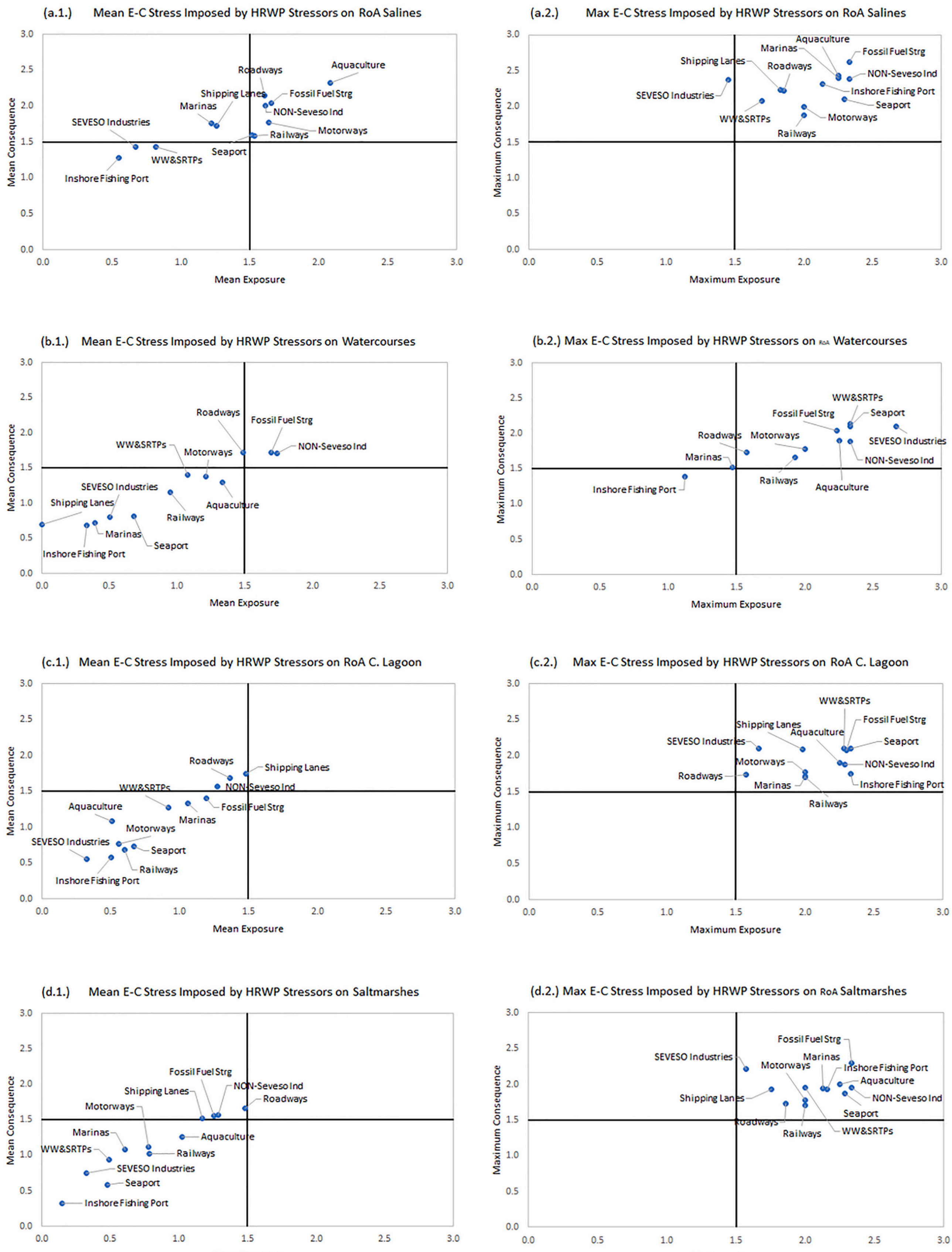

Fig. 12. HRWP stress imposed on the most threatened RdA habitats – mean and maximum scores.

