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Risk to the supply of ecosystem services across aquatic ecosystems

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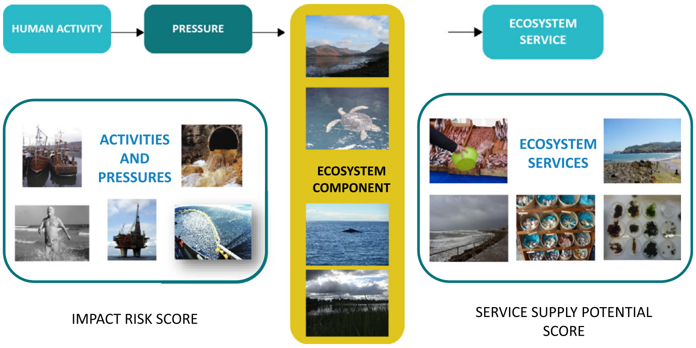
HIGHLIGHTS

- Human activities can cause impacts on aquatic ecosystems through multiple pressures.
- These impacts may affect the supply of ecosystem services from aquatic ecosystems.
- Risk assessment can help to explore these impacts.
- Rivers and Lakes had the highest risk to service supply.
- Protecting ecosystem service supply alone will not fully protect aquatic ecosystems.

GRAPHICAL ABSTRACT

Human activities, e.g. fishing, introduce pressures into the ecosystem e.g. extraction of species. These pressures may cause impacts on ecosystem components, e.g. fish, which can go on to cause changes to the supply of ecosystem services, e.g. seafood. We show how a comprehensive set of activities and their multiple pressures affect aquatic ecosystem components and their services in different aquatic realms and locations.



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ABSTRACT

The capacity of ecosystems to supply ecosystem services is decreasing. Sustaining this supply requires an understanding of the links between the impacts of pressures introduced by human activities and how this can lead to changes in the supply of services. Here, we apply a novel approach, assessing 'risk to ecosystem service supply' (RESS), across a range of aquatic ecosystems in seven case studies. We link aggregate impact risk from human activities on ecosystem components, with a relative score of their potential to supply services. The greatest RESS is found where an ecosystem component with a high potential to supply services is subject to high impact risk. In this context, we explore variability in RESS across 99 types of aquatic ecosystem component from 11 realms, ranging from oceanic to wetlands. We explore some causes of variability in the RESS observed, including assessment area, Gross Domestic Product (GDP) and population density. We found that Lakes, Rivers, Inlets and Coastal realms had some of the highest RESS, though this was highly dependent on location. We found a positive

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Marine
Coastal
Freshwater
Ecosystem-based management

relationship between impact risk and service supply potential, indicating the ecosystem components we rely on most for services, are also those most at risk. However, variability in this relationship indicates that protecting the supply of ecosystem services alone will not protect all parts of the ecosystem at high risk. Broad socio-economic factors explained some of the variability found in RESS. For example, RESS was positively associated with GDP and artificial and agricultural land use in most realms, highlighting the need to achieve balance between increasing GDP and sustaining ecosystem health and human wellbeing more broadly. This approach can be used for sustainable management of ecosystem service use, to highlight the ecosystem components most critical to supplying services, and those most at risk.

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1. Introduction

Ecosystem services support human wellbeing in many ways, providing essential sources of nutrition and materials, regulating and maintaining global systems and enhancing our quality of life (Costanza et al., 2007; MA, 2005; Maes et al., 2016). There is increasing recognition that the ecosystem's capacity to supply services, including those supported by marine and freshwater ecosystems, is decreasing (Costanza et al., 2014; MA, 2005). The importance of understanding and managing this risk to ecosystem service supply is on the agenda for sustainable management at the highest level: for example, the United Nations Sustainable Development Goals (SDG) target 15.1 of SDG 15 mandates the "*restoration, conservation and sustainable use of terrestrial and inland freshwater ecosystems and their services*" while, Goal 14 explicitly recognises the role of the oceans in maintaining a world fit for human habitation (UN, 2015). However, despite global aspirations, managers and decision makers have struggled to operationalise the ecosystem services concept in management decisions. This is partly because, for ecosystem services other than those where supply and demand are readily understood (e.g. seafood), it has been difficult to understand what to regulate and how (e.g. to maintain the sustainable supply of the 'climate regulation' service).

In order to understand what elements of a social ecological system to manage to sustain ecosystem service supply, it is necessary to understand what parts of the ecosystem supply services, and how human activities affect this supply. Changes in ecosystem state or condition are tightly linked to changes in service supply, since it is the ecosystem structures, processes and functions that underpin their supply (Müller and Burkhard, 2007; Quintessence, 2016). Thus, if we know something about the state of ecosystems and how those ecosystems supply services, we can use this to indicate how service supply is likely to change. This has been the basis of much work so far, that aims to assess changes in ecosystem services based on ecosystem condition, and two broad approaches have been taken. The first links a measure of change in ecosystem condition to a change in services. For example, Costanza et al. (2014) linked changing areas of broad habitat types to changes in benefits from services, while Mace et al. (2015) assessed risk to natural capital by assessing ecosystem state of habitats, as measured against environmental policy targets. These studies have tended to be comprehensive in their consideration of habitats and services, but have not explicitly linked change in service supply to manageable human activities causing those changes (although see Tzilivakis et al. (2015) on assessing vulnerability of ecosystem services to climate change). Freshwater and marine ecosystems are subjected to multiple human activities and pressures (Dudgeon et al., 2006; Halpern et al., 2008). These pressures cause changes to ecological state and alter the capacity of the system to supply services. Thus, to implement management for sustainable service use, we need to explicitly recognise how the distribution of ecosystem impact from drivers of change relates to the capacity or potential of the ecosystem to supply benefits to people, i.e. ecosystem services (e.g. see Elliott et al., 2017).

The second approach to ecosystem service assessment, and the one we follow here, takes a standard impact risk assessment to link manageable human activities introducing threats to ecosystems (see examples in Arkema et al., 2014; Borgwardt et al., 2019, this issue; Cormier et al., 2019; Halpern et al., 2008; Knights et al., 2015; Samhouri and Levin, 2012; Sharp et al., 2014). We use an exposure-effect approach to risk assessment (see review in Knights et al., 2015), where impact risk is linked to vulnerability in the supply of services, given the potential of specific habitats to supply them. In this way, the risk analysis is extended beyond linking pressure and ecosystem impact to explore the consequences of ecosystem state change on the capacity to supply services. To date, similar studies in aquatic systems that have linked risk right through activities to service supply, have built on habitat mapping approaches used in terrestrial ecosystems but tend to focus on a small number of activities and pressures e.g. from fishing, and/or on a limited variety of habitats e.g. coastal habitats, and/or services e.g. seafood (Arkema et al., 2015; Cabral et al., 2015; Guerry et al., 2012; Hooper et al., 2017). To better understand the systems we are trying to manage, we also need to understand more about the broad relationships between human activities introducing impact risk and service supply, and what drives them. In this study, we link 'impact risk' (IR), i.e. the threat introduced by human activities to aquatic ecosystems, with the full suite of aquatic ecosystem services supplied by those systems (which we term 'service supply potential' or SSP) to establish a 'risk to ecosystem service supply' (RESS), for a comprehensive collection of human activities and a full range of freshwater, coastal and marine ecosystems.

