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

Knights, Antony

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3

4 **Authors:** Antony M. Knights<sup>1\*,§</sup>, Gerjan J. Piet<sup>2§</sup>, Ruud H. Jongbloed<sup>2§</sup>, Jacqueline E. Tamis<sup>2,§</sup>, Lydia  
5 White<sup>3</sup>, Ekin Akoglu<sup>4</sup>, Laura Boicenco<sup>5</sup>, Tanya Churilova<sup>6</sup>, Olga Kryvenko<sup>6</sup>, Vivi Fleming-Lehtinen<sup>7</sup>,  
6 Juha-Markku Leppanen<sup>7</sup>, Bella S. Galil<sup>8</sup>, Freya Goodsir<sup>9</sup>, Menachem Goren<sup>10</sup>, Piotr Margonski<sup>11</sup>,  
7 Snejana Moncheva<sup>12</sup>, Temel Oguz<sup>13</sup>, K. Nadia Papadopoulou<sup>14</sup>, Outi Setälä<sup>7</sup>, Chris J. Smith<sup>14</sup>,  
8 Kremena Stefanova<sup>6</sup>, Florin Timofte<sup>5</sup>, and Leonie A. Robinson<sup>3§</sup>

9

10 **Affiliation:**

11 <sup>1</sup>Marine Biology and Ecology Research Centre, Plymouth University, School of Marine Science and  
12 Engineering, Drake Circus, Plymouth, PL4 8AA. UK.

13 <sup>2</sup>Institute for Marine Resources and Ecosystem Studies (IMARES), Haringkade 1, 1976 CP, IJmuiden.  
14 The Netherlands.

15 <sup>3</sup>School of Environmental Sciences, University of Liverpool, Nicholson Building, Liverpool. L69 3GP.  
16 UK.

17 <sup>4</sup>Instituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Borgo Grotta Gigante 42/C,  
18 Sgonico, Italy.

19 <sup>5</sup>National Institute for Marine Research and Development "Grigore Antipa", 900581 Constanta,  
20 Romania.

21 <sup>6</sup>A.O. Kovalevskiy Institute of Biology and Southern Seas. National Academy of Sciences of Ukraine 2,  
22 Nakhimov Av., Sevastopol, 99011 Crimea, Ukraine.

23 <sup>7</sup>Marine Research Centre, Finnish Environment Institute (SYKE), PO Box 140, FI-00251, Helsinki,  
24 Finland.

25 <sup>8</sup>National Institute of Oceanography, Israel Oceanographic & Limnological Research (NIO-IOLR), Tel  
26 Shikmona, 21080 Haifa, Israel.

27 <sup>9</sup>Cefas, Pakefield Road, Lowestoft, Suffolk, NR33 0HT. UK

28 <sup>10</sup>Department of Zoology, Tel Aviv University, Tel Aviv 69778, Israel.

29 <sup>11</sup>Department of Fisheries Oceanography and Marine Ecology, National Marine Fisheries Research  
30 Institute, ul. Kollataja 1, 81-332, Gdynia, Poland.

31 <sup>12</sup>Institute of Oceanology – BAS 9000 Varna, PO Box 152, Bulgaria.

32 <sup>13</sup>Institute of Marine Sciences, Middle East Technical University, PO Box 28, 33731, Erdemli, Turkey.

33 <sup>14</sup>Hellenic Centre for Marine Research, Institute of Marine Biological Resources and Inland Waters,  
34 PO Box 2214, Heraklion 71003, Crete.

35

36 \*Corresponding Author: Tel: +44 (0) 1752 587889; Email: [antony.knights@plymouth.ac.uk](mailto:antony.knights@plymouth.ac.uk)

37 § Indicates these authors wish to be considered as joint first authors

38

### 39 **Abstract**

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

52

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

55

### 56 **1. Introduction**

57 Current rates of resource exploitation are unsustainable and the ecosystem-approach has been widely  
58 promoted as the framework to achieve sustainable use (Halpern *et al.*, 2008; Airoidi and Beck, 2007;  
59 EC, 2008). By definition, an ecosystem is a diverse range of physical and biological components  
60 which function as a unit (*sensu* Tansley, 1935) and therefore, an ecosystem approach should ideally  
61 consider the complete range of interactions that human activities have with the ecosystem and its  
62 components. However, the number of sectors that exploit the ecosystem and its components is often  
63 great, resulting in many different pressures and a complex network of interactions (Knights *et al.*,  
64 2013). Identification and prioritisation of interactions for management can therefore be difficult (Bottrill

65 *et al.*, 2008), presenting a major challenge to transforming the ecosystem approach from a concept  
66 into an operational framework (Leslie and McLeod, 2007).

67

68 The onus has been placed on the scientific community to identify the pathways through which  
69 activities cause harm (Leslie and McLeod, 2007; Fletcher *et al.*, 2010). The relationships between  
70 human activities and ecological components have commonly been described using linkage-based  
71 frameworks. These adopt the causal-chain concept to infer pressure-state relationships (Rounsevell *et*  
72 *al.*, 2010) and have been applied widely in both marine and terrestrial environments (e.g. Elliott, 2002;  
73 La Jeunesse *et al.*, 2003; Odermatt, 2004; Scheren *et al.*, 2004; Holman *et al.*, 2005). The simplicity of  
74 these frameworks is advantageous as key relationships can be captured and displayed in a relatively  
75 simple way (Rounsevell *et al.*, 2010). However, viewing linkages in isolation rather than accounting for  
76 the interplay across sectors, activities, pressures or components may be overly simplistic (Tallis *et al.*,  
77 2010) and can lead to ineffective management (Khalilian *et al.*, 2010). A flexible, problem-solving  
78 approach is therefore required that is capable of linking the relationship between the human activities  
79 and the environment while supporting the decision-making needs of environmental managers.

80

81 Risk assessment can provide a solution (Hope, 2006). Risk assessment in general describes the  
82 likelihood and consequences of an event. In an ecosystem-based management context, risk can be  
83 defined as the degree to which human activities interfere with the achievement of management  
84 objectives related to particular ecological components (see Samhuri & Levin 2012). It is increasingly  
85 seen as a way to integrate science, policy, and management and has been widely used to address a  
86 range of environmental issues (e.g. Fletcher, 2005; Francis, 1992; Smith *et al.*, 2007; Samhuri and  
87 Levin, 2012; Hobday *et al.*, 2011). There are several risk assessment approaches available using  
88 quantitative (e.g. Francis, 1992; Samhuri and Levin, 2012) or qualitative data (e.g. Fletcher, 2005;  
89 Fletcher *et al.*, 2010; Breen *et al.*, 2012). Many ecological risk assessments (Fletcher, 2005; Campbell  
90 and Gallagher, 2007; e.g. Astles *et al.*, 2006) are based on a likelihood-consequence approach for  
91 estimating the risk of a rare or unpredictable event (Williams *et al.*, 2011). But when an assessment of  
92 on-going (current) pressure is needed, then an exposure-effect analysis is more suitable (Smith *et al.*,  
93 2007). Several studies have used the exposure-effect concept to assess risk to habitats and species  
94 from on-going human activities (e.g. Bax and Williams, 2001; Stobutzki *et al.*, 2001) using qualitative  
95 descriptors such as habitat resistance (to physical modification) and resilience (the time taken for the  
96 habitat to recover to pre-impact condition) to assess habitat vulnerability (Bax and Williams, 2001).

