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Title: An exposure-effect approach for evaluating ecosystem-wide risks from human activities

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Abstract

Ecosystem-based management (EBM) is promoted as the solution for sustainable use. An ecosystem-wide assessment methodology is therefore required. In this paper, we present an approach to assess the risk to ecosystem components from human activities common to marine and coastal ecosystems. We build on: (1) a linkage framework that describes how human activities can impact the ecosystem through pressures, and (2) a qualitative expert judgement assessment of impact chains describing the exposure and sensitivity of ecological components to those activities. Using case study examples applied at European regional sea scale, we evaluate the risk of an adverse ecological impact from current human activities to a suite of ecological components and, once impacted, the time required for recovery to pre-impact conditions should those activities subside. Grouping impact chains by sectors, pressure type or ecological components enabled impact risks and recovery times to be identified, supporting resource managers in their efforts to prioritise threats for management, identify most at-risk components and generate time-frames for ecosystem recovery.

Key words: exposure-effect; risk framework; marine; ecosystem-based management; human activities; impact

1. Introduction

Current rates of resource exploitation are unsustainable and the ecosystem-approach has been widely promoted as the framework to achieve sustainable use (Halpern *et al.*, 2008; Airoldi and Beck, 2007; EC, 2008). By definition, an ecosystem is a diverse range of physical and biological components which function as a unit (*sensu* Tansley, 1935) and therefore, an ecosystem approach should ideally consider the complete range of interactions that human activities have with the ecosystem and its components. However, the number of sectors that exploit the ecosystem and its components is often great, resulting in many different pressures and a complex network of interactions (Knights *et al.*, 2013). Identification and prioritisation of interactions for management can therefore be difficult (Bottrill *et al.*, 2008), presenting a major challenge to transforming the ecosystem approach from a concept into an operational framework (Leslie and McLeod, 2007).

The onus has been placed on the scientific community to identify the pathways through which activities cause harm (Leslie and McLeod, 2007; Fletcher *et al.*, 2010). The relationships between human activities and ecological components have commonly been described using linkage-based frameworks. These adopt the causal-chain concept to infer pressure-state relationships (Rounsevell *et al.*, 2010) and have been applied widely in both marine and terrestrial environments (e.g. Elliott, 2002; La Jeunesse *et al.*, 2003; Odermatt, 2004; Scheren *et al.*, 2004; Holman *et al.*, 2005). The simplicity of these frameworks is advantageous as key relationships can be captured and displayed in a relatively simple way (Rounsevell *et al.*, 2010). However, viewing linkages in isolation rather than accounting for the interplay across sectors, activities, pressures or components may be overly simplistic (Tallis *et al.*, 2010) and can lead to ineffective management (Khalilian *et al.*, 2010). A flexible, problem-solving approach is therefore required that is capable of linking the relationship between the human activities and the environment while supporting the decision-making needs of environmental managers.

Risk assessment can provide a solution (Hope, 2006). Risk assessment in general describes the likelihood and consequences of an event. In an ecosystem-based management context, risk can be defined as the degree to which human activities interfere with the achievement of management objectives related to particular ecological components (see Samhouri & Levin 2012). It is increasingly seen as a way to integrate science, policy, and management and has been widely used to address a range of environmental issues (e.g. Fletcher, 2005; Francis, 1992; Smith *et al.*, 2007; Samhouri and Levin, 2012; Hobday *et al.*, 2011). There are several risk assessment approaches available using quantitative (e.g. Francis, 1992; Samhouri and Levin, 2012) or qualitative data (e.g. Fletcher, 2005; Fletcher *et al.*, 2010; Breen *et al.*, 2012). Many ecological risk assessments (Fletcher, 2005; Campbell and Gallagher, 2007; e.g. Astles *et al.*, 2006) are based on a likelihood-consequence approach for estimating the risk of a rare or unpredictable event (Williams *et al.*, 2011). But when an assessment of on-going (current) pressure is needed, then an exposure-effect analysis is more suitable (Smith *et al.*, 2007). Several studies have used the exposure-effect concept to assess risk to habitats and species from on-going human activities (e.g. Bax and Williams, 2001; Stobutzki *et al.*, 2001) using qualitative descriptors such as habitat resistance (to physical modification) and resilience (the time taken for the habitat to recover to pre-impact condition) to assess habitat vulnerability (Bax and Williams, 2001).

Assessments have tended to focus on a single activity or target species (e.g. fishing, Bax and Williams, 2001; Fletcher, 2005; Hobday *et al.*, 2011) but have recently been broadened to include a greater number of activities and non-target species and applied at larger management scales (Samhouri and Levin, 2012).

Here, we illustrate how the exposure-effect approach can be used to assess the risk to ecosystems from human activities at considerably larger spatial scales than those previously described. Although the definition of “regional” can be broadly interpreted (e.g. Samhouri and Levin, 2012 used regional to describe the Puget Sound, USA), here we apply the regional definition given in the Marine Strategy Framework Directive (MSFD) (EC, 2008); a recent Europe-wide environmental policy mechanism. Therein, regional seas are defined as the North East Atlantic, the Baltic Sea, the Black Sea and the Mediterranean Sea (Fig. 1). We build on (1) a linkage framework comprised of potential pressure mechanisms describing how different sectors can impact ecological components of the ecosystem (Knights *et al.*, 2013), and (2) a pressure-based expert judgement assessment of the exposure and sensitivity of ecosystems to sector activities and their pressures (Robinson *et al.*, In prep), to show the potential risks to ecological components from a holistic range of sectors in each region and which are integral features of marine ecosystems worldwide.

2. Methods

An assessment of the risk to Europe’s regional sea ecosystems from human activities must consider a range of sectors, pressures and ecological components beyond those included in previous studies (e.g. Bax and Williams, 2001; Samhouri and Levin, 2012). We included (1) up to 17 sectors (the number of sectors included in a regional assessment was dependent on whether it is currently operational in the region), (2) 23 pressure types, and (3) 4 broad ecological components (Table A1). Two of the ecological components (fish and predominant habitats) were further disaggregated into ‘sub-components’ to give greater resolution and differentiation of the impact of sectors on those components (these sectors were identified as primary drivers of impact in each regional sea; Knights *et al.*, 2013), resulting in a total of 12 ecological components (Table A1). Here we provide an illustration of the approach rather than undertaking an exhaustive assessment. As such, we may not have considered all ecological components although a broad range are included. Furthermore, we only consider direct effects of sector-pressures on ecological components, but we recognise that indirect effects can play an important role in the functioning of an ecosystem (Dunne *et al.*, 2002).

2.1. Linkage mapping and pressure (threat) assessment

A first step in developing the assessment framework was the creation of a sector-pressure-ecological component linkage matrix. Each cell in the matrix describes the potential for impact on an ecological component from a sector, wherein a pressure is the mechanism through which an impact occurs. We refer to this linear interaction between a sector, pressure and ecological component as an "impact chain" herein. Impact chains were defined following an extensive review of the peer-reviewed scientific literature and published reports (see Knights *et al.*, 2013 for full details of the linkage matrix) resulting in a pre-pressure assessment matrix of 4,320 potential impact chains. Accurate calculation of threat and risk is reliant upon the inclusion of all possible impact chains and every effort was made to include all relevant chains (see Knights et al. 2013 for full details), although some more minor linkages may be missing as a result of uncertainty (Walker et al. 2003).

Threat from each chain was assessed using a pressure assessment (*sensu* exposure-effect) approach (see Robinson *et al.*, In prep for full details of the methodology). The pressure assessment methodology was designed with the concept of risk assessment in mind, such that the assessment criteria we developed could be used to evaluate the likelihood and consequences of a specific or combination of impact chains. The pressure assessment used expert judgment (Cooke and Goossens, 2004) to qualitatively assess each impact chain using a categorical assessment of five criteria: (1-2) two describing the exposure of the ecological component to a sector-pressure combination; (3) one describing the severity of the interaction; and (4-5) two describing recovery (Figure 2; Table A2). Each impact chain was evaluated considering prevailing conditions and applied here at a European regional sea scale, not least so that the outcomes of the assessment could support the objectives of the Marine Strategy Framework Directive (EC, 2008) (Figure 1). Some impact chains were excluded from the final assessment based on the absence of a sector (and thus its pressures) in the regional sea. As such, a separate network of impact chains was developed for each regional sea (see Knights *et al.*, 2013 for full details of the network model).