Considering this approach, there are a number of possible relationships between impact risk and service supply that might be expected. Although there is a continuum of ecosystem services from consumptive (e.g. nutrition from food) through to non-consumptive (e.g. aesthetic enjoyment of a view) and non-use (existence values) (O'Higgins et al., 2019), many services are tightly linked to human activities. For example, nutrition from seafood is a service we get from a human activity - fishing. As we actively exploit services, we introduce pressures to the ecosystem. Pressures associated with one specific activity may affect ecosystem components that are not the target of that activity. For example, fishing causes the pressure of 'extraction (and mortality)' of fish, but it can also introduce additional pressures like 'abrasion' of the sea or lake bed and 'underwater noise', which may act on components of the ecosystem that are not the target of the fishery. Thus, we may expect the impact risk to be greater in those habitats that also have the greatest potential to supply a wider range of services, as multiple activities (exploiting multiple services) introduce multiple pressures.

Conversely, if impact risk (IR) decreases as the service supply potential (SSP) increases, this could indicate that habitats and taxa can support further activity without compromising the capacity of the system to supply ecosystem services. As such, where systems are actively exploited but also being managed sustainably we might expect a high SSP and low IR. However, many ecosystems supply benefits which are experienced passively by humans e.g. regulation and maintenance services. High SSP with low IR could also be indicative of systems and habitats with high values for regulation and maintenance services, which do not require active exploitation, and are consequently at low risk from human activity (in the case where other services, like provisioning or cultural, are not also being exploited).

The relationships between impact on ecosystems and their service supply potential are critical to sustainable development and yet these relationships are likely to be specific to a given location. Factors such as magnitude and type of human activity in the catchment, management implementation, ecosystem type and cultural differences, all may influence the relationship between pressures and ecosystem service supply. This study aims to firstly establish the relationships between impact risk and ecosystem service supply potential for a range of aquatic ecosystems; secondly, to explore the risk to service supply across aquatic ecosystem types; and finally, to investigate the possible influence of some key factors that may shape these relationships.

2. Materials and methods

Data from seven case study ecosystems based around Europe were used for this study (Fig. 1, Table 1). Case studies ranged in size, from very large e.g. the North Sea, to very small e.g. Lough Erne. Case studies consisted of completely freshwater sites e.g. the Swiss Plateau, completely marine sites e.g. the Azores islands, and others that had a continuum from freshwater to marine sites e.g. the Ria de Aveiro Natura 2000 sites (see Lago et al., 2019, this issue for an overview). We purposefully chose such a wide range of sites in order to: carry out the approach at different spatial scales, develop a common approach that can explore connectivity across different aquatic ecosystems, and to include sites with different socio-economic contexts to identify commonalities in drivers of the relationship between impact risk and service supply potential across these.

The approach taken here involves initially, establishing the ecosystem components, the human activities and pressures, and the ecosystem services relevant for each case study. In this, we used common, and therefore comparable typologies of each of these. The ecosystem components serve as the link between, on the one side, human activities and pressures introducing risk to them and on the other side, ecosystem services they can supply. Thus, we defined what the ecosystem components in each case study are (Section 2.1), what the impact risk on each of those components is (Section 2.2), and what the potential of each component to supply ecosystem services is (Section 2.3), in order to then come up with an overall risk to service supply score (Section 2.4). Finally, we investigated different factors that could explain some of the variability around that score, based on the different contexts of the case studies (Section 2.5).

2.1. Ecosystem components

We used the European EUNIS habitat classification (Davies et al., 2004) to map case studies, in order to identify all aquatic habitats present. We defined aquatic habitats as those supporting the supply of aquatic ecosystem services, and the biodiversity supporting those services. Thus, we included habitats such as, those in the riparian zone of rivers and lakes, and terrestrial habitats in the coastal zone. Each case study was mapped to EUNIS level 3 where possible, though in some cases data were patchy and habitats were mapped at coarser levels (EUNIS level 1 or 2). We linked each of these habitats to a specific realm, defined as an ecosystem type that can occur associated with either marine, coastal or fresh waters and can support habitats and biotic groups that supply aquatic ecosystem services (Table A.1). Thus, one EUNIS habitat could occur in more than one realm. The same habitat type occurring in different realms were considered to be different 'ecosystem components' e.g. sublittoral sediment in Shelf, and sublittoral sediment in Coastal realms. We considered habitats to include the species living within them e.g. sessile benthic invertebrates or plants, and plankton in water column habitats. We separately identified the active mobile aquatic biotic groups e.g. mammals, adult insects, birds. This recognises that these taxa are not associated with any one habitat but can move between several, and that they can be subject to different types of pressures, or have a different response to pressures than sessile species. Thus, one ecosystem component consists of one habitat in one realm or one mobile biotic group (that can move between realms). The full ecosystem component classification is given in the supplementary material (Tables A.1-A.2) and further details on the distribution of habitats and components in these case studies can be found in Teixeira et al. (2019, this issue).