97 Assessments have tended to focus on a single activity or target species (e.g. fishing, Bax and Williams,  
98 2001; Fletcher, 2005; Hobday *et al.*, 2011) but have recently been broadened to include a greater  
99 number of activities and non-target species and applied at larger management scales (Samhuri and  
100 Levin, 2012).

101

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

114

## 115 **2. Methods**

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

129

130 *2.1. Linkage mapping and pressure (threat) assessment*

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

141

142 Threat from each chain was assessed using a pressure assessment (*sensu* exposure-effect)  
143 approach (see Robinson *et al.*, In prep for full details of the methodology). The pressure assessment  
144 methodology was designed with the concept of risk assessment in mind, such that the assessment  
145 criteria we developed could be used to evaluate the likelihood and consequences of a specific or  
146 combination of impact chains. The pressure assessment used expert judgment (Cooke and Goossens,  
147 2004) to qualitatively assess each impact chain using a categorical assessment of five criteria: (1-2)  
148 two describing the exposure of the ecological component to a sector-pressure combination; (3) one  
149 describing the severity of the interaction; and (4-5) two describing recovery (Figure 2; Table A2). Each  
150 impact chain was evaluated considering prevailing conditions and applied here at a European regional  
151 sea scale, not least so that the outcomes of the assessment could support the objectives of the Marine  
152 Strategy Framework Directive (EC, 2008) (Figure 1). Some impact chains were excluded from the final  
153 assessment based on the absence of a sector (and thus its pressures) in the regional sea. As such, a  
154 separate network of impact chains was developed for each regional sea (see Knights *et al.*, 2013 for  
155 full details of the network model).

156

157 *2.2. Assessing risk and recovery in large ecosystems*

158 Our approach builds on a long series of antecedents of productivity susceptibility analysis (e.g.  
159 Hobday *et al.*, 2011; Stobutzki *et al.*, 2001; Samhuri & Levin 2012). We applied numerical scores to  
160 each qualitative assessment category (Table A2) and used combinations of the assessment criteria to

161 describe two axes of information: *Impact Risk* and *Recovery lag* (Figure 2). Impact risk was  
162 constructed using a combination of exposure (2) and sensitivity (1) criteria, which describe the spatial  
163 extent and temporal (frequency) overlap of a sector-pressure within an ecological component, and the  
164 severity of the interaction where overlap occurs (degree of impact). These criteria were combined into  
165 the aggregate criterion, we refer to as Impact Risk, where the greater the Impact Risk score, the  
166 greater the threat to a component (Figure 2).

167

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

175

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

183

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

190

191 **3. Results**

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

198

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

211

212 Recovery lag scores were more varied than the impact risk scores for the same sector-grouped chains.  
213 Median values were relatively low and consistent across all regions (0.0055) indicating recovery to  
214 pre-impacted within ~11 yr (Figure 3). In nearly every case, sectors introduce a pressure that impact  
215 one or more ecological components resulting in a recovery lag of 0.55 (equivalent to  $>100$  yr to pre-  
216 impact recovery). In contrast to the impact risk scores (which were predominantly low; 99% had values  
217  $< 0.05$ ), there was greater proportion of impact chains with intermediate or high recovery lag scores of  
218 0.3 and upward. In fact, of the 3,347 impact chains considered, 18% had a recovery lag of 0.3 (590  
219 chains) and 6% (198 chains) of  $>0.55$ . Grouping impact chains by pressure type identified which  
220 pressures pose the greatest impact risk to the ecosystem. Median scores were low in all cases; 0.003  
221 in the Baltic Sea and NE Atlantic, 0.011 in the Mediterranean Sea and 0.005 in the Black Sea (Figure  
222 5). Greatest impact scores were associated with the pressure type "species extraction" (0.51-0.69)  
223 indicating widespread, common/persistent and acute impacts throughout all regions (Figure 5).

224

225 Recovery lag was highly dependent on the pressure type. Low recovery lag scores in all regions  
226 (between  $<0.006$  and  $0.01$ ;  $<15$  yr to recovery (Figure 3)) were associated with physical pressures  
227 such as abrasion, aggregate extraction (agg\_extract), collision, noise, smothering and species  
228 extraction (spp\_extract) (Figure 5). In contrast, biotic pressures (e.g. NIS), contaminant pressures (e.g.  
229 radionuclides, marine litter), and hydrological pressures (e.g. water flow regimes, wave exposure)  
230 were characterised by higher recovery lag scores, many of which equal to  $0.55$  (Figure 5) indicating  
231  $>100$  yr to recovery if the pressure were stopped. In some cases, there was little difference in recovery  
232 lag associated with a particular pressure type between regional seas (e.g. non-synthetic or synthetic  
233 contaminants). For other pressure types, such as nitrogen and phosphorus enrichment (N&P) and  
234 barriers to species movement (Barriers), there were marked differences between regions, where  
235 recovery lag scores were high in one region (Baltic Sea, N&P), but very low in others (Figure 5), due  
236 to differences in the susceptibility of different ecological components i.e. recover potential, and the  
237 persistence that pressure type in that region.

238

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

245

246 Recovery lags of the ecological components in different regional seas were largely comparable with  
247 few outliers, and were dependent on the ecological component impacted (Figure 6). For mobile  
248 species (i.e. seabirds, deep sea habitats and fish, demersal and pelagic fish and marine mammals  
249 and reptiles), recovery lag was highly variable due to differences in the impact mechanisms of specific  
250 sector-pressure combinations. In some cases, recovery from some sector-pressure combinations was  
251 predicted to take  $>100$  yr (RL =  $0.55$ ), although median values ranged between  $12$  yr ( $0.006$ ) and  $90$  yr  
252 ( $0.3$ ). Predominant habitats were in marked contrast, with median recovery predicted to take between  
253  $1$  ( $0.0001$ ) and  $10$  yr ( $0.004$ ) up to a maximum of  $\sim 40$  yr ( $0.06$ ) in worst case examples. In one  
254 exception, demersal fish in the Black Sea are predicted to recovery more quickly than the same  
255 component in other regional seas.

256

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

269

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

280

#### 281 **4. Discussion**

282 We have illustrated how a generic exposure-effect framework can be used to assess the risk to and  
283 recovery of ecosystems from human activities at a scale relevant to current environmental policy. We  
284 do this using two datasets: one that describes the relationships (linkages) between sectors, pressures  
285 and ecological components of regional sea ecosystems (Knights et al., 2013), and two, a qualitative  
286 assessment of each linkage using an expert judgement approach (Robinson *et al.*, 2013). The result is  
287 two axes of information describing: (1) Impact Risk - the likelihood of a negative interaction between a

288 sector and the environment (via the pressure mechanism) and its severity, and (2) Recovery Lag - the  
289 post-impact rate of recovery to pre-impact condition. The assessment reveals that in many cases, the  
290 impact risk from sector activities is relatively low, but there are a number of impact chains introduced  
291 by several sectors of high impact risk and potentially causing significant harm to the marine  
292 environment. Recovery from impact was more variable, but indicated that in many cases, recovery to  
293 pre-impact conditions may require many years for some ecological components.