2.2. Assessing risk and recovery in large ecosystems

Our approach builds on a long series of antecedents of productivity susceptibility analysis (e.g. Hobday et al., 2011; Stobutzki et al., 2001; Samhouri & Levin 2012). We applied numerical scores to each qualitative assessment category (Table A2) and used combinations of the assessment criteria to describe two axes of information: *Impact Risk* and *Recovery lag* (Figure 2). Impact risk was constructed using a combination of exposure (2) and sensitivity (1) criteria, which describe the spatial extent and temporal (frequency) overlap of a sector-pressure within an ecological component, and the severity of the interaction where overlap occurs (degree of impact). These criteria were combined into the aggregate criterion, we refer to as Impact Risk, where the greater the Impact Risk score, the greater the threat to a component (Figure 2).

Recovery lag was described using the combination of pressure persistence (the number of years before the pressure impact ceases following cessation of the sector introducing it) and ecological component resilience (recovery time) following cessation of the pressure impact. This aggregate criterion gives an indication of the time required for potential improvement in ecosystem state to be seen following the management of a specific impact chain, where the greater the recovery lag value, the longer time period required for an ecological component to recovery back to its pre-impacted state (Figure 2).

As assessment criterion had a varying number of assessment categories (as many as 5 and as few as 3), scores for each category were standardised using percentage scores, where the worst case equates to a score of 1 (Table A2). Each axis receives equivalent weight in estimating threat and under this framework, the impact risk and/or recovery lag for an ecological component increases with distance from the origin. The assessment allows the ‘worst’ impact chain or chains to be identified (either in terms of impact risk and/or recovery lag) in isolation or grouped in combinations e.g. by sector or pressure.

Impact risk and recovery lag scores were calculated for each impact chain as the product (multiplication) of the assigned categorical scores (Figure 2). Impact risk and recovery lag scores were then grouped, either by sector, pressure type or ecological component and the distribution of values presented using boxplots. As the maximum score of any category was 1, impact risk (IR) or recovery lag (RL) scores can range between 0.002 and 1 (IR) or 0.01 and 1 (RL), where 1 is the worst case (Figure 3; Table A2).

3. Results

Using expert judgement, we identified and evaluated 3,347 sector-pressures that can affect the ecological components of Europe's regional seas (Robinson *et al.*, 2013). The distribution of sector-pressures was split between predominant habitat types (1,817) and mobile species, such as fish, seabirds and marine mammals (1,530) with the number of impact chains affecting each component varying between regional seas as a result of differences in the types of sectors operating in each sea, and thus the type and number of pressures introduced.

Impact risk scores were generally low, with little variation between regions irrespective of the sector or pressure considered (Figure 4). The median impact risk score per chain per region ranged from 0.003 in the Baltic and Black Seas and NE Atlantic and 0.013 in the Mediterranean Sea (see Figure 3 for possible combinations). Outliers were, however, numerous and in some cases the impact risk values exceed 0.69 indicating that the presence of acute severity, spatially widespread and persistent introductions of some pressures (Figures 3 & 4). Grouping impact chains by sector indicated that the impact risk for the majority of pressures they introduce is relatively low (<0.01)(Figure 4) indicating relatively low severity impacts and/or spatially or temporally restricted impacts. Fishing was the sector posing the greatest risk, exhibiting multiple outliers with impact risk values > 0.4 indicating numerous widespread and frequent impact chains with severe consequences. Similar outliers were common to fishing in all regional seas suggesting the impact mechanisms are the same irrespective of regional differences in the sector activities (Figure 4).

Recovery lag scores were more varied than the impact risk scores for the same sector-grouped chains. Median values were relatively low and consistent across all regions (0.0055) indicating recovery to pre-impacted within ~11 yr (Figure 3). In nearly every case, sectors introduce a pressure that impact one or more ecological components resulting in a recovery lag of 0.55 (equivalent to >100 yr to pre-impact recovery). In contrast to the impact risk scores (which were predominantly low; 99% had values < 0.05), there was greater proportion of impact chains with intermediate or high recovery lag scores of 0.3 and upward. In fact, of the 3,347 impact chains considered, 18% had a recovery lag of 0.3 (590 chains) and 6% (198 chains) of >0.55. Grouping impact chains by pressure type identified which pressures pose the greatest impact risk to the ecosystem. Median scores were low in all cases; 0.003 in the Baltic Sea and NE Atlantic, 0.011 in the Mediterranean Sea and 0.005 in the Black Sea (Figure 5). Greatest impact scores were associated with the pressure type "species extraction" (0.51-0.69) indicating widespread, common/persistent and acute impacts throughout all regions (Figure 5).

Recovery lag was highly dependent on the pressure type. Low recovery lag scores in all regions (between <0.006 and 0.01; <15 yr to recovery (Figure 3)) were associated with physical pressures such as abrasion, aggregate extraction (agg_extract), collision, noise, smothering and species extraction (spp_extract) (Figure 5). In contrast, biotic pressures (e.g. NIS), contaminant pressures (e.g. radionuclides, marine litter), and hydrological pressures (e.g. water flow regimes, wave exposure) were characterised by higher recovery lag scores, many of which equal to 0.55 (Figure 5) indicating >100 yr to recovery if the pressure were stopped. In some cases, there was little difference in recovery lag associated with a particular pressure type between regional seas (e.g. non-synthetic or synthetic contaminants). For other pressure types, such as nitrogen and phosphorus enrichment (N&P) and barriers to species movement (Barriers), there were marked differences between regions, where recovery lag scores were high in one region (Baltic Sea, N&P), but very low in others (Figure 5), due to differences in the susceptibility of different ecological components i.e. recover potential, and the persistence that pressure type in that region.

Grouping impact chains by ecological components indicated that many sector-pressure combinations are low impact risks (Figure 6). There were, however, a greater number of outliers in comparison to groupings by sector or pressure indicating variability in the impact of specific sector-pressure combinations on an ecological component. In many of these cases, impact risk scores exceeded 0.5 (acute, widespread and common or persistent) and the majority of ecological components impacted by an acute severity impact chain that is either locally persistent or occasionally widespread (0.28).

Recovery lags of the ecological components in different regional seas were largely comparable with few outliers, and were dependent on the ecological component impacted (Figure 6). For mobile species (i.e. seabirds, deep sea habitats and fish, demersal and pelagic fish and marine mammals and reptiles), recovery lag was highly variable due to differences in the impact mechanisms of specific sector-pressure combinations. In some cases, recovery from some sector-pressure combinations was predicted to take >100 yr (RL = 0.55), although median values ranged between 12 yr (0.006) and 90 yr (0.3). Predominant habitats were in marked contrast, with median recovery predicted to take between 1 (0.0001) and 10 yr (0.004) up to a maximum of ~40 yr (0.06) in worst case examples. In one exception, demersal fish in the Black Sea are predicted to recovery more quickly than the same component in other regional seas.

In addition or instead of considering all impact chains in a holistic assessment, the impact of a single sector (grouped by pressure type) on the ecosystem can be singled-out for assessment. We illustrate this using the sector 'fishing' and the ecological component, 'sublittoral sediment', although data can be grouped by any sector, pressure type or ecological component. Fishing introduces a suite of 13 different pressure types, many of which were relatively low in impact, and from which, the ecosystem is able to recover quickly (Figure 7). Unsurprisingly, species extraction (spp_extract) is the pressure type with the greatest impact risk, but noting that the recovery lag of the ecosystem to this pressure type is estimated to be relatively fast (median = 0.0055; equivalent to ~11 yr for recovery (Figure 3)), driven by the low persistence of this pressure despite relatively low resilience scores for some ecological components. Conversely, several pressures were characterised as relatively low in terms of impact risk, but with high recovery lag scores (e.g. non-indigenous species (NIS), and marine litter), driven by the difficulties of eradicating invasive species (Galil, 2003).

Grouping impact chains by sector or pressure for a single ecological component can be used to illustrate specific risks. Focusing on sublittoral sediments (Figure 8), the impact risk from the majority of sectors is low, although some sectors such as aggregate extraction, aquaculture, fishing and navigational dredging introduce impact chains of higher risk. Fishing, in particular, introduces impact chains of especially high risk in the Baltic Sea, Mediterranean Sea and NE Atlantic regions, indicating widespread, frequent and severe interactions with the seafloor as a result of this sector. Grouping by pressure type revealed the pressures driving those high impact scores i.e. aggregate extraction and species extraction, and pressures of particular regional importance such as sealing in the Mediterranean Sea (a pressure linked to a number of sectors such as coastal infrastructure and tourism-recreation) (Figure 8).