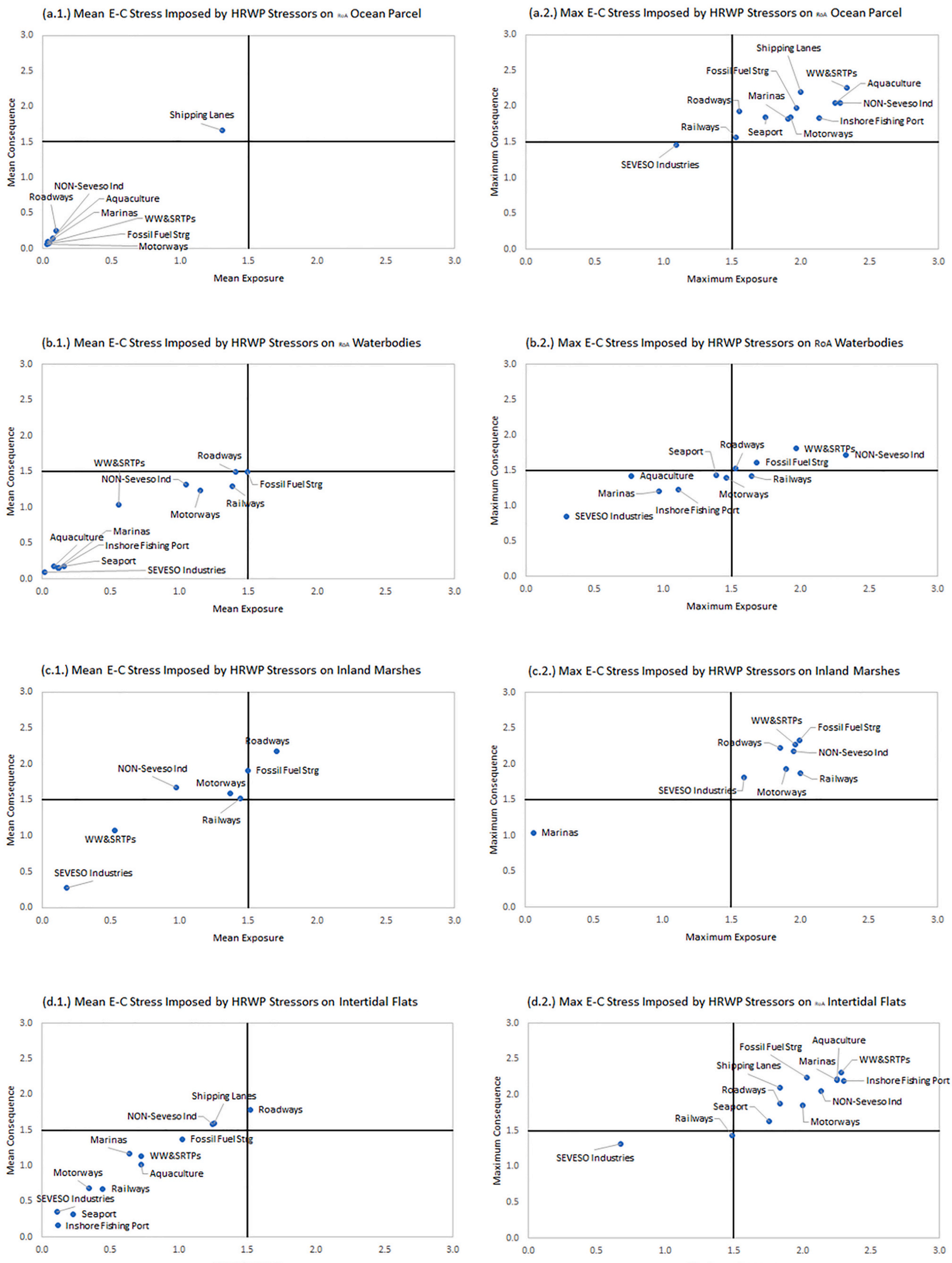

Fig. 13. HRWP stress imposed on the least threatened RdA habitats – mean and maximum scores.

what changes would we need to implement? In which habitats would we need to focus our action? On which HRWP stressors to focus first? Which criteria should be used? Questions that could be tackled by comparing alternative risk reduction strategies (e.g., reducing the spatial overlap between pressures and habitats or reducing the duration and/or frequency with which pressures impact habitats) (Samhouri and Levin, 2012). In this endeavor the relative costs constitute another critical variable to take into account, along with perceived public values and benefits obtained from natural systems and/or from alternative use of land.