294

295 Our framework adopted perhaps the most extensive description of links between human activities and  
296 the ecosystem to date (Knights *et al.*, 2013; Koss *et al.*, 2011). The holistic assessment is therefore  
297 relevant to environmental policy and conservation objectives that require an ecosystem approach  
298 (McLeod and Leslie, 2009). Here, more than 3,500 impact chains were considered forming a complex  
299 network of linkages (Knights *et al.*, 2013), which was simplified by grouping chains by “sector”,  
300 “pressure type” or “ecological component”. We presented the results in two ways to demonstrate the  
301 flexibility of the approach to identify the impact chains posing the greatest risk and/or slowest recovery.  
302 Firstly, in broad terms considering all sectors, pressures and ecological components, then secondly, in  
303 a more targeted way wherein risk and recovery from a specific sector’s impacts or to a single  
304 ecological component were assessed. The criteria used to assess each impact chain were relatively  
305 coarse (Robinson *et al.*, 2013), but changes in impact risk/recovery lag could be differentiated within  
306 and between groupings (e.g. sector, pressure type, component), allowing managers to identify and  
307 prioritise impact chains for management in terms of their impact risk (Bottrill *et al.*, 2008), as well as  
308 giving a clear understanding of the expected time frame for recovery if management is effectively  
309 implemented, enforced and complied with (Knights *et al.*, 2014b). Given that management resources  
310 are often finite and therefore insufficient to address all issues (Joseph *et al.*, 2009), the framework  
311 therefore can act as a decision-support tool (Fletcher, 2005). Managers can defend management  
312 trade-off decisions based on scientific evidence linked to a specific conservation objective and identify  
313 the societal and economic costs and benefits of that decision from the outset; both of which deemed  
314 critical components to the success of an ecosystem approach (Knights *et al.*, 2014a; Altman *et al.*,  
315 2011).

316

317 The risk assessment was underpinned by a structured expert judgement analysis of linkages, which is  
318 effective for achieving consensus between groups of individuals (Cooke and Goossens, 2004). A  
319 significant benefit of such an approach is that it can be applied in all systems; even those that are data

320 poor, and undertaken at relatively low financial cost to the stakeholder (Fletcher et al., 2010). This is of  
321 particular value to regions such as the Mediterranean Sea and Black Sea where they not only face the  
322 challenge of implementing EBM as obligated under regional sea environmental policy, but have the  
323 added complication that the resources (e.g. stocks that straddle international boundaries) are also  
324 exploited by stakeholders not bound by the same environmental regulations or ambition levels, which  
325 may counteract any management measure(s) implemented by the EU Member State(s) (Stokke,  
326 2000). To counteract the uncertainty surrounding the exploitation of resources by non-EU  
327 stakeholders, the assessment can be undertaken using a precautionary approach, and use data such  
328 as anecdotal evidence to support the pressure evaluation in lieu of empirical data. A manager is then  
329 not precluded from making an assessment of regional priorities, but includes uncertainty such that risk  
330 to ecosystems is not underestimated.

331

332 We applied the risk assessment to the suite of sectors, pressures and broad ecological components  
333 that are common to global marine ecosystems; the ecological components assessed are  
334 representative of a healthy ecosystem (Costanza and Mageau, 1999) and have been identified as  
335 relevant characteristics of Good Environmental Status (GES) under the Marine Strategy Framework  
336 Directive. We can therefore interpret directly from our analysis the risk to the ecosystem from different  
337 sectors (Fletcher et al., 2010; Samhuri and Levin, 2012). Application of the risk assessment  
338 framework identified the sectors and pressures that are recognised as primary drivers of change in the  
339 ecosystem and its components. There were cross-regional similarities in risk and included well-  
340 recognised primary sector drivers of ecosystem change such as commercial fishing (e.g. Coll et al.,  
341 2010; Piet and Jennings, 2005) and coastal infrastructure (Bulleri and Chapman, 2009), and perhaps  
342 less well-recognised sectors such as navigational dredging (Suedel *et al.*, 2008) and tourism  
343 (Davenport and Davenport, 2006). Many of the pressure types with higher risk scores are also well  
344 recognised, such as selective extraction from fishing (Pauly et al., 1998) and nitrogen and phosphorus  
345 run-off from agriculture (Zillen et al., 2008). These were linked to high-risk sectors (e.g. Graneli et al.,  
346 1990; Smayda, 1990), which is unsurprising given that direct links can be made between sector-  
347 pressures and ecological components (Knights et al., 2013; Liu et al., 2007). As the underlying  
348 assessment of the linkages (Robinson *et al.*, 2013) considered prevailing conditions, results indicate  
349 that the regulation of some sector activities have failed to limit their impact as intended (e.g. Khalilian  
350 et al., 2010) and elsewhere, harmful impacts have been ignored (Walker *et al.*, 2003).

351

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

362

363 The number of high-risk impact chains introduced by different sectors reinforces the need for holistic  
364 management, which adopts a combination of management measures to achieve the objectives of the  
365 ecosystem approach (Knights et al., 2013; Tallberg, 2002). The protection of some components is  
366 likely to be easier to achieve than for others (Khalilian et al., 2010). For example, an improvement in  
367 sublittoral habitat state (Figure 8) would likely require management of fishing, aggregates, aquaculture,  
368 navigational dredging and research (including scientific research and bio-prospecting) sectors (Figure  
369 8), whereas pelagic fish species are threatened by fishing, tourism, research and aquaculture.  
370 Reductions in risk would therefore likely require different (and most likely more complex) levels of  
371 control. Identifying combinations of management measures to reduce risk are outside the scope of this  
372 paper (see Piet et al. submitted to this journal for such an assessment), but the analysis does indicate  
373 that the complexity of management strategies required to reduce risk will be dependent, not only on  
374 the region, but also the conservation objective. Although not undertaken here, the approach could be  
375 used to evaluate management strategies by assessing the reduction in risk to the ecosystem or  
376 targeted characteristics. Risk reductions could be achieved in several ways via changes in exposure  
377 or sensitivity or a combination of the two (Smith et al., 2007). Managers would then be able to make  
378 trade-offs and develop more socially acceptable management strategies (Hassan et al., 2005), which  
379 can lead to greater compliance (Tallberg, 2002), a reduction in enforcement costs (Sutinen and Soboil,  
380 2003) and an increased likelihood of reaching the environmental objective.