4. Discussion

We have illustrated how a generic exposure-effect framework can be used to assess the risk to and recovery of ecosystems from human activities at a scale relevant to current environmental policy. We do this using two datasets: one that describes the relationships (linkages) between sectors, pressures and ecological components of regional sea ecosystems (Knights et al., 2013), and two, a qualitative assessment of each linkage using an expert judgement approach (Robinson *et al.*, 2013). The result is two axes of information describing: (1) Impact Risk - the likelihood of a negative interaction between a sector and the environment (via the pressure mechanism) and its severity, and (2) Recovery Lag - the post-impact rate of recovery to pre-impact condition. The assessment reveals that in many cases, the impact risk from sector activities is relatively low, but there are a number of impact chains introduced by several sectors of high impact risk and potentially causing significant harm to the marine environment. Recovery from impact was more variable, but indicated that in many cases, recovery to pre-impact conditions may require many years for some ecological components.

Our framework adopted perhaps the most extensive description of links between human activities and the ecosystem to date (Knights *et al.*, 2013; Koss *et al.*, 2011). The holistic assessment is therefore relevant to environmental policy and conservation objectives that require an ecosystem approach (McLeod and Leslie, 2009). Here, more than 3,500 impact chains were considered forming a complex network of linkages (Knights *et al.*, 2013), which was simplified by grouping chains by “sector”, “pressure type” or “ecological component”. We presented the results in two ways to demonstrate the flexibility of the approach to identify the impact chains posing the greatest risk and/or slowest recovery. Firstly, in broad terms considering all sectors, pressures and ecological components, then secondly, in a more targeted way wherein risk and recovery from a specific sector’s impacts or to a single ecological component were assessed. The criteria used to assess each impact chain were relatively coarse (Robinson *et al.*, 2013), but changes in impact risk/recovery lag could be differentiated within and between groupings (e.g. sector, pressure type, component), allowing managers to identify and prioritise impact chains for management in terms of their impact risk (Bottrill *et al.*, 2008), as well as giving a clear understanding of the expected time frame for recovery if management is effectively implemented, enforced and complied with (Knights *et al.*, 2014b). Given that management resources are often finite and therefore insufficient to address all issues (Joseph et al., 2009), the framework therefore can act as a decision-support tool (Fletcher, 2005). Managers can defend management trade-off decisions based on scientific evidence linked to a specific conservation objective and identify the societal and economic costs and benefits of that decision from the outset; both of which deemed critical components to the success of an ecosystem approach (Knights *et al.*, 2014a; Altman *et al.*, 2011).

The risk assessment was underpinned by a structured expert judgement analysis of linkages, which is effective for achieving consensus between groups of individuals (Cooke and Goossens, 2004). A significant benefit of such an approach is that it can be applied in all systems; even those that are data poor, and undertaken at relatively low financial cost to the stakeholder (Fletcher et al., 2010). This is of particular value to regions such as the Mediterranean Sea and Black Sea where they not only face the challenge of implementing EBM as obligated under regional sea environmental policy, but have the added complication that the resources (e.g. stocks that straddle international boundaries) are also exploited by stakeholders not bound by the same environmental regulations or ambition levels, which may counteract any management measure(s) implemented by the EU Member State(s) (Stokke, 2000). To counteract the uncertainty surrounding the exploitation of resources by non-EU stakeholders, the assessment can be undertaken using a precautionary approach, and use data such as anecdotal evidence to support the pressure evaluation in lieu of empirical data. A manager is then not precluded from making an assessment of regional priorities, but includes uncertainty such that risk to ecosystems is not underestimated.

We applied the risk assessment to the suite of sectors, pressures and broad ecological components that are common to global marine ecosystems; the ecological components assessed are representative of a healthy ecosystem (Costanza and Mageau, 1999) and have been identified as relevant characteristics of Good Environmental Status (GES) under the Marine Strategy Framework Directive. We can therefore interpret directly from our analysis the risk to the ecosystem from different sectors (Fletcher et al., 2010; Samhouri and Levin, 2012). Application of the risk assessment framework identified the sectors and pressures that are recognised as primary drivers of change in the ecosystem and its components. There were cross-regional similarities in risk and included well-recognised primary sector drivers of ecosystem change such as commercial fishing (e.g. Coll et al., 2010; Piet and Jennings, 2005) and coastal infrastructure (Bulleri and Chapman, 2009), and perhaps less well-recognised sectors such as navigational dredging (Suedel *et al.*, 2008) and tourism (Davenport and Davenport, 2006). Many of the pressure types with higher risk scores are also well recognised, such as selective extraction from fishing (Pauly et al., 1998) and nitrogen and phosphorus run-off from agriculture (Zillen et al., 2008). These were linked to high-risk sectors (e.g. Graneli et al., 1990; Smayda, 1990), which is unsurprising given that direct links can be made between sector-pressures and ecological components (Knights et al., 2013; Liu et al., 2007). As the underlying assessment of the linkages (Robinson *et al.*, 2013) considered prevailing conditions, results indicate that the regulation of some sector activities have failed to limit their impact as intended (e.g. Khalilian et al., 2010) and elsewhere, harmful impacts have been ignored (Walker *et al.*, 2003).

The assessment was also able to identify and prioritise sectors and pressures that are of region-specific concern. For example, in the Baltic Sea, the effects of Nitrogen and Phosphorus enrichment (N&P) are long-lasting (Figure 2). While direct impacts on ecosystem components are relatively low risk, indirect effects are numerous and of greater concern but which were not assessed here. Nutrient enrichment by persistent point source introductions coupled with extremely low turnover rates in soils and sediments has led to nutrients being released for decades beyond cessation of discharges in the Baltic Sea region (HELCOM, 2010) and can have lasting effects on many characteristics of the ecosystem (Diaz and Rosenberg 2008; Graneli et al. 1990; Moncheva et al. 2001; Smayda 1990). As such, eutrophication is a heavily targeted issues in the Baltic Sea, with management in place to limit or prevent further introductions of nutrients (HELCOM, 2010).

The number of high-risk impact chains introduced by different sectors reinforces the need for holistic management, which adopts a combination of management measures to achieve the objectives of the ecosystem approach (Knights et al., 2013; Tallberg, 2002). The protection of some components is likely to be easier to achieve than for others (Khalilian et al., 2010). For example, an improvement in sublittoral habitat state (Figure 8) would likely require management of fishing, aggregates, aquaculture, navigational dredging and research (including scientific research and bio-prospecting) sectors (Figure 8), whereas pelagic fish species are threatened by fishing, tourism, research and aquaculture. Reductions in risk would therefore likely require different (and most likely more complex) levels of control. Identifying combinations of management measures to reduce risk are outside the scope of this paper (see Piet et al. submitted to this journal for such an assessment), but the analysis does indicate that the complexity of management strategies required to reduce risk will be dependent, not only on the region, but also the conservation objective. Although not undertaken here, the approach could be used to evaluate management strategies by assessing the reduction in risk to the ecosystem or targeted characteristics. Risk reductions could be achieved in several ways via changes in exposure or sensitivity or a combination of the two (Smith et al., 2007). Managers would then be able to make trade-offs and develop more socially acceptable management strategies (Hassan et al., 2005), which can lead to greater compliance (Tallberg, 2002), a reduction in enforcement costs (Sutinen and Soboil, 2003) and an increased likelihood of reaching the environmental objective.

A limitation of the approach was that intensity was not explicitly included within the pressure assessment, although part of the definition of the sensitivity criterion “degree of impact” (see Robinson et al., In prep for a full description). This was reflected in the regional assessments by identification of the pressures “Introduction of synthetic compounds” and “Introduction of non-synthetic compounds” as higher recovery lag issues (Figure 5). Although both pressure types have the potential to cause widespread and catastrophic impacts when and where they occur (Korpinen et al., 2012; Peterson et al., 2003), the intensity of introduction tends to be relatively low and generally fails to exceed the concentration required for adverse impacts (see low impact risk scores; Figure 5) despite widespread, low-intensity introductions being common (Robinson et al., In prep). The assessment is therefore precautionary, in that some of the issues highlighted may not be of immediate concern unless a rare or catastrophic event was to occur (Peterson et al., 2003).

