Options for Delivering Ecosystem-Based Marine Management

An exposure-effect risk assessment methodology to evaluate the performance of management scenarios: Case study examples from Europe's regional seas

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Executive Summary

- This report uses an exposure-effect risk assessment methodology developed in the ODEMM project and published in Knights et al. (in prep) to assess a series of case studies. The case studies address issues specific to Europe's regional seas based around the achievement of Good Environmental Status (GES) for one or more of the Marine Strategy framework Directive's high level objectives (GES Descriptors, e.g. Foodwebs, Seafloor Integrity, Biodiversity).
- An over-arching theme of this report is evaluating how management measures could be employed to reduce the risk of harm to ecological components of the marine ecosystem. The approach does not predict how reductions in risk are manifested as a change in state in one or more of these components. Rather, it illustrates how a management measure, or combination of management measures (i.e. a strategy), could be used to reduce risk in a regional sea ecosystem.
- Three Management Options (MO) are assessed in each regional sea tackling broad issues, such as fishing, marine litter and eutrophication from nitrogen and phosphorus enrichment. Using ODEMM's integrated Management Strategy Evaluation (*i*MSE) tool, reductions in impact risk following the implementation of each MO are predicted and the effectiveness of each MO compared. Regional differences are revealed between the impact risk associated with different sectors and pressure types and the effectiveness of different MOs in reducing impact risk. The results are discussed and placed in a wider context of decision-making while implementing environmental policy.

Introduction

Current rates of resource exploitation are unsustainable and the ecosystem-approach has been widely promoted as the framework to achieve sustainable use (Airoldi and Beck 2007, EC 2008, Halpern et al. 2008). Success of the ecosystem approach in theory should consider the complete range of interactions that human activities have with the ecosystem and its components. However, a number of sectors exploit several ecosystem components (Ban et al. 2010), which introduces a suite of pressures that cause harm to the environment (Knights et al. 2013). This creates a complex network of sector-specific pressures and impacts, which makes the identification and management of detrimental pathways difficult and presents 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, which adopt the causal-chain concept to infer pressure-state relationships (Rounsevell et al. 2010) and have been applied in marine and terrestrial environments (Elliott 2002, La Jeunesse et al. 2003, Odermatt 2004, Scheren et al. 2004, Holman et al. 2005). The number of potential links between sectors and the state of the ecosystem (Airoldi and Beck 2007, Knights et al. 2013) can make identification and prioritisation of linkages for management problematic (Bottrill et al. 2008). A flexible, problem-solving approach is therefore required that is capable of linking the relationship between the human activities and the environment to 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. But in the context of ecosystem-based management, it evaluates the degree to which human activities interfere with the achievement of management objectives related to particular ecological characteristics (see Samhouri & Levin 2012). It is increasingly seen as a way to integrate science, policy, and management (CENR 1999). There are several risk assessment approaches available that use 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, e.g. Astles et al. 2006, Campbell and Gallagher 2007) are based on a likelihood-consequence approach for estimating the risk of a rare or unpredictable event (Williams et al. 2011). However, 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). Qualitative descriptors such as habitat resistance (to physical modification) and resilience (the time taken for the habitat to recover to pre-impact condition) were used to assess the vulnerability of habitats (Bax and Williams 2001). The majority of assessments have tended to consider a single activity or target species (e.g. fishing, Bax and Williams 2001, Fletcher 2005, Hobday et al. 2011). More recently, the approach has been broadened further to include a greater number of activities, target and non-target species, and has been applied at a relatively large sub-regional management scale (Samhouri and Levin 2012).

In this report, we illustrate how an exposure-effect approach can be used to assess the risk to ecosystems from human activities at a regional or large marine ecosystem (LME) scale. We apply the definition from the Marine Strategy Framework Directive (MSFD) (EC 2008), with regional seas defined as the North East Atlantic, the Baltic Sea, the Black Sea and the Mediterranean Sea (Fig. 1). Building 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, severity and recovery lag of ecosystems to sector activities and their pressures (Robinson et al. In prep), we show the potential risks to ecological components from the wide range of sectors that are integral features of marine ecosystems worldwide. We also evaluate how an exposure-effect risk assessment approach can be used to evaluate the performance of management measures in reducing risk. In each regional sea, hypothetical scenarios are used to demonstrate the approach and how specific management measures or combinations of measures could be used to address issues of particular relevance for each region.