381

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

393

394 Limited fiscal resources, ever increasing demands for resources (Hallerberg et al., 2007; Halpern et al.,  
395 2008) and the complex relationship between humans and their environment (Liu et al., 2007) are  
396 significant challenges to ecosystem-based management. Risk assessment is gaining momentum as a  
397 decision-support tool that allows managers and policy makers to prioritise human drivers of  
398 environmental change (Fletcher, 2005; Fletcher et al., 2010; Hobday et al., 2011; Samhuri and Levin,  
399 2012), and makes a fundamental contribution toward ecosystem-based management objectives. The  
400 development of a reliable risk assessment has been challenging because of the inherent complexity  
401 associated with multiple sectors targeting multiple ecosystem characteristics (resources) making  
402 attributing risk to specific sectors and their activities difficult. The approach illustrated here provides a  
403 rapid, structured, transparent assessment of current risk to ecosystems so that resource managers on  
404 the national, international or regional-stage can identify the most harmful activities and potential  
405 management measures suggested and corresponding science-based timeframes for improvement  
406 such that confidence in the stewardship of resources by managers is built (Knights et al., 2014).  
407 Coupled with an evaluation of the costs and benefits regarding the impact of a measure on the  
408 environment, societal and economic metrics (Hassan et al., 2005) will increase the likelihood that the  
409 overarching objective of ecosystem-based management – sustainable use – is achieved.

410

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414 (University of Liverpool) and Tony Smith (CSIRO) for their helpful comments on this paper.

415

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521 **Figure Legends**

522

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

527

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

536

537 **Figure 3.** Impact risk and recovery lag scores for all possible combinations of the assessment criteria.  
538 Impact risk scores are log (LN) transformed. Significant regressions are shown (Impact Risk -  $y =$   
539  $0.68 \cdot e^{-0.24x}$  ( $R^2 = 0.98$ ,  $p < 0.01$ ); Recovery Lag -  $y = 1.98 \cdot e^{-0.55x}$  ( $R^2 = 0.96$ ,  $p < 0.01$ )). Assessment  
540 criteria categories are given in Table S2. Inset: The relationship between recovery lag scores and  
541 minimum years to recovery based on category definitions shown in Table S2. A significant regression  
542 is shown;  $y = 174.56 \cdot x^{0.523}$  ( $R^2 = 0.69$ ,  $p < 0.05$ ).

543

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

551

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

557

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

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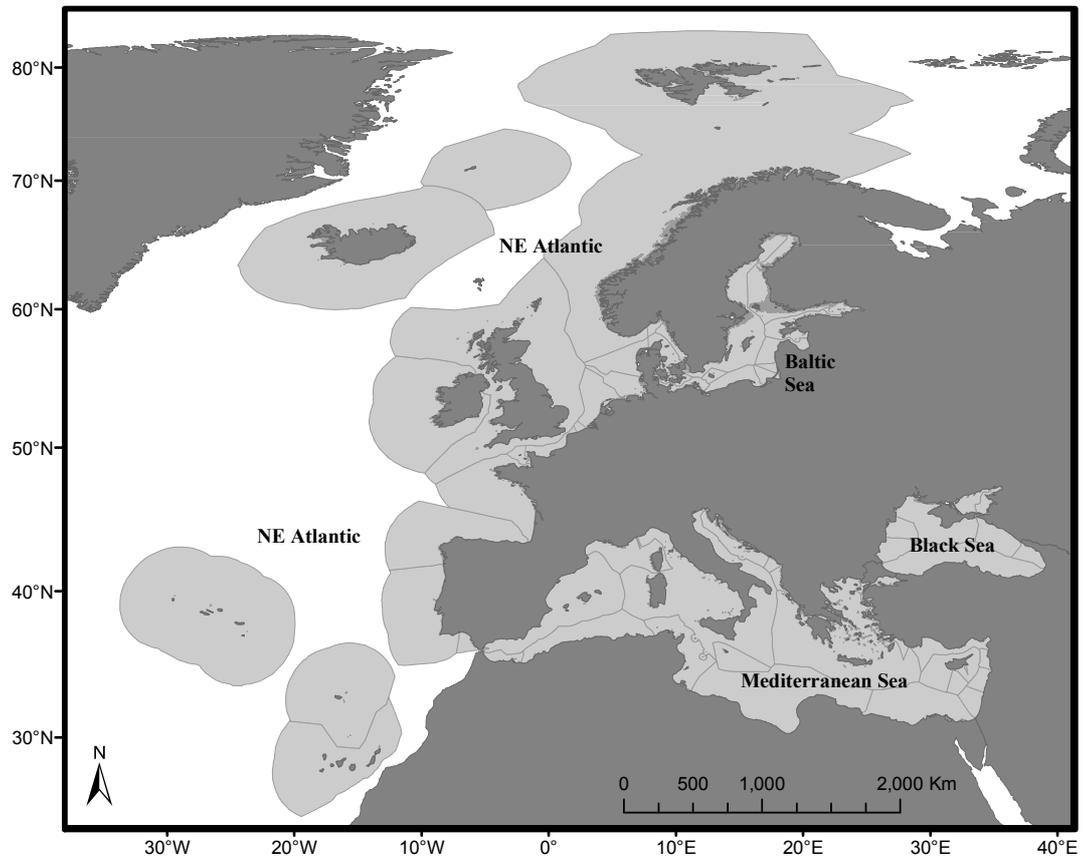
564 **Figure 7.** Distribution of impact risk and recovery lag scores to all ecological components from fishing  
565 grouped by pressure in each of four European regional seas (Baltic Sea – green; Black Sea – yellow;  
566 Mediterranean Sea – orange; NE Atlantic – grey). The maximum impact risk and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

568

569 **Figure 8.** Distribution of impact risk and recovery lag scores to sublittoral sediments grouped by sector  
570 and pressure in each of four European regional seas (Baltic Sea – green; Black Sea – yellow;  
571 Mediterranean Sea – orange; NE Atlantic – grey). Sectors/pressures posing no risk are excluded from  
572 the plot. The maximum impact risk score for any chain is 0.7. Boxplot information is given in the  
573 legend of Figure 4.

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577 **Figure 1**

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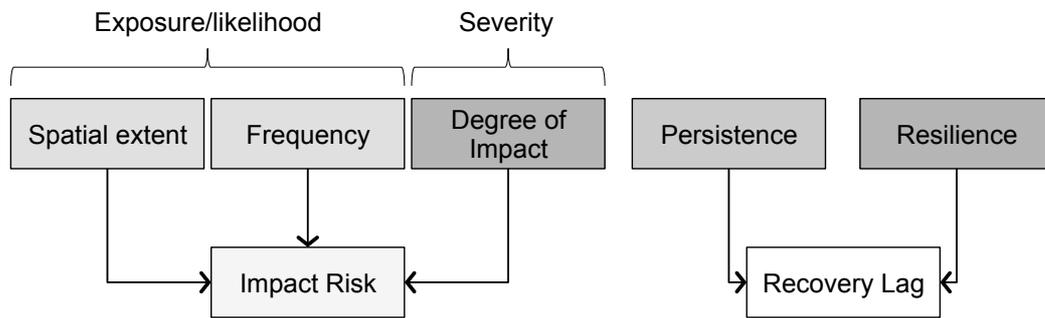
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593 **Figure 2.**