Limited fiscal resources, ever increasing demands for resources (Hallerberg et al., 2007; Halpern et al., 2008) and the complex relationship between humans and their environment (Liu et al., 2007) are significant challenges to ecosystem-based management. Risk assessment is gaining momentum as a decision-support tool that allows managers and policy makers to prioritise human drivers of environmental change (Fletcher, 2005; Fletcher et al., 2010; Hobday et al., 2011; Samhouri and Levin, 2012), and makes a fundamental contribution toward ecosystem-based management objectives. The development of a reliable risk assessment has been challenging because of the inherent complexity associated with multiple sectors targeting multiple ecosystem characteristics (resources) making attributing risk to specific sectors and their activities difficult. The approach illustrated here provides a rapid, structured, transparent assessment of current risk to ecosystems so that resource managers on the national, international or regional-stage can identify the most harmful activities and potential management measures suggested and corresponding science-based timeframes for improvement such that confidence in the stewardship of resources by managers is built (Knights et al., 2014). Coupled with an evaluation of the costs and benefits regarding the impact of a measure on the environment, societal and economic metrics (Hassan et al., 2005) will increase the likelihood that the overarching objective of ecosystem-based management – sustainable use – is achieved.

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Figure Legends

Figure 1. Regional Sea areas of Europe as defined by the Marine Strategy Framework Directive (light grey areas indicate the spatial coverage of the directive). Impact chains were assessed at the scale of the region for the NE Atlantic, Baltic Sea, Black Sea and Mediterranean Sea. Exclusive economic zone (EEZ) borders are shown.

Figure 2. Exposure-effect assessment criteria used in the calculation of risk and recovery lag. Criteria definitions are given in Robinson et al. (2013). Definitions: *Impact risk* is a measure of the likelihood of an adverse ecological impact occurring following a sector-pressure introduction. The greater the impact risk, the greater the likelihood and severity of an impact. An adverse impact is defined as a negative effect on the state of the ecosystem component, but the state or reduction in state as a result of the impact are not defined. *Recovery lag* is a measure of management potential given the persistence of a pressure and resilience of the impacted ecological component. Recovery lag is defined as the time (yr) it takes for an ecological component to return to pre-impacted condition.

Figure 3. Impact risk and recovery lag scores for all possible combinations of the assessment criteria. Impact risk scores are log (LN) transformed. Significant regressions are shown (Impact Risk - $y = 0.68 \cdot e^{-0.24x}$ ($R^2 = 0.98$, $p < 0.01$); Recovery Lag - $y = 1.98 \cdot e^{-0.55x}$ ($R^2 = 0.96$, $p < 0.01$)). Assessment criteria categories are given in Table S2. Inset: The relationship between recovery lag scores and minimum years to recovery based on category definitions shown in Table S2. A significant regression is shown; $y = 174.56 \cdot x^{0.523}$ ($R^2 = 0.69$, $p < 0.05$).

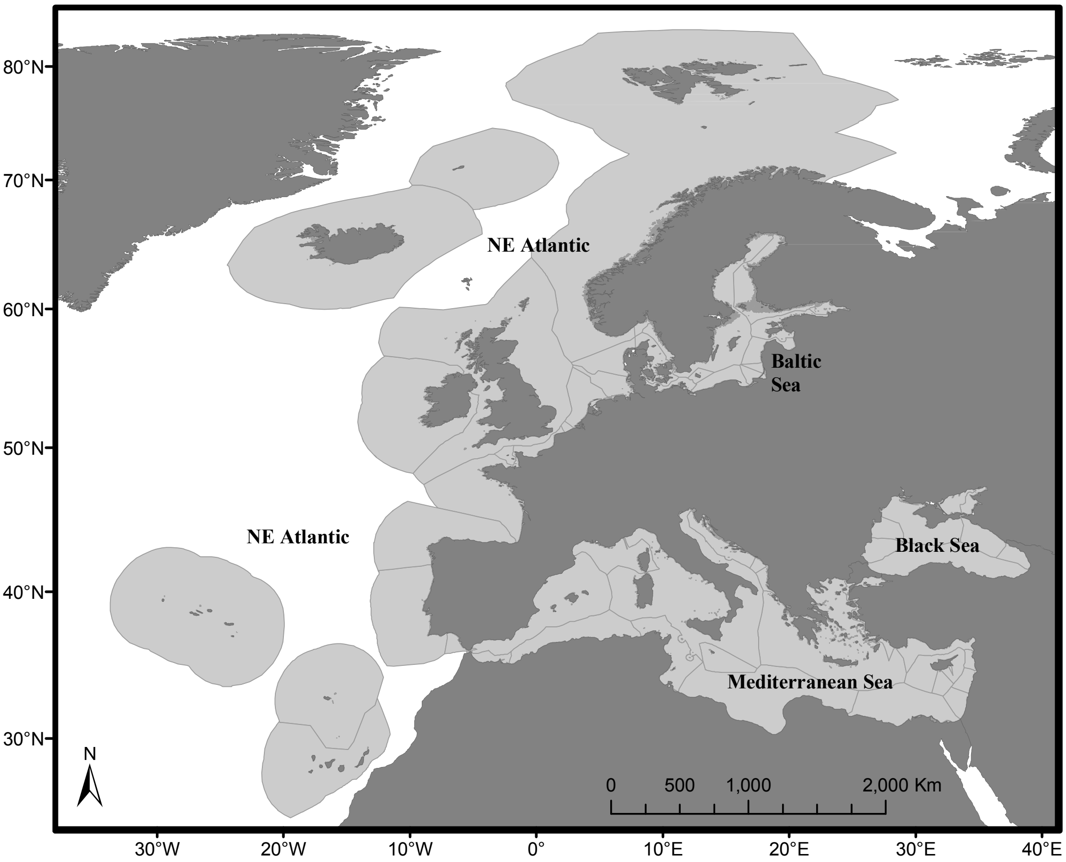
Figure 4. Distribution of impact risk and recovery lag scores grouped by sector in each of four European regional seas (Baltic Sea – green; Black Sea – yellow; Mediterranean Sea – orange; NE Atlantic – grey). The maximum impact risk and recovery lag score for any chain is 0.7 and 1.0 respectively. Blank regions indicate the absence of the sector in this region. Middle lines of boxplots represent median values; hinge lengths (end of box) represent 25% quartiles from the median; whiskers represent 1.5 times the interquartile range (IQR) beyond the hinge. Outliers are shown as black dots. The same format applies to subsequent boxplots.

Figure 5. Distribution of impact risk and recovery lag scores grouped by pressure type in each of four European regional seas (Baltic Sea – green; Black Sea – yellow; Mediterranean Sea – orange; NE Atlantic – grey). The maximum impact risk and recovery lag score for any chain is 0.7 and 1.0 respectively. The blank value indicates the absence of the pressure in this region. Boxplot information is given in the legend of Figure 4.

Figure 6. Distribution of impact risk and recovery lag scores grouped by ecological component in each of four European regional seas (Baltic Sea – green; Black Sea – yellow; Mediterranean Sea – orange; NE Atlantic – grey). The maximum impact risk and recovery lag score for any chain is 0.7 and 1.0 respectively. Blank values indicate the ecological component is not present in this region. Boxplot information is given in the legend of Figure 4.

Figure 7. Distribution of impact risk and recovery lag scores to all ecological components from fishing grouped by pressure in each of four European regional seas (Baltic Sea – green; Black Sea – yellow; Mediterranean Sea – orange; NE Atlantic – grey). The maximum impact risk and recovery lag score for any chain is 0.7 and 1.0 respectively. Boxplot information is given in the legend of Figure 4.