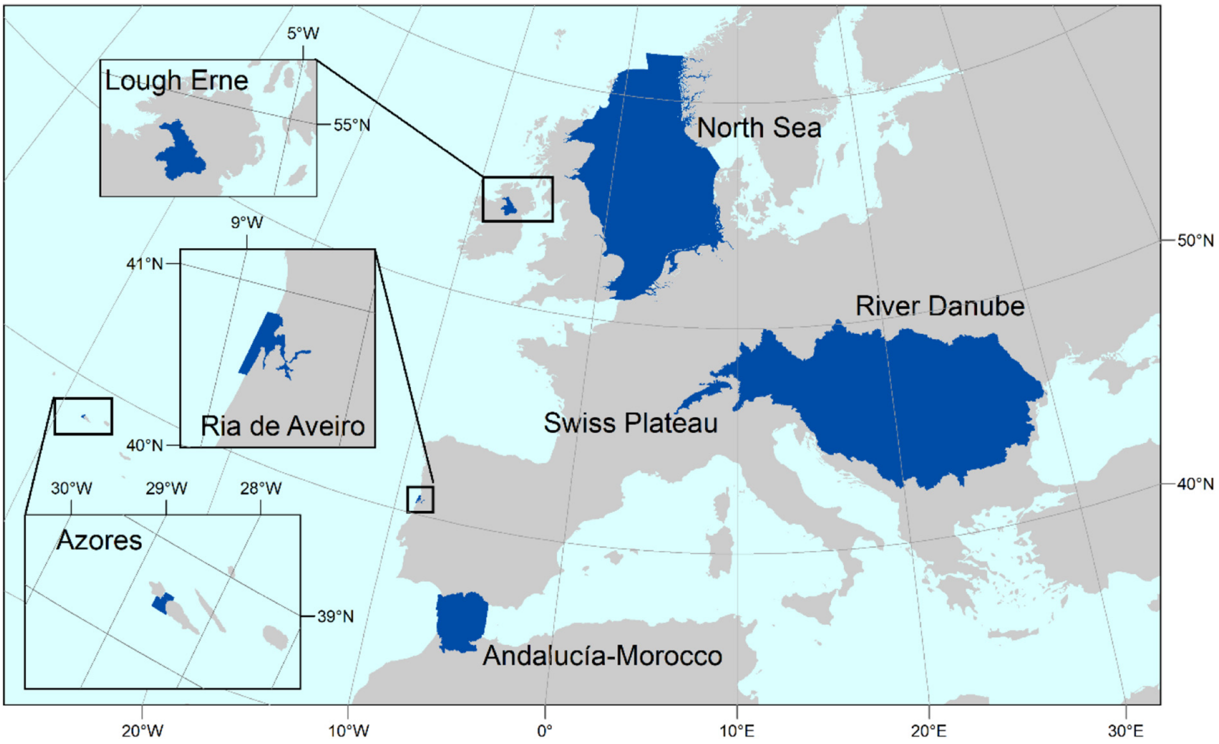

Fig. 1. Location of the seven case studies used in this study with blue areas reflecting the aquatic systems included.

Table 1
Overview of case studies used in this study. See supplementary material for details of specific realms, habitats and taxa included in case studies (Table A.2) and for derivation of population, GDP and land cover (Table A.6).

Case Study (key reference)	Aquatic Systems Included	Area of Case Study area (km^2)	Population Density in the Catchment (inhabitants per km^2)	Gross Domestic Product (GDP) per capita in the catchment (€)	Proportion of Artificial and Agricultural Land Cover in the catchment (%)
Andalucía/Morocco (Barbosa et al., 2019, this issue)	Freshwater, Coastal, Marine	47,937	194	14,767	27.1
Azores: Faial-Pico Channel	Coastal, Marine	237	107	15,000	60.1
Lough Erne (Robinson et al., 2019, this issue)	Freshwater	48	69	22,500	79.2
North Sea (Piet et al., 2019, this issue)	Coastal, Marine	547,224	223	34,226	55.5
Ria de Aveiro (Lillebø et al., 2019, this issue; Martínez-López et al., 2019, this issue)	Freshwater, Coastal, Marine	512	396	14,433	36.5
River Danube (Funk et al., 2019, this issue)	Freshwater	19,522	99	14,896	56.0
Swiss Plateau (Kuemmerlen et al., 2019, this issue)	Freshwater	312	511	54,967	67.9

2.2. Impact risk on ecosystem components

As a first step in determining the risk to ecosystem service supply, an impact risk score was obtained for each ecosystem component in each case study, based on the number of activities and pressures acting on them and the properties of the interactions of those activities and pressures with components. This impact risk assessment, where risk from human activities across aquatic ecosystems is explored in detail, is described fully in Borgwardt et al. (2019, this issue). In brief, all activities and all pressures introduced by those activities that interact with one or more ecosystem components within a case study were identified (Tables A.3-A.4). Each activity-pressure-ecosystem component interaction makes up one impact chain (sensu Knights et al., 2013) with each impact chain then weighted, using expert judgement based on local data and literature, according to five impact risk criteria: (i) spatial extent of overlap between an activity and a component, (ii) temporal frequency of a pressure introduction from an activity to a component, (iii) persistence of the pressure once the activity stops, (iv) dispersal potential of the pressure and (v) the severity of the interaction with the component, where an interaction occurs. These criteria were assigned scores (see details in Borgwardt et al., 2019, this issue) and considered to contribute to either the exposure or the consequence of an activity-pressure on an ecosystem component, similar to the approach taken in other impact risk assessments (e.g. Arkema et al., 2014; Knights et al., 2015; Samhouri and Levin, 2012). Using Euclidean distance, this allowed a semi-quantitative risk score between 0 and 1 to be determined for each impact chain, where one is the maximum possible risk when all five criteria have a maximum score. A total impact risk score (IR) for each ecosystem component was then obtained by summing the scores across all activities and pressures acting on a component (i.e. summing all impact chains per ecosystem component) (Eq. (1)). We consider this to be the best possible reflection of the total risk to an ecosystem component, where some components are subject to more activities and pressures than others, and some activities introduce more pressures than others (see Piet et al., 2017). Thus, while antagonistic or synergistic effects are currently poorly understood, the sum best reflects the total risk to the ecosystem component. Impact risk (IR) scores were calculated for components at EUNIS classification level 3, where possible or at coarser levels where not possible. We then scaled this to be between 0 and 1 by taking the maximum risk value found across case studies as being equal to one.

$$Impact\ Risk_a\ (IR) = \sum_{i=1}^{n_{IC}} \frac{1}{\sqrt{(E-1)^2 + (C-1)^2}} \tag{1}$$

where…

a is a given ecosystem component

n_{IC} is the total number of impact chains (i.e. activity-pressure combinations) linked to an ecosystem component

i is one impact chain (IC)

E is the exposure (see Eq. (2))

C is the consequence, a score based on one criterion, the severity of an activity pressure combination

$$Exposure\ (E) = \frac{E_{Extent} + E_{Dispersal} + E_{Frequency} + E_{Persistence}}{n_E} \tag{2}$$

where…

E_{Extent} is the Exposure criterion score given based on the extent of an activity pressure combination

$E_{Dispersal}$ is the Exposure criterion score given based on the dispersal potential of an activity pressure combination

$E_{Frequency}$ is the Exposure criterion score given based on the frequency of an activity pressure combination

$E_{Persistence}$ is the Exposure criterion score given based on the persistence of an activity pressure combination

n_E is the number of Exposure criteria used

2.3. Ecosystem service supply potential

Ecosystem service supply potential was calculated for each ecosystem component in each case study. This is fully described in Teixeira et al. (2019), this issue where ecosystem service supply of these case studies is explored in detail, but in brief, the ecosystem services (including the abiotic outputs, which we include here as part of ecosystem services) supplied by each component were identified. We followed the CICES classification of ecosystem services and abiotic outputs (Haines-Young and Potschin, 2018), with 33 in total at the 'Group' level (Table A.5), because this classification covers provisioning, regulation and maintenance, cultural and abiotic services, and is comprehensive in its coverage of those. It is also the European Union (EU) reference typology, meaning that the approach taken here will have direct relevance to management in the EU case studies, and that comparisons can be made across European studies.