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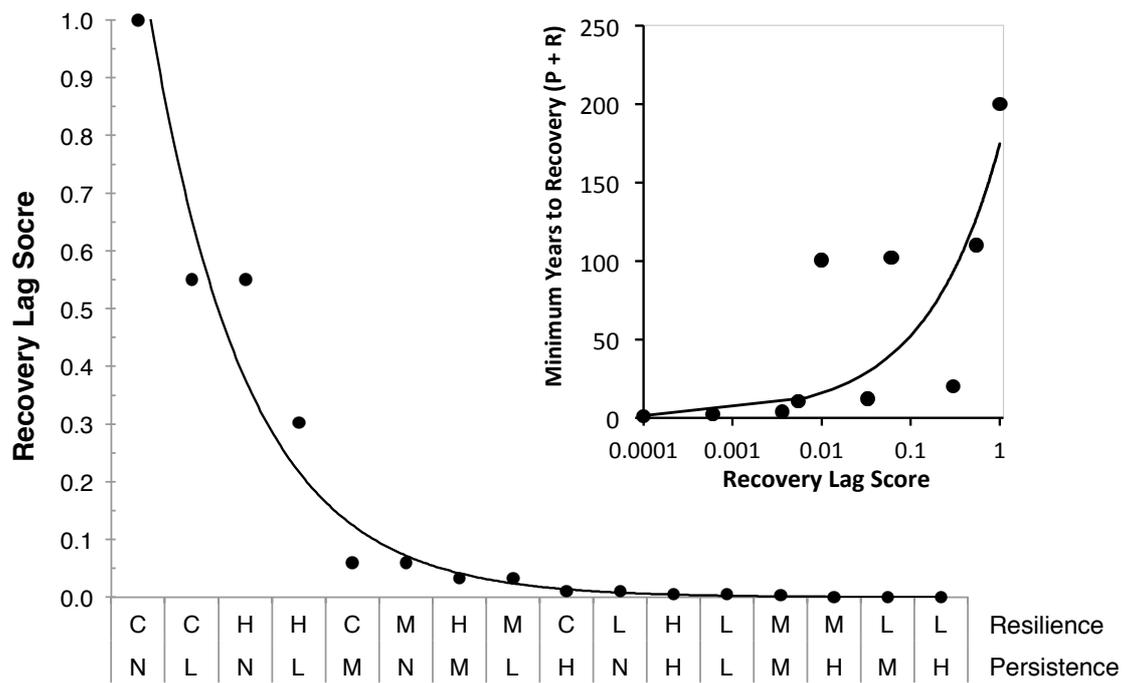
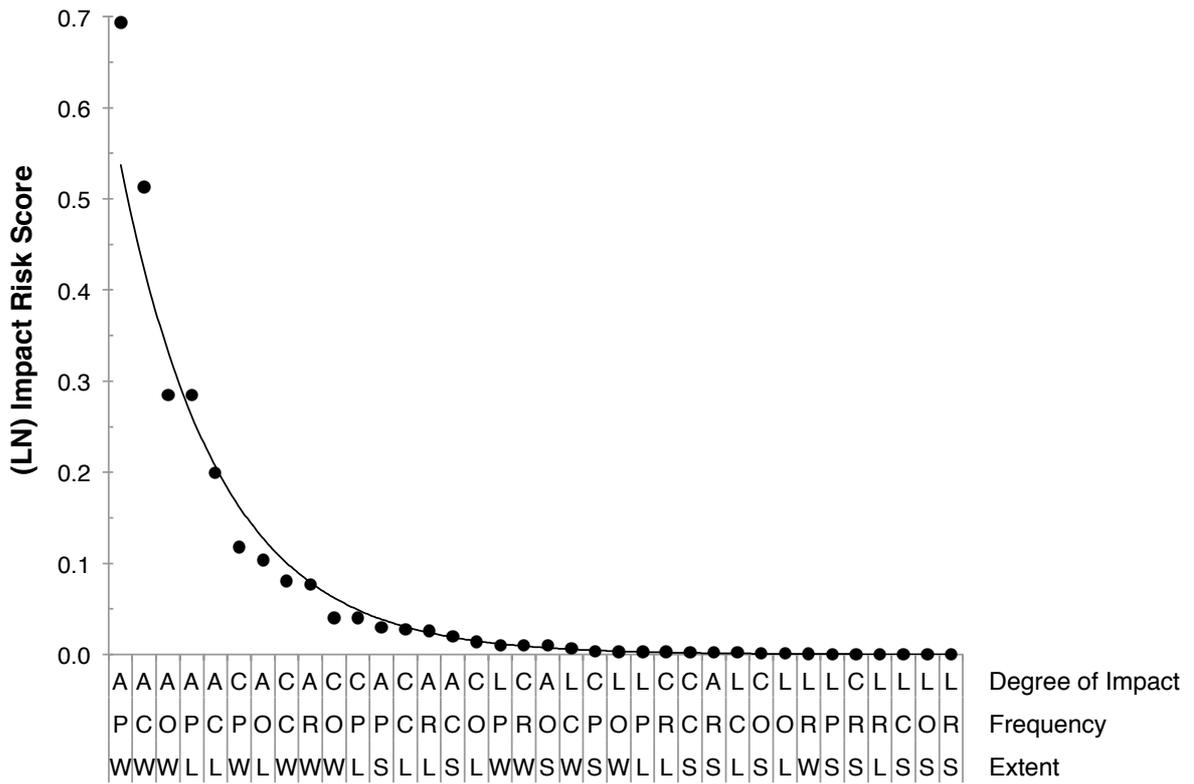
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Assessment Category

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605 **Figure 3**

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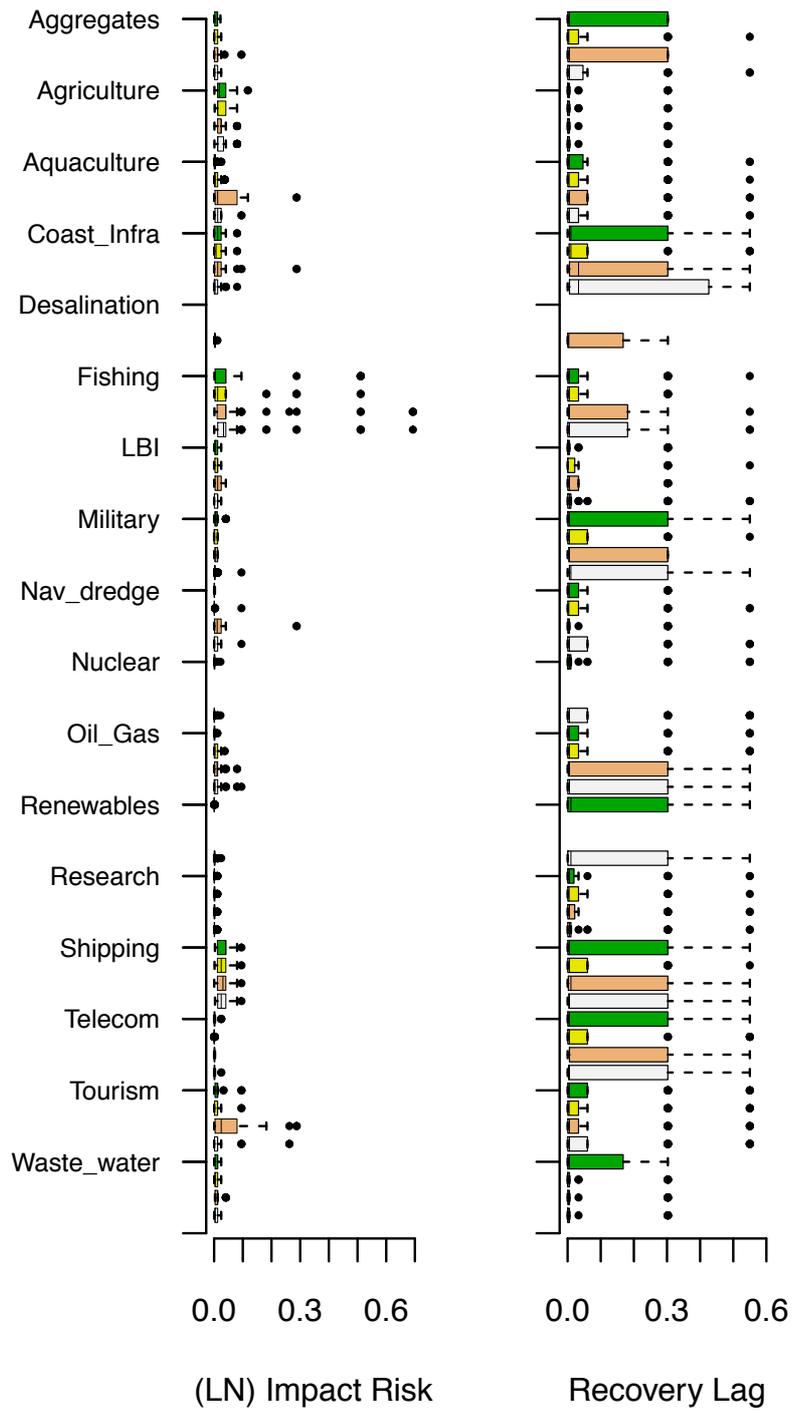