Figure 8. Distribution of impact risk and recovery lag scores to sublittoral sediments grouped by sector and pressure in each of four European regional seas (Baltic Sea – green; Black Sea – yellow; Mediterranean Sea – orange; NE Atlantic – grey). Sectors/pressures posing no risk are excluded from the plot. The maximum impact risk score for any chain is 0.7. Boxplot information is given in the legend of Figure 4.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70°N
60°N
50°N
40°N
30°N
NE Atlantic
NE Atlantic
Baltic Sea
Black Sea
Mediterranean Sea
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30°W
20°W
10°W
0°
10°E
20°E
30°E
40°E

Figure 1

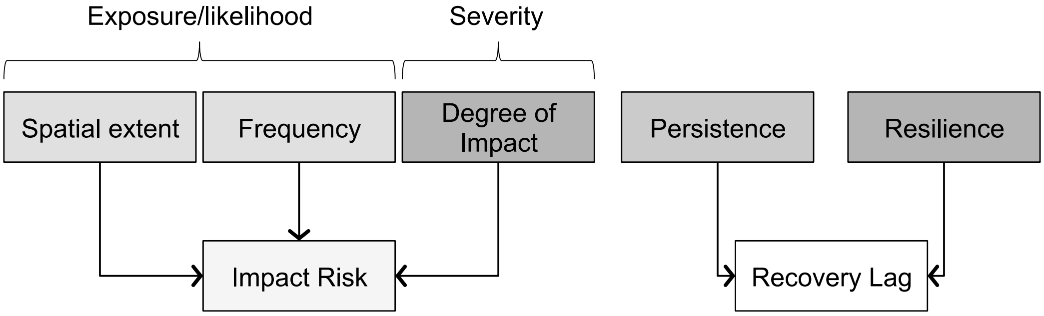

Exposure/likelihood
Severity
Spatial extent
Frequency
Degree of Impact
Persistence
Resilience
Impact Risk
Recovery Lag

Figure 2.

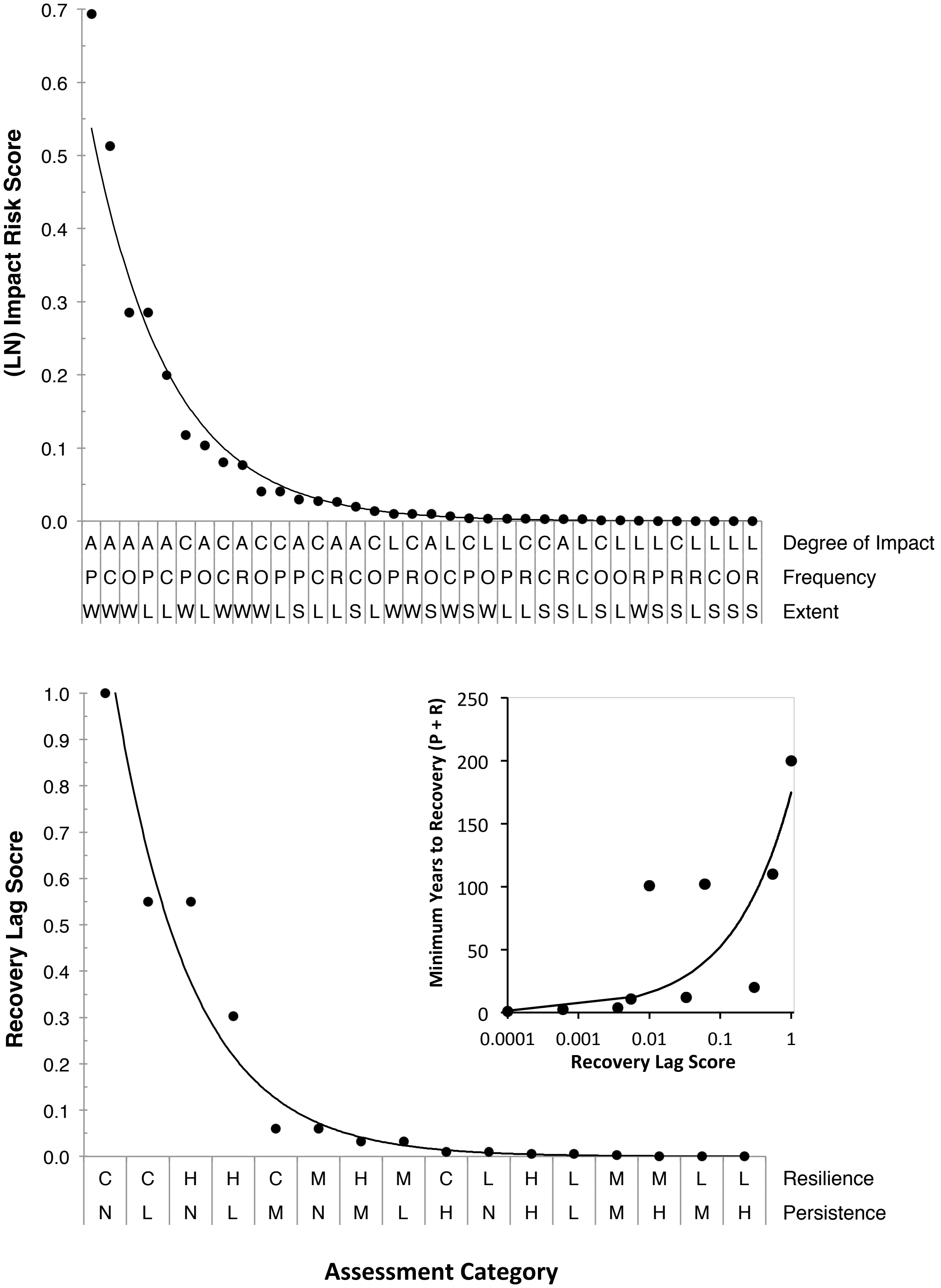
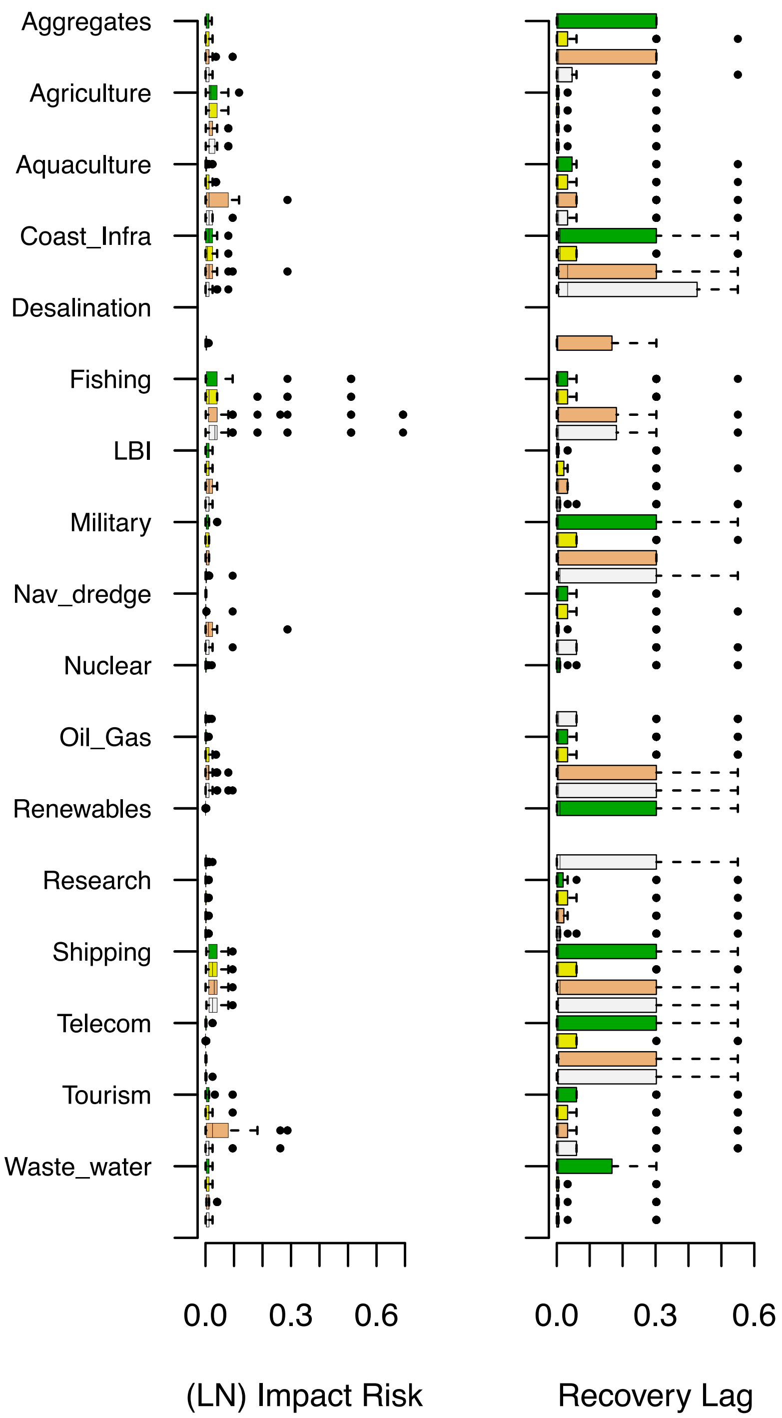

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
(LN) Impact Risk Score
A A A A A C A C A C C A C A A C L C A L C L L C C A L C L L L C L L L L
P C O P C P O C R O P P C R C O P R O C P O P R C R C O O R P R R C O R
W W W L L W L W W W L S L L S L W W S W S W L L S S L S L W S S L S S S
Degree of Impact
Frequency
Extent
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Recovery Lag Socre
C C H H C M H M C L H L M M L L
N L N L M N M L H N H L M H M H
Resilience
Persistence
250
200
150
100
50
0
Minimum Years to Recovery (P + R)
0.0001
0.001
0.01
0.1
1
Recovery Lag Score
Assessment Category

Figure 3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Aquaculture
Coast_Infra
Desalination
Fishing
LBI
Military
Nav_dredge
Nuclear
Oil_Gas
Renewables
Research
Shipping
Telecom
Tourism
Waste_water
0.0
0.3
0.6
(LN) Impact Risk
0.0
0.3
0.6
Recovery Lag

Figure 4.