Once the relevant services were identified, we used expert judgement to assign a weight according to whether the component supplies the service but is not very relevant (a weight of 1), or supplies the service and is very relevant (a weight of 2), relative to other ecosystem components in the case study. For example, intertidal areas of marine habitats are very important for physical and experiential interactions (such as recreation and leisure), while subtidal habitats do supply this service but are not as important. This follows a similar approach to others that have assigned a relative contribution of habitats to service supply (e.g. Hooper et al., 2017; Potts et al., 2014). We did not consider the actual area of the habitats here, only the potential for service supply, given the habitat type (see further discussion on this in Teixeira et al., 2019, this issue). A total potential for service supply was taken as the sum of the weights across all ecosystem services supplied by an ecosystem component. This was then divided by the maximum service supply potential found across all case studies to get a service supply potential score between 0 and 1. Service supply potential scores were calculated at the EUNIS 3 level, where possible (Eq. (3)).

$$Service\ Supply\ Potential_a(SSP) = \frac{\sum_{j=1}^{n_{ES}} RC_{ES}}{n_{ES} \times RC_{max}} \tag{3}$$

where…

a is a given ecosystem component

n_{ES} is the total number of ecosystem services

j is one ecosystem service

RC_{ES} is the relative contribution assigned to a given ecosystem component for one ecosystem service

RC_{max} is the maximum relative contribution of an ecosystem component found

To link to the impact risk (IR) scores, we aggregated the EUNIS level 3 service supply potential (SSP) scores where IR scores were only available at coarser EUNIS levels. To do this, we took the maximum SSP score across EUNIS level 3 habitats within the EUNIS level 2 (or coarser) category. This gives the maximum potential service supply for a habitat, though it may overestimate the full potential of the coarser EUNIS level habitat if not all sub-habitats within it have the same potential.

2.4. Risk to ecosystem service supply

We considered the relationship between impact risk (IR) on a particular ecosystem component and the service supply potential (SSP) of that same component. We consider that greater IR alongside greater SSP would result in an overall higher risk to service supply. This is on the basis that components with a high SSP are more important for supplying services and thus, there is a greater likelihood of loss of services, if those components are further degraded due to a higher IR. We derived a total risk to service supply score (RESS) by finding the Euclidean distance of each ecosystem component in each case study along the axes of IR and SSP, i.e. the distance from the origin of each point (Eq. (4)). We used Euclidean distance (as opposed to finding the product) because this gives a more precautionary score (higher risk) where the score is moderate (Sharp et al., 2014).

$$Risk\ to\ Ecosystem\ Service\ Supply_a(RESS) = \frac{1}{\sqrt{(IR-1)^2 + (SSP-1)^2}} \tag{4}$$

2.5. Explanatory variables

Finally, we considered a number of potential explanatory variables that define the attributes of the case study, related to the socio-economic context, which could be driving differences in the impact risk (IR), service supply potential (SSP) and risk to service supply (RESS) relationship. These were: area of case study area (km^2) as defined by case study experts (scientists and stakeholders) (Table 1); realm of the ecosystem component (Tables A.1–A.2); population density and Gross Domestic Product (GDP) in the catchment, derived from EU or other case study specific available information (Table 1, Table A.6); proportion of area of land in the catchment covered by artificial and agricultural land, derived from CORINE land cover (CLC, 2012) or other appropriate case study specific data (Table 1, Table A.6). Here we were explicitly considering how these broad variables explain variability in IR, SSP and RESS, rather than how supply of services and risk to this this drives socio-economic attributes.

2.6. Data analysis

All analyses were carried out in R (R Development Core Team, 2016). Data were checked for normality and assumptions of tests. Pearson product moment correlation, r, (calculated using the function *cor.test*) was used to assess the overall relationship between IR and SSP and the relationship for each case study and realm, where we consider both variables to be dependent on each other. We first used a linear model to examine the relationship between IR, SSP and RESS with realm and case study. We then excluded the case study term from the models and included the case study explanatory variable attributes. Linear models were carried out using the *car* package (Fox and Weisberg, 2011) and interaction plots were produced using the *effects* package (Fox, 2003). All other plots were produced using *ggplot2* (Wickham, 2009).

3. Results

There was an overall positive relationship between impact risk (IR) and the service supply potential (SSP) ($r = 0.38$, d.f. $= 189$, $p < 0.001$) (Fig. 2). However, there was variability in this relationship both between and within case studies and realms. The relationship was positive in all case studies apart from the Swiss Plateau where there was a negative relationship between ecosystem components with the greatest SSP and IR; in that case only, the components with the greatest SSP were not those at greatest risk. However, the relationship was significant in only three of seven case studies, indicating that there is variability within them (Table 2). Some of this variability may be explained by the differences in the shape of the relationship across realms (Fig. 2(b)). All realms, other than wetlands, showed a positive relationship between IR and SSP. This was significant in eight out of eleven realms.

Four case studies, the North Sea, River Danube, Lough Erne and Swiss Plateau tended to have higher IR, while the Azores, Andalucía-Morocco and Ria de Aveiro showed lower IR (Fig. 2(a)). River Danube, Swiss Plateau and Andalucía-Morocco showed the greatest SSP. Mobile taxa generally showed high IR and relatively low SSP. Rivers, lakes, inlets and riparian habitats all showed the greatest SSP.

There were significant differences in the impact risk (IR), service supply potential (SSP) and risk to service supply (RESS) across case studies and realms (Table 3). The North Sea had the highest overall RESS, while Ria de Aveiro had the lowest (Fig. 3(a)). Some case studies had high RESS within realms, such as Rivers in the Danube, while others showed much lower RESS. Rivers and lakes had some of the highest RESS found (Fig. 3(b)). Some realms had high RESS in some case studies e.g. Coastal and Inlets Transitional in the North Sea.

When the case study term was broken down to socio-economic attributes, realms in larger case studies were found to have greater impact risk (IR), except for Riparian, Rivers and Wetland realms, where those in smaller case studies had greater IR, and there was little or no effect in Ocean and Other realms (Table 4, Fig. A.4). In bigger case studies, population density tended to be smaller, and IR tended to be larger (Fig. A.5). For example, Ria de Aveiro is a small site, with a relatively high population density in the catchment and has lower risk compared to the River Danube, which covers a very large area, has relatively low population density and has relatively high IR. In case studies with a bigger GDP, a greater IR to ecosystem components was found. IR was not found to be related to land cover.