Figure 4.

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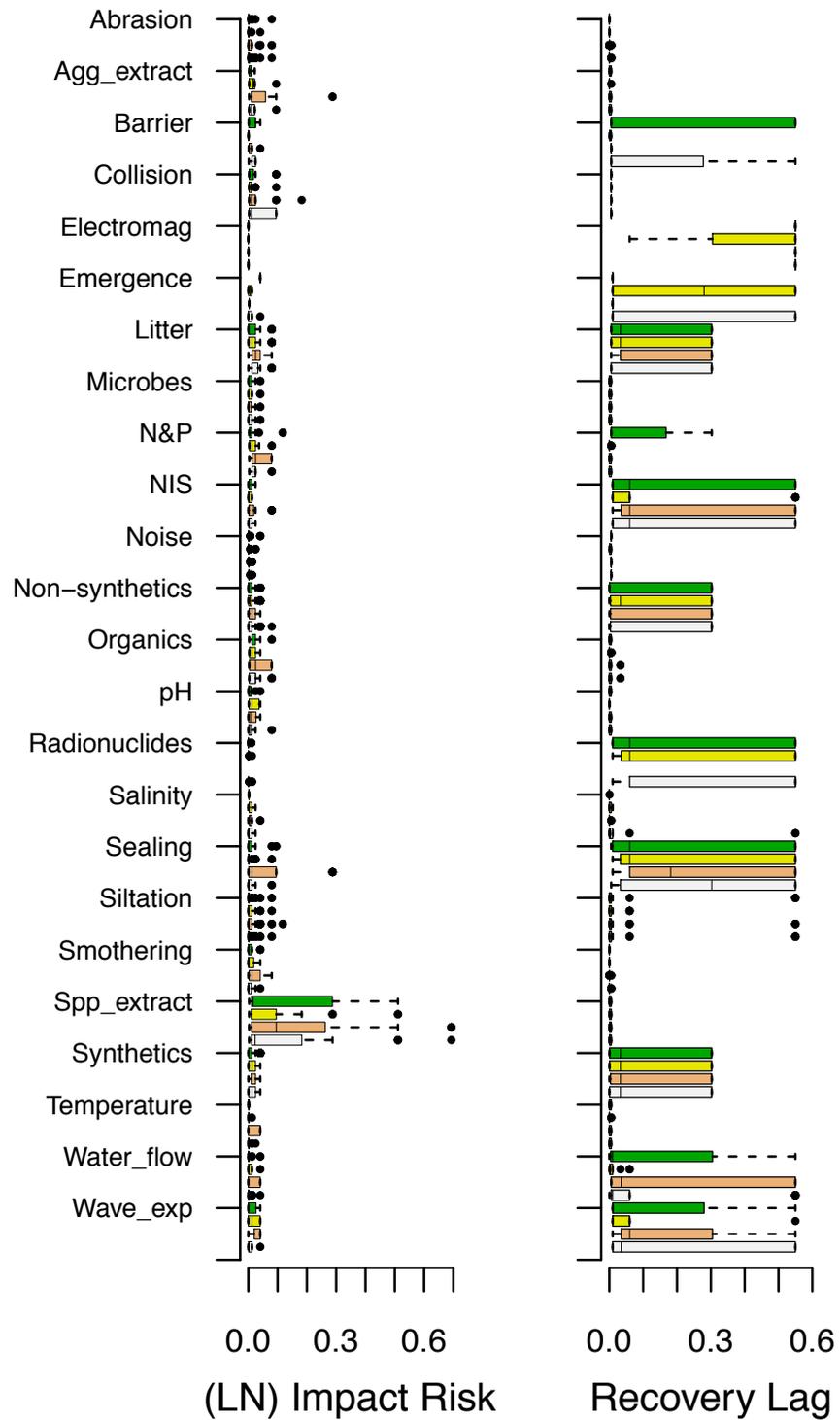


Figure 5.