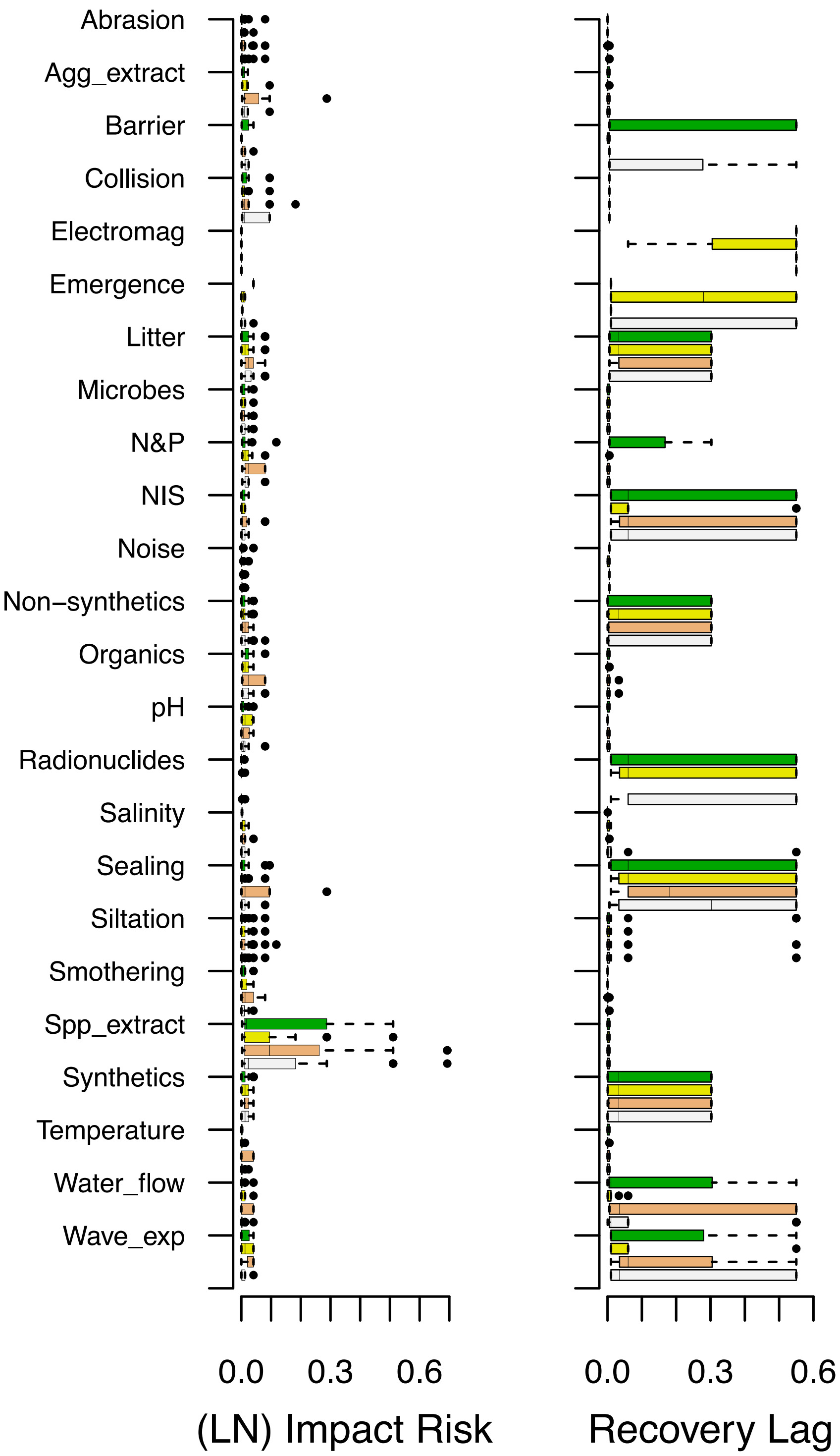
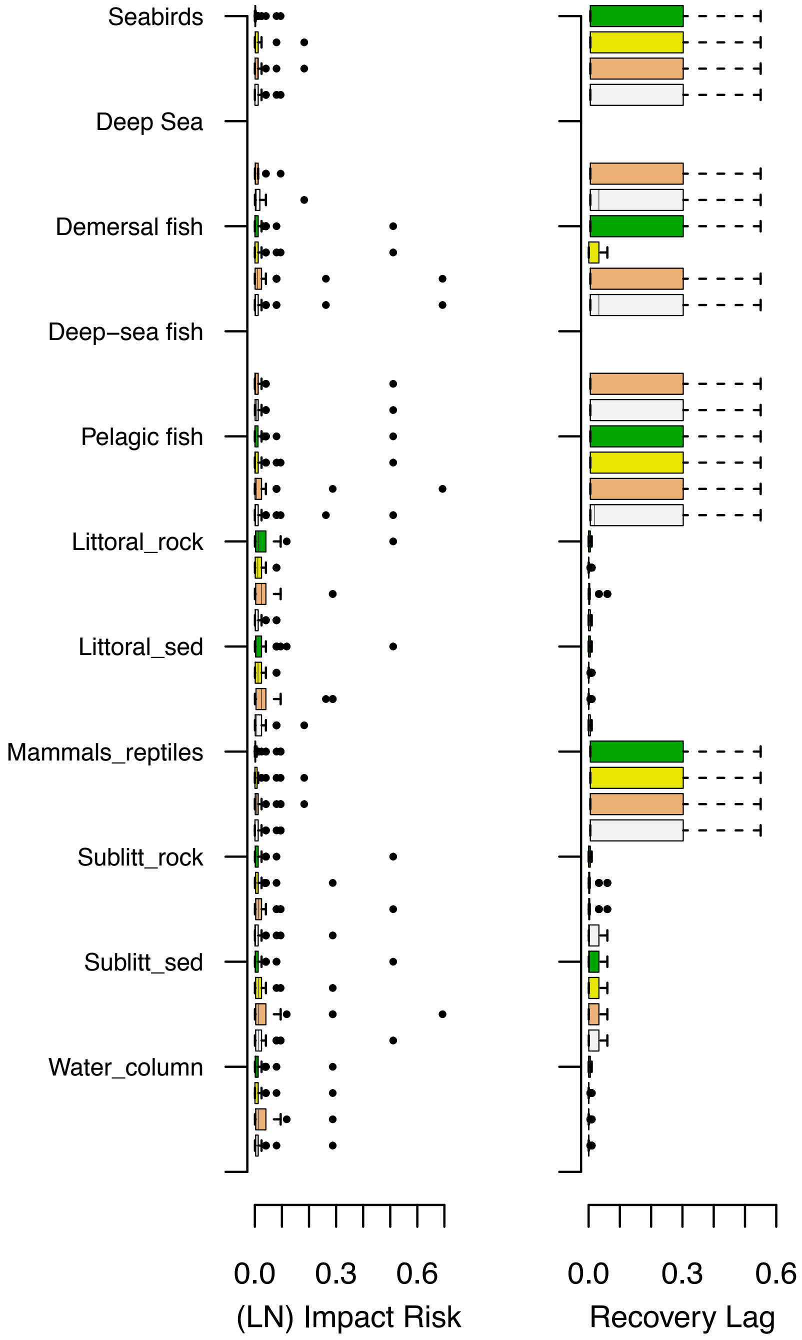

Abrasion
Agg_extract
Barrier
Collision
Electromag
Emergence
Litter
Microbes
N&P
NIS
Noise
Non−synthetics
Organics
pH
Radionuclides
Salinity
Sealing
Siltation
Smothering
Spp_extract
Synthetics
Temperature
Water_flow
Wave_exp
0.0
0.3
0.6
(LN) Impact Risk
0.0
0.3
0.6
Recovery Lag

Figure 5.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Deep Sea
Demersal fish
Deep–sea fish
Pelagic fish
Littoral_rock
Littoral_sed
Mammals_reptiles
Sublitt_rock
Sublitt_sed
Water_column
0.0
0.3
0.6
(LN) Impact Risk
0.0
0.3
0.6
Recovery Lag

Figure 6.