For most realms, GDP and artificial and agriculturally modified land cover was positively, and population density negatively, related to service supply potential (SSP). For population density, this effect was not found in Oceanic, Other, Riparian, Rivers or Wetlands (Fig. A.6). For GDP, the effect was not found for Mobile taxa, Other, Riparian or Shelf realms (Fig. A.7), and for land cover, the effect was not found in Oceanic,

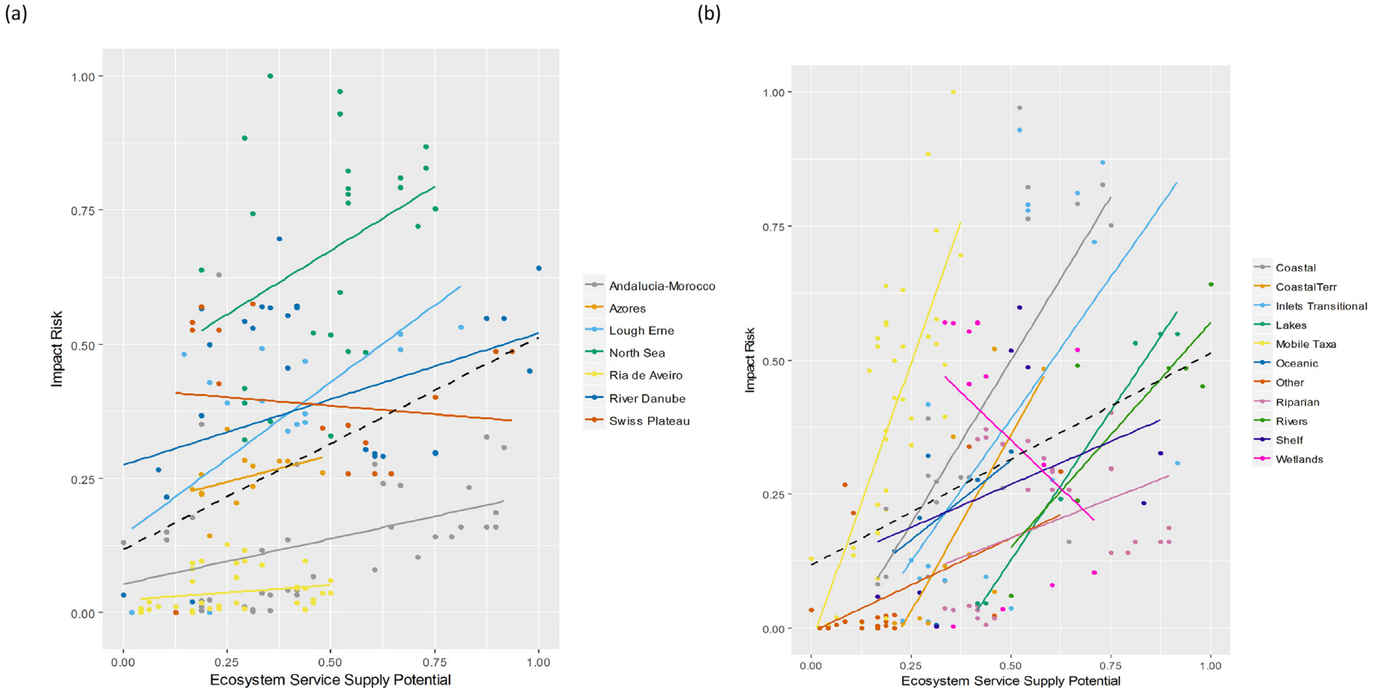

Fig. 2. The relationship between impact risk and aquatic ecosystem service supply potential. The dashed black line shows the overall relationship between impact risk and service supply potential for all cases. Solid colour and trend lines indicate the factors (a) location of case study, and (b) aquatic realm ('Other' includes agricultural, urban and terrestrial natural habitats that support aquatic ecosystem services or species). Each point represents one ecosystem component (n = 191).

Other, Riparian, Shelf and Wetland realms (Fig. A.8). Service supply was not found to be related to the size of the case study area.

Risk to service supply (RESS) was found to be negatively related to population density and positively related to the size of the case study area, GDP and proportion of area covered by artificial and agricultural land, but only for particular realms (Table 3). The effect of the size of the case study area was the opposite in Riparian, Rivers and Wetlands, and was not observed in the Other realm (Fig. A.9). The land cover effect on the RESS was only not observed for two realms, Oceanic and Other (Fig. A.12). For Oceanic realms the land cover as measured here would hardly apply. For Other realms, which include a large proportion of area used as urban and for agriculture and only a small portion reported as terrestrial natural ecosystems, the service supply from an aquatic services supply perspective is rather low. There was a negative correlation between RESS and population density for some realms, similarly to land cover, this effect was not observed for Oceanic and Other realms, but also not for Coastal, Mobile taxa or Riparian realms (Fig. A.10). In addition, the effect of GDP was particularly small or not apparent for Other and Riparian realms (Fig. A.11).

Table 2
Results of Pearson Product Moment Correlation for the relationship between impact risk and ecosystem service supply potential for seven case studies and eleven aquatic realms. Significant relationships ($p < 0.05$) are in bold.

	d.f.	t	*p*	Correlation coefficient
Case Study				
Andalucía-Morocco	41	2.502	**0.016**	0.360
Azores	11	1.422	0.183	0.394
Lough Erne	14	3.588	**0.003**	0.692
North Sea	24	1.924	0.066	0.366
Ria de Aveiro	41	1.454	0.154	0.221
River Danube	30	2.201	**0.036**	0.373
Swiss Plateau	15	−0.421	0.680	−0.108
Realm				
Coastal	17	4.530	**0.000**	0.740
Coastal Terrestrial	9	3.741	**0.005**	0.780
Inlets Transitional	16	2.991	**0.009**	0.599
Lakes	5	16.989	**<0.001**	0.991
Mobile Taxa	35	6.713	**<0.001**	0.750
Oceanic	4	1.180	0.303	0.508
Other (Agricultural, Urban, Terrestrial Natural)	26	2.912	**0.007**	0.496
Riparian	34	2.273	**0.030**	0.363
Rivers	5	3.440	**0.018**	0.838
Shelf	7	1.109	0.304	0.387
Wetlands	11	−1.408	0.187	−0.391

4. Discussion

We found a positive relationship between the potential for ecosystem service supply and the risk of impacts from human activities across ecosystem components from different aquatic realms in different locations. This relationship suggests that, overall, the parts of the ecosystem we rely on the most for the supply of ecosystem services, are also those most at risk from human activities. This relationship does vary from location to location, with potential drivers for this being the type of aquatic realm where the service is supplied and attributes of the specific case study considered, such as the size of the area, the population density, land cover and GDP.