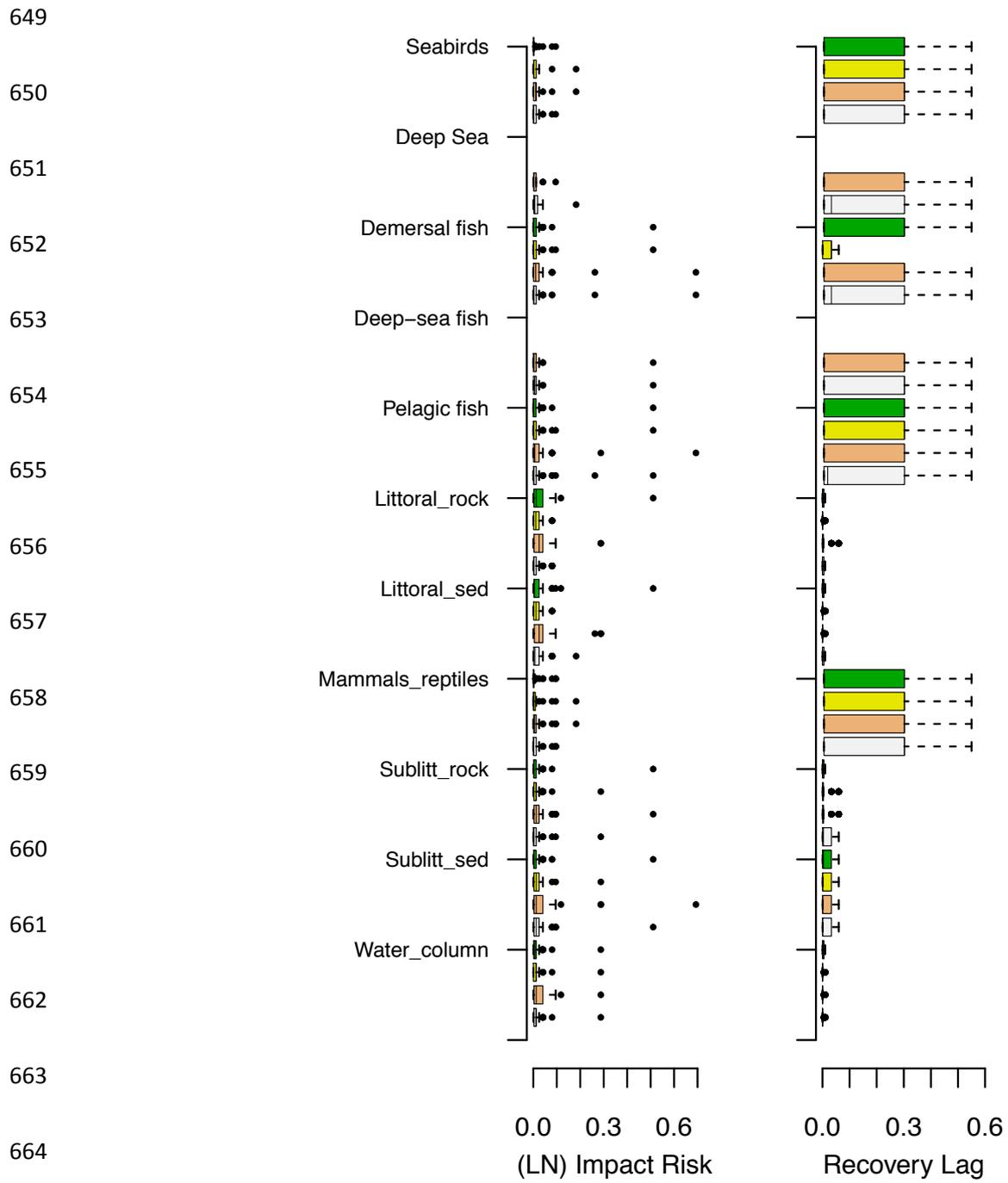


Figure 6.

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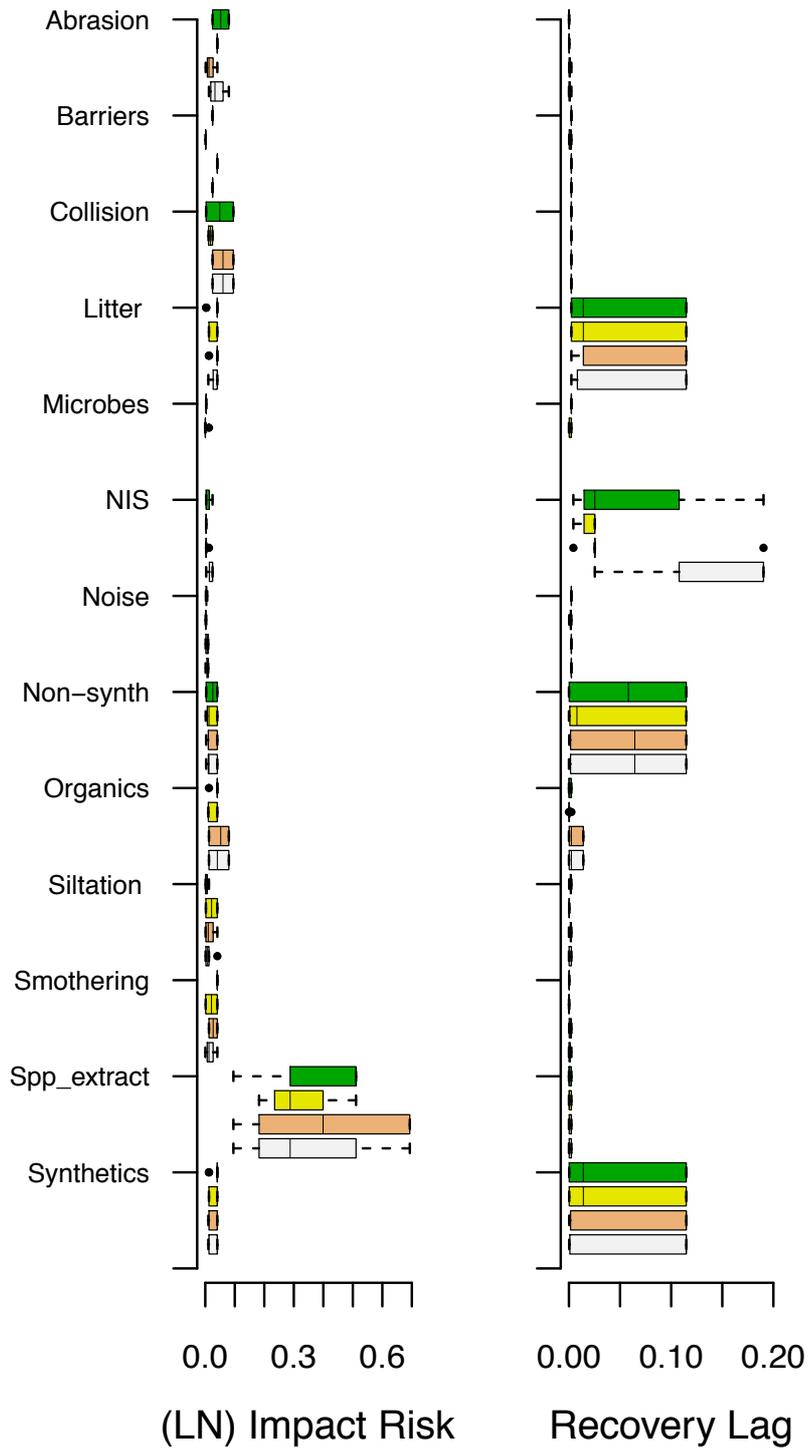
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690 **Figure 7.**