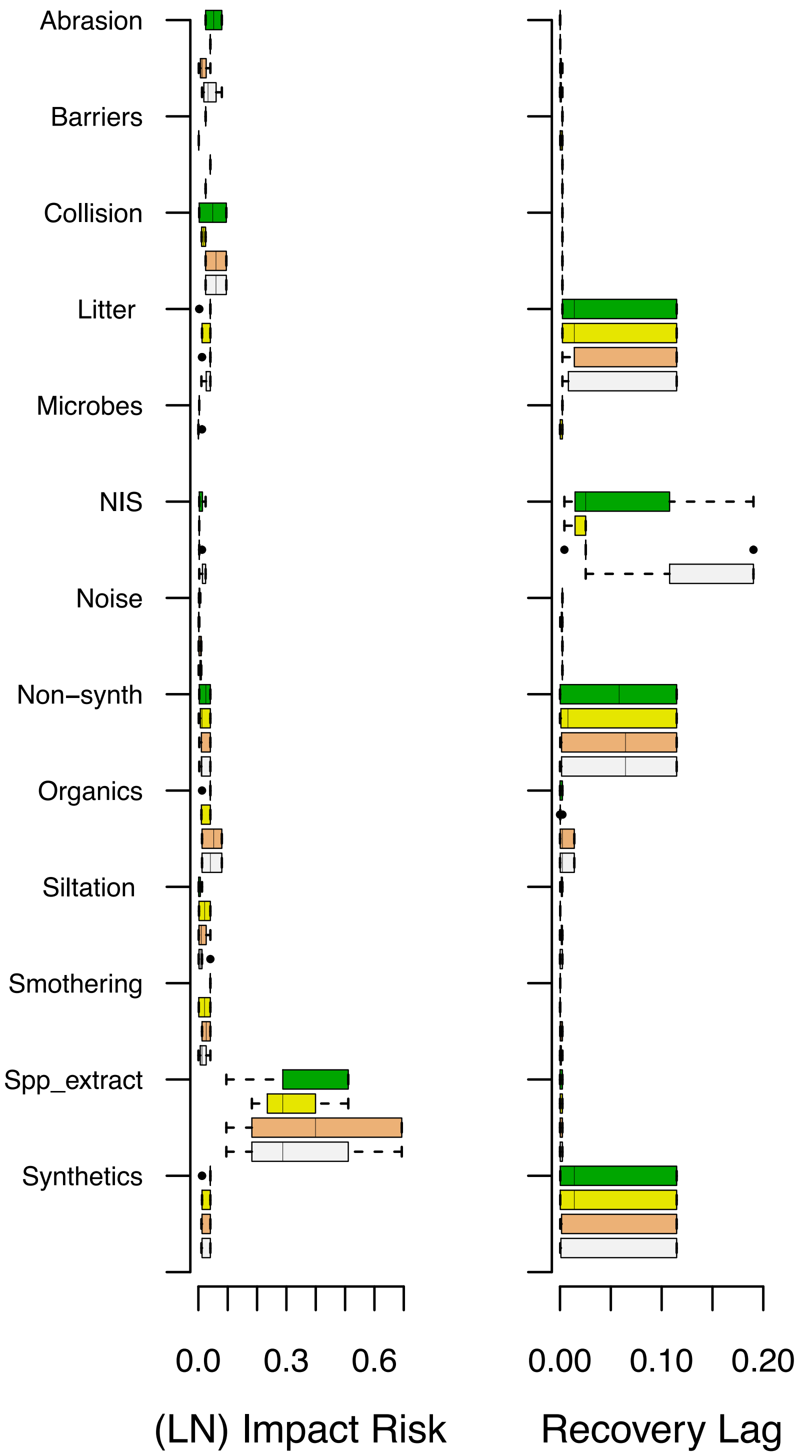
Abrasion
Barriers
Collision
Litter
Microbes
NIS
Noise
Non−synth
Organics
Siltation
Smothering
Spp_extract
Synthetics
0.0
0.3
0.6
(LN) Impact Risk
0.00
0.10
0.20
Recovery Lag

Figure 7.

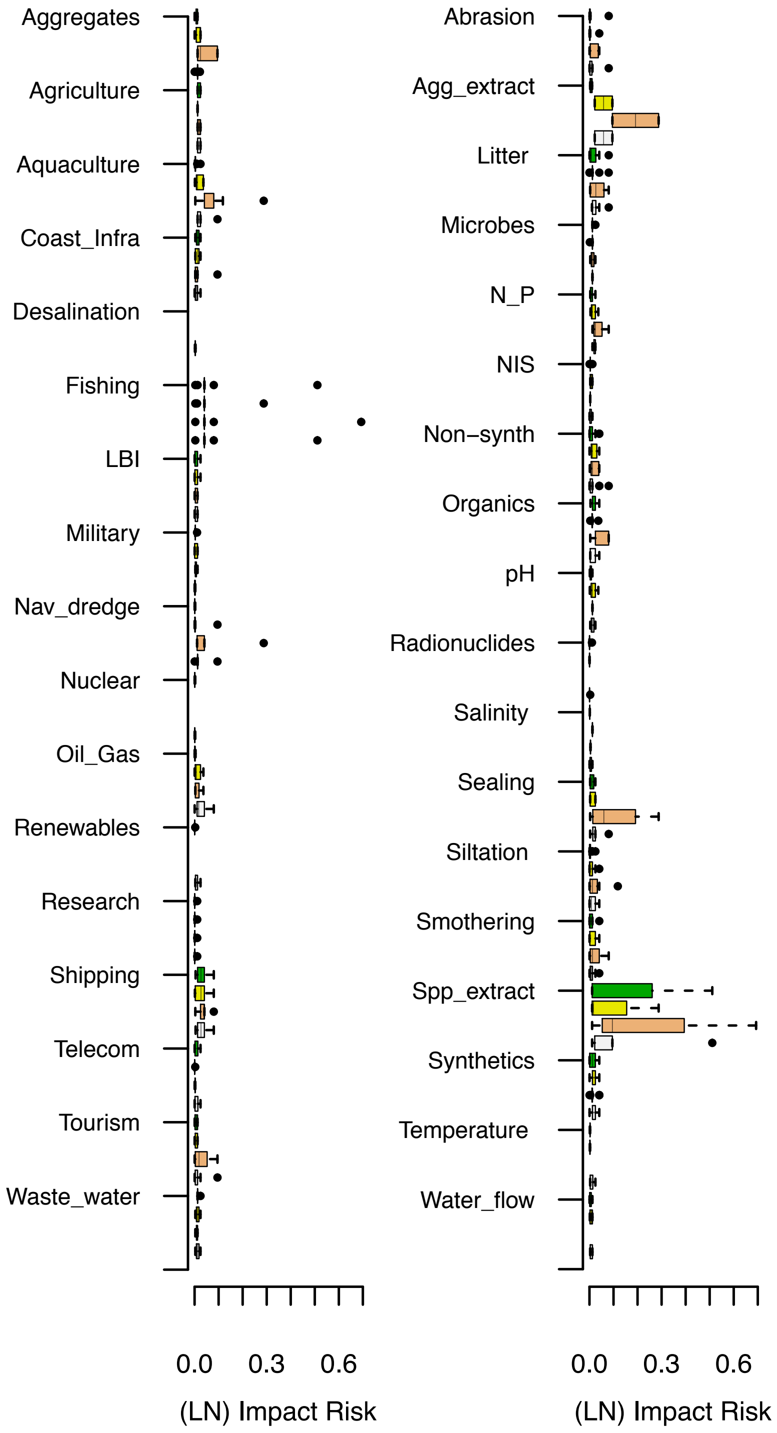
Aggregates
Agriculture
Aquaculture
Coast_Infra
Desalination
Fishing
LBI
Military
Nav_dredge
Nuclear
Oil_Gas
Renewables
Research
Shipping
Telecom
Tourism
Waste_water
0.0
0.3
0.6
(LN) Impact Risk
Abrasion
Agg_extract
Litter
Microbes
N_P
NIS
Non−synth
Organics
pH
Radionuclides
Salinity
Sealing
Siltation
Smothering
Spp_extract
Synthetics
Temperature
Water_flow
0.0
0.3
0.6
(LN) Impact Risk

Figure 8.