Even if the launching of effective policies requires further analysis, – logistics, financial, political - our results provide sound evidence for moving towards ecosystem-based management (EBM) in this Natura 2000 site. Contingently, in future research new criteria may be added to the InVEST default ones that we considered here.

5. Conclusions

This study is aimed at supporting the development of ecosystem-based management (EBM) in fragile marine, coastal, estuarine and freshwater socioecological systems (MCEF-SES) surrounded by heavily industrialized and urbanized areas – namely by determining which are the most important anthropogenic activities threatening those habitats. To this end, a spatially explicit assessment of high-risk water pollution (HRWP) stressors putting pressure on MCEF-SES water quality is performed, by combining the InVEST-HRA model with a targeted expert panel survey, applied to the Ria de Aveiro (RdA) lagoon case study in Portugal. Hence, this study contributes to the existing copious continuous-persistent/diffuse-source pollution research by adding knowledge about sudden-accidental/point-source in fragile (water and wetland) ecosystems – namely its interrelation with complex socio-economic development drivers.

Results show that HRWP does play a critical role in the shaping of fragile ecosystems' health status and has to be taken into account in regional development plans, alongside diffuse-source pollution. As pointed out in multiple studies (AMBIECO/PLRA, 2011, pp. 104), RdA MCEF-SES still show a 'fair to good' conservation status despite being located in a widely industrialized and urbanized region. Yet, two risk hotspot areas are identified in the RdA MCEF-SES – namely where several anthropogenic pressures over sensitive habitats (Salines, Watercourses, Coastal lagoon and Saltmarshes) coincide. Even though risk sources to RdA habitat structures and functions vary widely, depending on the location of each specific habitat, globally some major HRWP stressors stand out, namely: Fossil fuel processing, storage and sale units (FFPSSUs), Aquaculture, Marinas, Industrial activities (both SEVESO and Non-SEVESO industries), and Wastewater treatment plants, Solid residues treatment plants, Landfills and sewage submarine emissaries (WWTPs-SRTPs-LSSEs).

Some overarching outcomes point to the advantages of exploiting synergies among activities and/or pollution abatement measures, meaning that, by activating one, a full chain of beneficial effects might be triggered. As a first example, negative externalities produced by aquaculture can be mitigated through the implementation of integrated multi-trophic aquaculture (IMTA) management practices, while allowing for the development of a whole set of new sustainable industries embodying the cluster of the new "blue economy". Second, the full activation of a circular economy will reduce the environmental impact of human activities, while forcing the consolidation of the whole cluster of waste reuse and waste treatment. Finally, replacing fossil fuels with clean and sustainable energies will have a positive impact over the whole MCEF systems, by reducing the pressure produced by both sudden-accidental pollution (e.g. tanker oil spills) and continuous-persistent pollution (e.g. continuous leakages from pipelines and underground storage tanks).

Some caveats remain. First, the lack of a systematic profile of the quality of habitats for all RdA lagoon ecosystems (Waterbodies, Wetlands, Agricultural areas and Forest and semi-natural areas). Second, the absence of a centralized register of the location and type of all polluting entities. Third, the composition of the used sample of experts which can still be improved despite being much more diversified than in others previous studies; the building of a panel of experts, regularly updated and focused on attributing weights to pressures and pollution events, could help building a database aimed at supporting the enhancement of environmental resilience and EBM consolidation in the region. Fourth, the use of a wider scale, such as 0–100, could provide more granularity to obtained outputs. Fifth, translating these pressures into monetary values, might enhance the probability of being better perceived and more used by stakeholders for policy making. Finally, shortcomings of this study refer to the small size of the expert panel sample, along with the fact of being based upon a single site of analysis – albeit the used method is easily applied to different settings for diagnosing risks faced in other regions. This caveat might have contributed to the large standard deviations of applied stressors' buffers, which might justify a sensitivity analysis to be performed for these buffers, in future works.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoinf.2023.102144.

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