The impact risk (IR) - service supply potential (SSP) relationship is a simple representation of complex interactions between society and nature, but is reflective of the full suite of ecosystem services that can be supplied by an ecosystem component, and the full range of activities that can impact it. While the benefits of some services are obtained largely passively by people (e.g. climate regulation), others are actively exploited to obtain their benefits (e.g. seafood, raw materials) (Fisher et al., 2009). Thus, it can be expected that an ecosystem component with a high SSP could also be heavily impacted by human activities that are aiming to actively exploit at least some of those services. For example, reservoirs for hydropower can facilitate the exploitation of energy, water and food services from river systems but at the same time result in environmental degradation and losses to multiple other services (Wang et al., 2010). Similarly, there are trade-offs related to the balance between commercial and recreational exploitation of fish with leaving fish in the water to contribute to carbon storage and other services (Martin et al., 2016). This highlights the circularity and trade-off

Table 3

General linear model results for variation in impact risk (model 1), ecosystem service supply potential (model 2) and risk to ecosystem service supply (model 3) in ecosystem components in relation to case study and realm for seven European case studies (n = 191) (Response ~Case Study + Realm + Case Study ∗ Realm). Significant relationships ($p < 0.05$) are in bold. Plots of the significant interactions can be found in the supplementary material (Figs. A.1–A.3).

Term	model 1: Impact Risk			model 2: Ecosystem Service Supply Potential			model 3: Risk to Ecosystem Service Supply		
	d.f.	F	*p*	d.f.	F	*p*	d.f.	F	*p*
Case Study	6	132.602	**<0.001**	6	11.248	**<0.001**	6	48.983	**<0.001**
Realm	10	20.606	**<0.001**	10	36.41	**<0.001**	10	17.029	**<0.001**
Case Study ∗ Realm	29	3.57	**<0.001**	29	1.948	**0.006**	29	3.455	**<0.001**

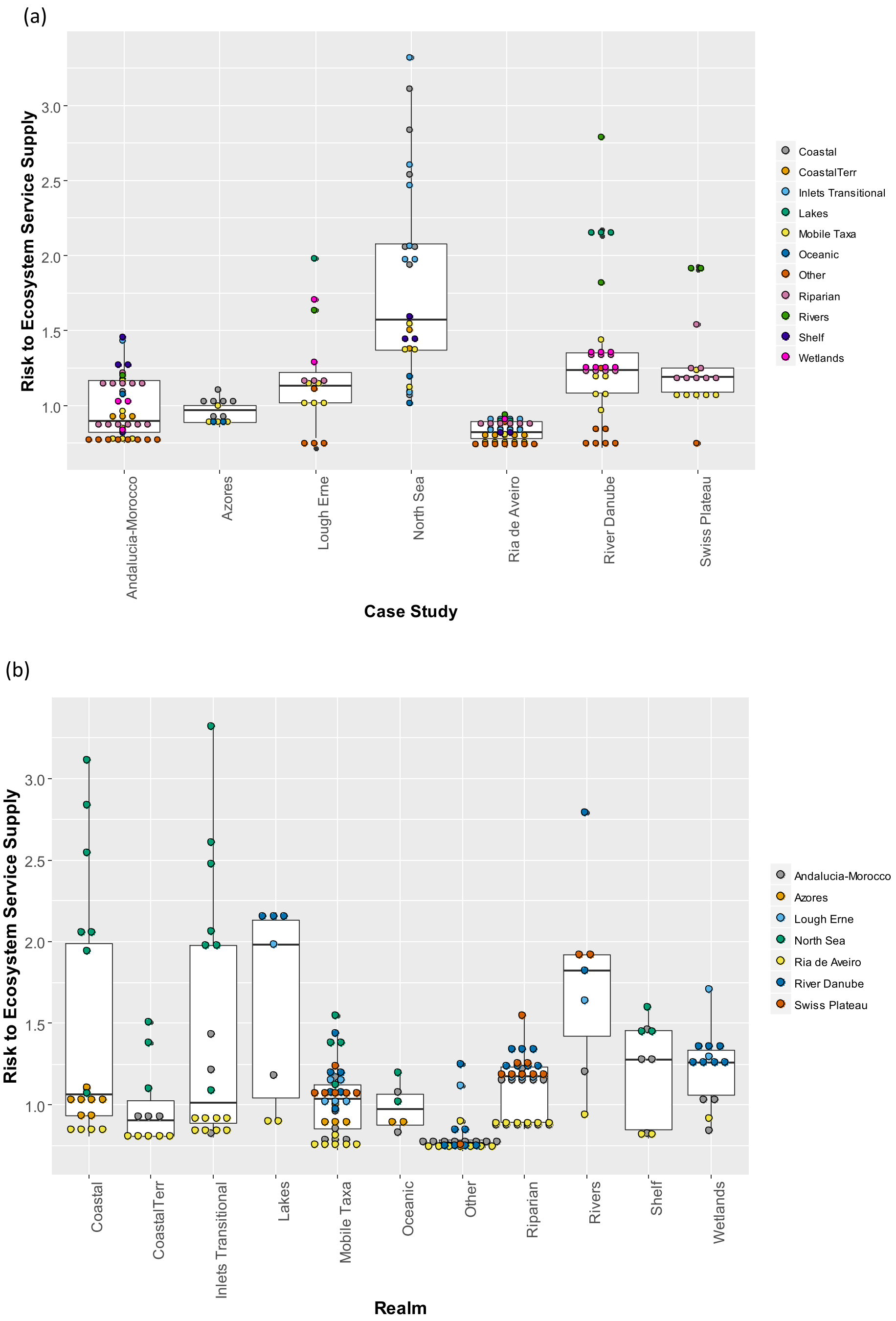

Fig. 3. Median, interquartile range and minimum and maximum values of overall risk to service supply across (a) case studies, with coloured dots indicating individual ecosystem components in different realms, and (b) aquatic realms, with coloured dots indicating individual ecosystem components in different case studies; (n = 191).

Table 4
General linear model results for variation in impact risk (model 1), ecosystem service supply potential (model 2) and risk to ecosystem service supply (model 3) in ecosystem components in relation to general socio-economic indicators for seven European case studies ($n = 191$) (Response ~Realm + Area of Case Study + Population density + GDP + Land cover + Realm ∗ Area of Case Study + Realm ∗ Population density + Realm ∗ GDP + Realm ∗ Land cover + Area of Case Study ∗ Population density + Area of Case Study ∗ GDP). Significant relationships ($p < 0.05$) are in bold. Plots of the significant interactions can be found in the supplementary material (Figs. A.4–A.12).