Table Legends (Supplemental material)

Table A1. List of sectors, pressure types and ecological characteristics included in the risk assessment and evaluated using the ODEMM pressure assessment. Abbreviations used in figures are shown in brackets (where applicable).

Table A2. The pressure assessment criteria and categories used to evaluate each impact chain (after Robinson et al., 2013) and the numerical risk scores assigned to each category.

Table A1. List of sectors, pressure types and ecological characteristics included in the risk assessment and evaluated using the ODEMM pressure assessment. Abbreviations used in figures are shown in brackets (where applicable). **No links between sector, pressure type and ecological components are inferred**.

Sector	**Pressure Type**	**Ecological Components**
Aggregate Extraction (Aggregates)	**Abrasion** – the interaction of human activities with the seafloor and with seabed fauna/flora	**Predominant Habitat** • Littoral rock (Littoral_rock) • Littoral sediment (Littoral_sed) • Sublittoral rock (Sublitt_rock)* • Sublittoral sediment (Sublitt_sed) • Deep Sea§ (Deep Sea)
Agriculture	**Barrier to species movement** (Barrier) - e.g. due to barrages, causeways, wind turbines etc.	**Fish** • Demersal • Pelagic • Deep sea$^{\$}$
Aquaculture	**Change in wave exposure** (Wave_exp) - e.g. regionally due to climate change, or more locally due to coastal structures)	**Marine mammals & Reptiles** (Mammals_reptiles)
Coastal Infrastructure (Coast_Infra)	**Changes in Siltation** (Siltation) - e.g. suspended sediments in the water column from runoff, dredging etc.	**Seabirds**
Desalination *(Mediterranean Sea only)*	**Death or Injury by Collision** (Collision) - e.g. bird strikes with wind turbines, collision with vessels etc.	▨

Sector	Pressure Type	Ecological Components
Fishing	**Electromagnetic changes** (Electromag) - e.g. due to underwater cables	▨
Land-based Industry (LBI)	**Emergence regime changes** (Emergence) - e.g. widespread sea level rise due to climate change or local due to barrages etc.	▨
Military	**Input of organic matter** (Organics) - organic enrichment e.g. from industrial and sewage effluent into rivers and coastal areas, from aquaculture etc.)	▨
Navigational Dredging (Nav_dredge)	**Introduction of non-indigenous spp. and translocations** (NIS)	▨
Non-renewable Energy (Nuclear**)** *(NE Atlantic and Baltic Sea only)*	**Nitrogen and phosphorus enrichment** (N&P) - input of fertilisers, and other N & P rich substances	▨
Non-renewable Energy (Oil & Gas) (Oil_Gas)	**Marine Litter** (Litter)	▨
Renewable Energy (Windfarms) (Renewables) *(NE Atlantic and Baltic Sea only)*	**pH changes** (pH) - widespread due to climate change or local due to e.g. Runoff from land-based industry)	▨

Sector	**Pressure Type**	**Ecological Components**
Research	**Salinity regime changes** (Salinity) - e.g. Regionally due to climate change, or locally due to constructions affecting water flow)	
Shipping	**Selective extraction of non-living resources on seabed and subsoil** (Agg_extract) - e.g. sand or gravel extraction, exploration of subsoil	
Telecom	**Selective extraction of species** (Spp_extract) - including incidental non-target catch e.g. by commercial fishing, recreational angling and collecting/harvesting	
Tourism/ Recreation (Tourism)	**Smothering** - by man-made structures or disposal of materials to the seafloor)	
Waste Treatment (Waste_water)	**Sealing** - sealing by permanent construction, e.g. coastal defences, wind turbines	
	Thermal regime changes (Temperature) - e.g. Due to climate change, or more locally due to outfalls etc.)	
	Underwater noise (Noise) - e.g. from shipping, acoustic surveys, drilling, pile driving etc.	
	Water flow rate changes (Water_flow) - e.g. Widespread change in currents due to climate change or local changes due to barrages etc.)	
	Introduction of Synthetic compounds (Synthethics) - e.g. pesticides, anti-foulants,	

Sector	Pressure Type	Ecological Components
	pharmaceuticals	
	Introduction of Non-synthetic compounds (Non-synthetics) - e.g. heavy metals, hydrocarbons	
	Introduction of microbial pathogens (Microbes)	

[§] Deep-sea predominant habitat was not assessed in the Black Sea because it is classified as a "dead zone" (Diaz and Rosenberg 2008)

[§] Deep-sea predominant habitat was not assessed in the Baltic Sea due to its limited geographic size.

[$] Deep-sea fish species are not found in the Baltic or Black Sea and are therefore excluded.

Table A2. The pressure assessment criteria and categories used to evaluate each impact chain (after Robinson et al., 2013) and the numerical risk scores assigned to each category.

Extent Category	**Description** The spatial extent of overlap between a pressure type and ecological characteristic	**Raw value (% overlap)**	**Standardised value (proportion of max)**
Widespread	Where a sector overlaps with an ecological component by 50% or more.	75	1.00
Local	Where a sector overlaps with an ecological component by >5% but <50%. Taken the mean of the two values i.e. 30%	22.5	0.30
Site	Where a sector overlaps with an ecological component by >0% but <5%. Taken the mean of the two values i.e. 5%	2.5	0.03

Frequency Category	**Description** How often a pressure type and ecological characteristic interaction occurs measured in months per year	**Months per year**	**Standardised value (proportion of max)**
Persistent	Where a pressure is introduced throughout the year	12	1.00
Common	Where a pressure is introduced in 8 months of the year	8	0.67
Occasional	Where a pressure is introduced in 4 months of the year	4	0.33
Rare	Where a pressure is introduced in 1 month per year	1	0.08

Degree of Impact Category	**Description** An Acute (A) interaction is an impact that kills a high proportion of individuals and causes an immediate change in the characteristic feature. A Chronic (C) interaction is an impact that could have detrimental consequences if it occurs often enough and/or at high enough levels. A Low severity (L) interaction never causes high levels of mortality, loss of habitat or change in the typical species or functioning irrespective of the frequency and extent of the event(s).	**Severity per interaction**	**Standardised value (proportion of max)**
Acute	Severe effects after a single interaction	1	1.00
Chronic	Severe effects occur when Frequency of introductions more than common (>8)	0.125	0.13
Low	Severe effect not expected. For precautionary reasons, we assume a potential effect after 100 introductions.	0.01	0.01

Persistence Category	**Description**	**Persistence (yr)**	**Standardised value (proportion of max)**
	The time period over which the pressure continues to cause impact following cessation of the activity introducing that pressure.		
Continous	The pressure continues to impact the ecosystem for more than 100 yrs	100	1.00
High	The pressure continues to impact the ecosystem for between 10 and 100 yrs. I have taken the mean value of the maxima and minima given the range is so large	55	0.55
Moderate	The pressure continues to impact the ecosystem for between 2 and 10 yrs	6	0.06
Low	The pressure continues to impact the ecosystem for between 0 and 2 yrs	1	0.01

Resilience Category	**Description**	**Recovery (yr)**	**Standardised value (proportion of max)**
	The resilience (recovery time) of the ecological characteristic to return to pre-impact conditions. Recovery times for species assessments were based on turnover times (e.g. generation times). For predominant habitat assessments, recovery time was the time taken for a habitat to recover its characteristic species or features given prevailing conditions.		
None	The population/stock has no ability to recover and is expected to go "locally" extinct. The recovery in years is therefore very high to reflect the unlikely recovery	100	1.00
Low	The population will take between 10 and 100 yrs to recover. I have taken the mean value of the maxima and minima given the range is so large	55	0.55
Moderate	The population will take between 2 and 10 yrs to recover.	6	0.06
High	The population will take between 0 and 2 yrs to recover.	1	0.01