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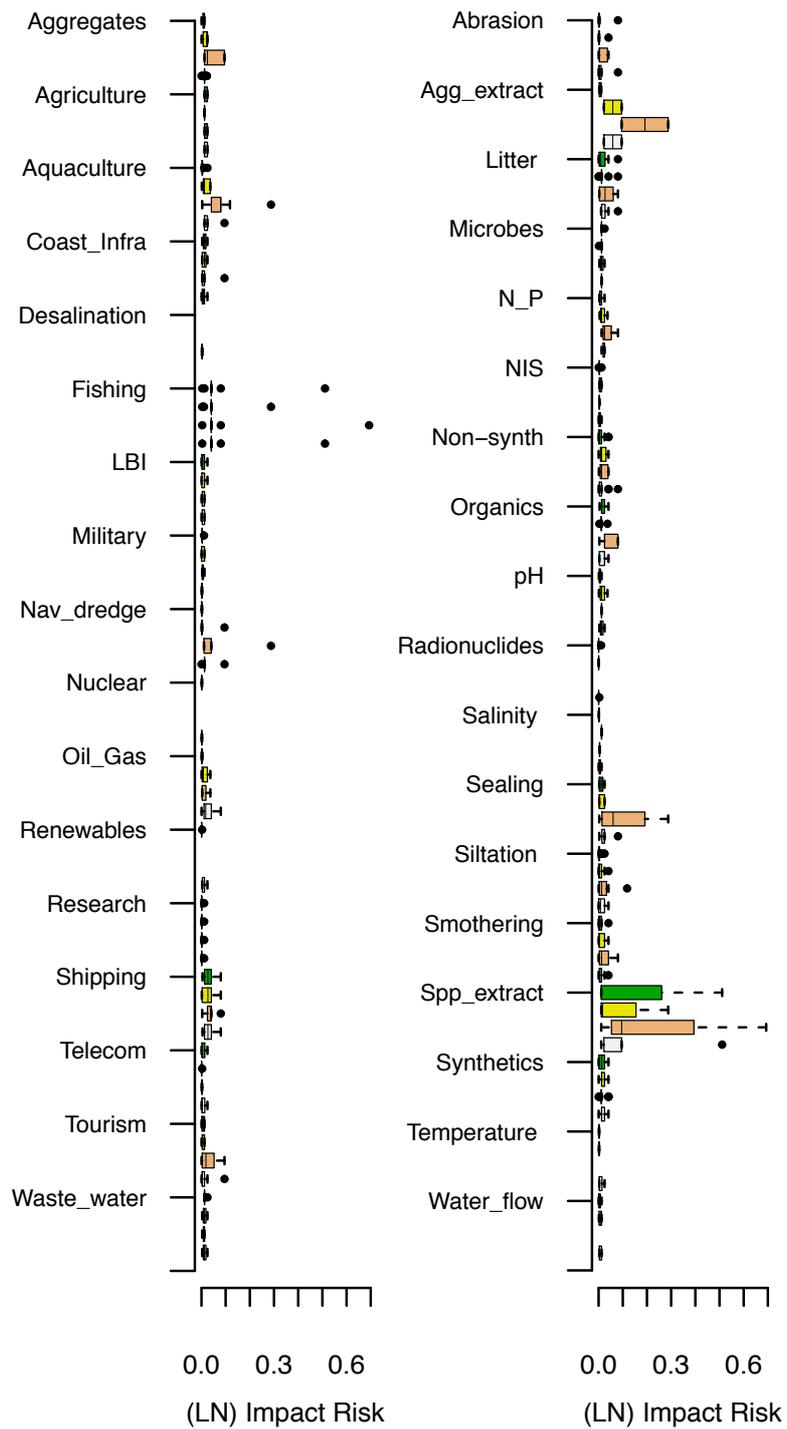
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712 **Figure 8.**

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715 **Table Legends (Supplemental material)**

716

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

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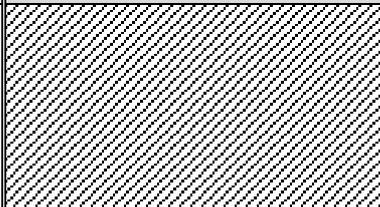
721 **Table A2.** The pressure assessment criteria and categories used to evaluate each impact chain (after  
722 Robinson et al., 2013) and the numerical risk scores assigned to each category.

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725

726 **Table A1.** List of sectors, pressure types and ecological characteristics included in the risk  
 727 assessment and evaluated using the ODEMM pressure assessment. Abbreviations used in figures are  
 728 shown in brackets (where applicable). **No links between sector, pressure type and ecological**  
 729 **components are inferred.**  
 730

Sector	Pressure Type	Ecological Components
<b>Aggregate Extraction</b> (Aggregates)	<b>Abrasion</b> – the interaction of human activities with the seafloor and with seabed fauna/flora	<b>Predominant Habitat</b> <ul style="list-style-type: none"> <li>• Littoral rock (Littoral_rock)</li> <li>• Littoral sediment (Littoral_sed)</li> <li>• Sublittoral rock (Sublitt_rock)*</li> <li>• Sublittoral sediment (Sublitt_sed)</li> <li>• Deep Sea<sup>§</sup> (Deep Sea)</li> </ul>
<b>Agriculture</b>	<b>Barrier to species movement</b> (Barrier) - e.g. due to barrages, causeways, wind turbines etc.	<b>Fish</b> <ul style="list-style-type: none"> <li>• Demersal</li> <li>• Pelagic</li> <li>• Deep sea<sup>§</sup></li> </ul>
<b>Aquaculture</b>	<b>Change in wave exposure</b> (Wave_exp) - e.g. regionally due to climate change, or more locally due to coastal structures)	<b>Marine mammals &amp; Reptiles</b> (Mammals_reptiles)
<b>Coastal Infrastructure</b> (Coast_Infra)	<b>Changes in Siltation</b> (Siltation) - e.g. suspended sediments in the water column from runoff, dredging etc.	<b>Seabirds</b>
<b>Desalination</b> (Mediterranean Sea only)	<b>Death or Injury by Collision</b> (Collision) - e.g. bird strikes with wind turbines, collision with vessels etc.	

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

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

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

731 §Deep-sea predominant habitat was not assessed in the Black Sea because it is classified as a  
 732 “dead zone” (Diaz and Rosenberg 2008)

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

735 §Deep-sea fish species are not found in the Baltic or Black Sea and are therefore excluded.

736

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

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740

Extent Category	Description	Raw value (% overlap)	Standardised value (proportion of max)
	The spatial extent of overlap between a pressure type and ecological characteristic		
<i>Widespread</i>	Where a sector overlaps with an ecological component by 50% or more.	75	1.00
<i>Local</i>	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
<i>Site</i>	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	Months per year	Standardised value (proportion of max)
	How often a pressure type and ecological characteristic interaction occurs measured in months per year		
<i>Persistent</i>	Where a pressure is introduced throughout the year	12	1.00
<i>Common</i>	Where a pressure is introduced in 8 months of the year	8	0.67
<i>Occasional</i>	Where a pressure is introduced in 4 months of the year	4	0.33
<i>Rare</i>	Where a pressure is introduced in 1 month per year	1	0.08

Degree of Impact Category	Description	Severity per interaction	Standardised value (proportion of max)
	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).		
<i>Acute</i>	Severe effects after a single interaction	1	1.00
<i>Chronic</i>	Severe effects occur when Frequency of introductions more than common (>8)	0.125	0.13
<i>Low</i>	Severe effect not expected. For precautionary reasons, we assume a potential effect after 100 introductions.	0.01	0.01

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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.		
<i>Continous</i>	The pressure continues to impact the ecosystem for more than 100 yrs	100	1.00
<i>High</i>	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
<i>Moderate</i>	The pressure continues to impact the ecosystem for between 2 and 10 yrs	6	0.06
<i>Low</i>	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.		
<i>None</i>	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
<i>Low</i>	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
<i>Moderate</i>	The population will take between 2 and 10 yrs to recover.	6	0.06
<i>High</i>	The population will take between 0 and 2 yrs to recover.	1	0.01

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