Term	model 1: Impact Risk			model 2: Ecosystem Service Supply Potential			model 3: Risk to Ecosystem Service Supply		
	d.f.	F	p	d.f.	F	p	d.f.	F	p
Realm	21	12.658	<**0.001**	21	18.250	<**0.001**	21	9.480	<**0.001**
Area of case study	1	23.059	<**0.001**	1	0.709	0.401	1	3.230	0.074
Population density	1	12.558	<**0.001**	1	0.008	0.930	1	4.993	**0.027**
GDP	1	18.193	<**0.001**	1	1.866	0.174	1	1.402	0.2238
Land cover (artificial)	1	1.457	0.229	1	<0.001	0.985	1	0.010	0.752
Realm ∗ Area of case study	10	3.206	<**0.001**	10	1.634	0.102	10	4.431	<**0.001**
Realm ∗ Population density	10	1.195	0.299	10	2.821	**0.003**	10	2.225	**0.019**
Realm ∗ GDP	6	1.836	0.096	6	3.665	**0.002**	6	2.610	**0.020**
Realm ∗ Land cover (artificial)	3	2.317	0.078	3	2.696	**0.048**	3	3.767	**0.012**
Area of case study ∗ Population density	1	18.179	<**0.001**	1	0.842	0.360	1	2.188	0.141
Area of case study ∗ GDP	1	<0.001	0.986	1	0.012	0.913	1	0.003	0.958

between the introduction of pressures through activities to ecosystems and our reliance on benefits we get from them. Ensuring managers consider the economic and other values of all ecosystem services, including those more difficult to quantify, such as regulation and maintenance services, will lead to different trade-offs in management than if we focus on the supply of only a few services.

Lakes, Rivers, Inlets and Coastal realms had some of the highest risk to service supply (RESS), though for the latter two in particular, this was highly variable across case studies. This reflects what is already known, that freshwater biodiversity is under greater threat from human activities than either marine or terrestrial (Dudgeon, 2010), and that coastal areas are the most heavily impacted marine habitats from human activities (Halpern et al., 2008). RESS is a factor of the potential for ecosystem components in realms to supply services and the location of the realm, which determines the level of activity there. Both, impact risk and service supply, are dependent on human activities and location to different degrees. It has been found that the natural capacity for service supply is highest in coastal areas for marine ecosystems, simply because the abiotic conditions in those areas support such a diverse range of taxa (Culhane et al., 2018). In turn service supply is also linked to complementary built, social and human capital, that allows the benefits of services to be realised (Costanza et al., 2014). Thus, accessibility to people may result in more activities and use of more services, which in turn may be affected by the existence of built capital such as roads, slip ways, etc., leading us to target particular locations more heavily (O'Higgins et al., 2010). In this study, those realms with the highest RESS were all highly accessible to people, support many activities and supply many services, when compared to realms with lower RESS, such as the Oceanic.

Factors we associate with greater levels of activity were found to explain some of the variability in the risk to service supply (RESS) in most aquatic realms, including GDP, artificial and agricultural land cover and the size of the area. For example, the North Sea and the River Danube are two large case studies that showed high levels of RESS. The Swiss Plateau and Lough Erne are smaller but also had high RESS in some realms. Both these smaller case studies have high GDP and higher levels of artificial and agricultural land cover in the catchment than other sites. This pattern reflects trends found in many countries, where GDP is increasing at the same time that natural capital (and thus the potential for service supply) is decreasing (Mumford, 2016). Population density was found to negatively correlate with RESS. Though we could not test the interaction here, this may be related to land cover, as an activity such as agriculture that introduces risk, is also associated with lower population densities.

While the perspective that human activities causing pressures can reduce the capacity to supply services has often been considered (e.g. Grizzetti et al., 2016), it is also important to consider that a high potential to supply ecosystem services can also drive human activities, where these services are sought out and used by society e.g. supply driving demand. For example, people have been documented to migrate to places with nice weather (Rappaport, 2007), and value living near coasts and lakes, as indicated by the premium on house prices close to these ecosystems (Lyons, 2012). Service supply potential (SSP) was positively correlated to GDP and artificially and agriculturally modified land cover in several marine and freshwater realms across case studies. This indicates that some aspects of SSP are linked to the demand for service supply. However, we cannot determine the causal direction of this positive relationship between GDP, modified land cover and SSP here: in the long run, higher SSP could increase activities (and thus GDP or modified land cover), or a higher GDP or modified land cover could be associated with additional environmental protection or investment in complementary capital to enhance services, itself increasing SSP, or some combination of both.

The opposite impact risk (IR) - service supply potential (SSP) relationship was found for Wetlands when compared to the other realms, with an increase in SSP associated with decreasing IR. Thus, Wetlands in some areas had a low service supply potential and a high impact risk, while in other areas, they had a high service supply potential and a low impact risk. We also found that, unlike in most other realms, lower artificial and agriculturally modified land cover in Wetlands was associated with a higher SSP, though higher modified land cover was associated with higher risk to service supply (RESS). This suggests a decoupling between human activities and flows of benefits in Wetlands that is not found in other realms, and these flows of benefits are obtained without the need for harmful activities to exploit them.

In Europe, the most important services coming from Wetlands may be regulation and maintenance services, like flood control, or cultural services, like recreation (Maltby and Acreman, 2011). This could indicate that the services supplied by wetlands are not driving high impact human activities, and instead are substituting for costly alternatives (e.g. the construction of flood barriers). In developed countries, such as in Europe, most wetlands have already been lost, and those remaining have been protected under instruments such as the RAMSAR convention for many years already (Maltby and Acreman, 2011). Thus, the areas at lower risk may be highly protected, and this environmental protection may be enhancing their potential to supply services such as flood control, while in the high impact risk areas, the service supply potential is much lower. This relationship may be in contrast to developing countries, where people still rely on wetlands heavily, often for more consumptive services (Maltby and Acreman, 2011).

The overall impact risk (IR) - service supply potential (SSP) relationship supports prioritisation of management on those ecosystem components with both the greatest SSP and the highest IR. However, it is important to also consider that there may be components with high IR but low SSP where management should still be a priority. Ecosystem service supply and demand are not necessarily coupled (O'Higgins et al., 2019; Villamagna et al., 2013). In cases where there is a high demand, or an unregulated demand of services by society, the risk to supply may also increase, independently of the intrinsic ecosystem supply potential or capacity. In addition, alongside the impacts introduced through the exploitation of services are other activities not directly associated to service supply, for example, cargo shipping introduces pressures but is not linked to any specific ecosystem service. Thus, the ecosystem is subject to pressures from both service exploitation as well as from other sources, and this introduces variability into the overall relationship. The ecosystem service approach is, in general, a means to achieve better management of ecosystems and is embedded in environmental policies such as the EU Marine Strategy Framework Directive (MSFD) (EC, 2008) and the Biodiversity Strategy (EC, 2011). However, the variability in this relationship shows that protecting the supply of ecosystem services alone will not fully protect all parts of the ecosystem, where there are components with high impact risk (IR) and relatively low service supply potential (SSP), such as indicated for the Mobile taxa here. Despite the low SSP found here, we know that some of the Mobile taxa, such as fish, can have high market values and contribute a lot to a few services, like nutrition and recreational cultural services (Martin et al., 2016). This echoes the recommendations of others, to take the ecosystem service approach as being complementary to other approaches framed around conserving biodiversity (Boulton et al., 2016).

There are a number of other factors, not assessed here, that could also contribute to the variability in the risk to service supply (RESS) across case studies and realms. Impact risk (IR) and RESS across realms was higher in the North Sea, Lough Erne, the River Danube and the Swiss Plateau, and lower in the Azores, Ria de Aveiro and Andalucía-Morocco. The latter three sites all have substantial conservation status (each sited entirely within a Marine Protected Area (MPA); Natura 2000 network of sites; and International Biosphere Reserve, respectively), such that it is expected that human activities are more limited in these sites, and IR would be lower than the other sites. The North Sea has around 20% of its area protected by MPAs, but these areas are not yet considered to be ecologically coherent or representative (EEA, 2015) and in many cases, the protected sites were chosen where activity was already low (thus would not contribute to lowering impact risk). Lough Erne, though having high IR and RESS, is a Special Area of Conservation (EU Habitats Directive) and is under the RAMSAR convention for specific listed habitats and species. At the same time, the area is a heavily modified waterbody under the EU Water Framework Directive. The conservation status of the area may not be sufficient to limit the activities introducing risk, as the area is heavily used for activities such as hydropower (Robinson et al., 2019, this issue). In the Swiss Plateau, the impact risk (IR) - service supply potential (SSP) relationship was slightly negative, different to other case studies. This is related to the perceived high risk of Mobile taxa (that have low SSP) in this region, while habitats are subject to a new, ambitious national restoration programme, expected to reduce IR. Thus, on-going environmental management programs are likely to be an important factor to consider in the risk to ecosystem service supply, and while there may be potential for management to reduce this risk, just conserving targeted habitats or species may not be as effective as protecting networks of habitats (Hermoso et al., 2012; Wiens, 1995).

The approach we have presented can be a useful tool for risk assessment of ecosystem service supply. We suggest it can be used for initial screening of critical areas in management contexts, and to identify the parts of the ecosystem important for service supply, that are most at risk. Here, we have not highlighted the specific ecosystem components present in a case study or realm, or the specific type of activities and the pressures they introduce e.g. commercial fishing versus hydropower. Additionally we have not specified the services that are culturally important in a particular area or at a particular scale e.g. recreation may be very important in a small area, but climate regulation may not be, while climate regulation is very relevant at the regional and global scale. These specific attributes are likely to vary across locations and realms and explain some of the variability found in the relationship. Future work should investigate some of these aspects and how they contribute to risk to service supply. This can further help management by identifying the activities and pressures introducing the most risk, the specific habitats, the species and the services most at risk in a given location (e.g. see Piet et al., 2019, this issue).

The results highlighted here are dependent on the scale at which assessments are carried out, because the area of the case study did influence the risk to service supply. In most realms, the larger the case study, the greater the risk, as more activities introducing pressures are likely to be found, and potentially impacting the ecosystem services being supplied in that region. However, the opposite pattern was found in Riparian habitats, Rivers and Wetlands, showing that a number of additional factors come into play. Scale may be particularly relevant when considering Mobile taxa, which were found to be at high risk. Mobile groups are often considered separately from habitats in policy instruments, e.g. the MSFD (EC, 2008), to account for their mobility, which means they can move between habitats and ecosystems and in some cases aquatic realms, and also in and out of case study regions. In doing so, they can interact with human activities and pressures in any of the habitats they are associated with. We followed this rationale here. However, ideally the Mobile taxa should also be associated to their habitats and realms, because impact risk does vary between realms, and mobile groups are affected by the state of their habitats (Culhane et al., 2018; Teixeira et al., 2019, this issue). To this end, mapping of the relative contribution of specific habitat types to supporting individual service providing mobile groups may be useful (Jordan et al., 2012; O'Higgins et al., 2010).

We used EUNIS habitat data, enabling the same methodology to be used anywhere within Europe and as such it represents a first EU-wide standardised approach to the analysis of risk to service supply. The approach here used expert judgement to assess impact risk and service supply potential. Data availability has been recognised as an issue in several similar approaches (Cabral et al., 2015; Hooper et al., 2017) but the value of using expert judgement in these situations has also been recognised (Lillebø et al., 2016; Mace et al., 2015). Here, one approach was applied across marine and freshwater ecosystems, across different geographic locations, and across data rich and data poor situations. Future development of the understanding of the relationship between human activities, the pressures they introduce and the effect these have on the sustainability of ecosystem services is needed before we can fully validate what now requires an expert judgement approach.

5. Conclusion

We developed a replicable and transferrable methodology to assess risk to ecosystem service supply (RESS) and applied it to seven case study sites across Europe. This method enables comparison of RESS between different systems and aquatic realms and may be applied at any scale where relevant data are available. Our study showed variability in the impact risk - service supply potential relationship in different locations and aquatic realms, and significantly different RESS in different aquatic realms, with Lakes and Rivers exhibiting the highest, but Coastal and Inlet habitats also having very high RESS in some places. This finding broadly confirms the association between levels of activity and risk to ecosystem services, and notably the Oceanic realm (at furthest remove from human population) experienced least risk. Blue growth, the sustainable development of offshore industry (EC, 2012), is likely to increase risk to the Oceanic realm in the future, as these areas host more activities but also, as they become more important for the supply of services. However, even with this growth, risk is unlikely to exceed that in areas most accessible to human populations, and those acting as hubs for transferring the products of blue growth to society, such as at the coast.

The challenge of sustainability has been described as achieving the balance between maximising economic return while minimising ecosystem and service losses (Arkema et al., 2015). We showed that the habitats with the greatest potential to supply services are also those most at risk, and this was linked to broad socio-economic factors such as increased GDP. We also found ecosystem components that are at high risk but have a low service supply potential. This shows that protecting the supply of ecosystem services alone will not protect ecosystems fully. Thus, we may not be achieving the balance required to sustain service supply, and there are potentially trade-offs between increasing GDP with environmental sustainability and broader aspects of wellbeing. In Europe, lower GDP still comes with some associated environmental regulation. Had this study more widely included lower income and underdeveloped countries, the relationship between risk to service supply and GDP may differ and this may be particularly true for aquatic ecosystems, where people are heavily reliant on aquatic services for their livelihoods and they are frequently overexploited and little managed (e.g. Green et al., 2015). The three sites (Azores, Andalucía -Morocco, Ria de Aveiro) studied here with the greatest level of management, are also those with the lowest risk to service supply, demonstrating the influence management can have on the level of activity introducing pressures and risk to ecosystem service supply.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.12.346.

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