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 18 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) four broad ecological components (Appendix A). Two of the ecological components (fish and predominant habitats) were further disaggregated into 'sub- components', resulting in a total of 12 ecological components (Appendix A). Disaggregation was undertaken to provide greater resolution and differentiation of the impact of the sectors identified as primary drivers in the regional seas.

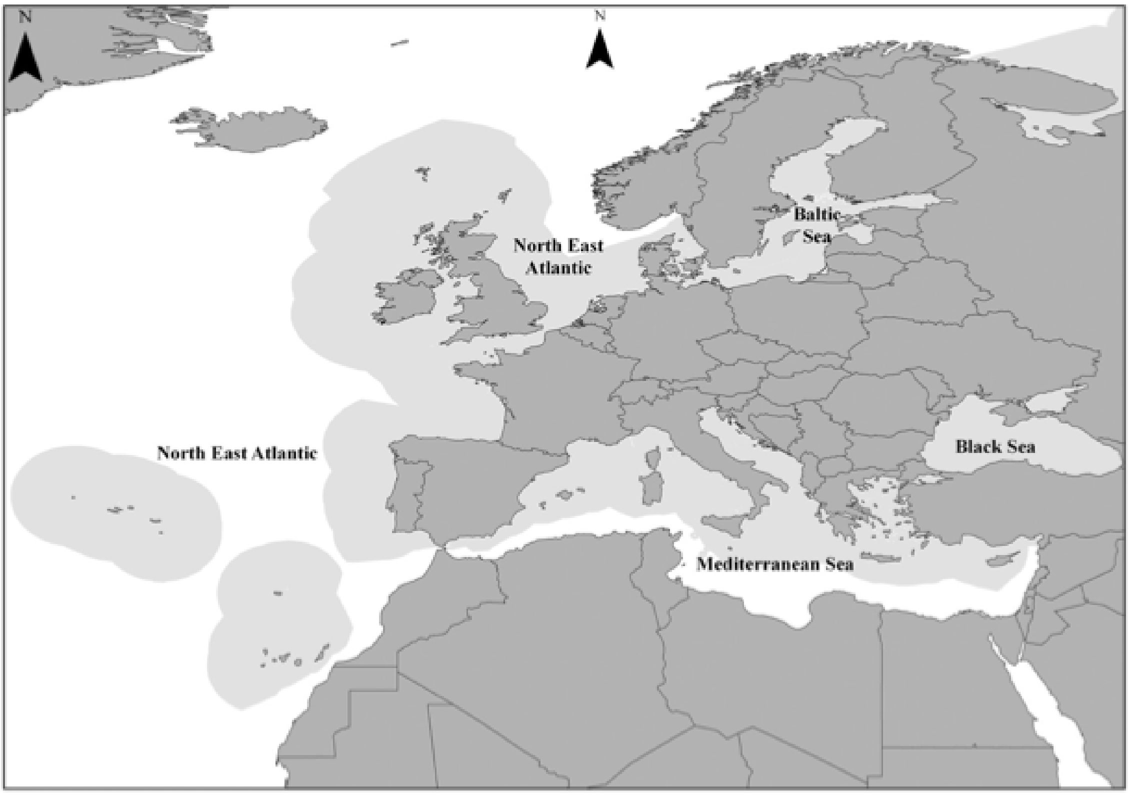


Figure 1. Regional Sea areas of Europe as defined by the Marine Strategy Framework Directive (light grey areas indicate the spatial coverage of the directive). Impact chains were assessed at the scale of the region for the NE Atlantic, Baltic Sea, Black Sea and Mediterranean Sea. Redrawn from Breen et al. (2012).

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, where each cell of the matrix describes the potential for impact on an ecological component from a sector, and the pressure is the mechanism through which an impact occurs. We refer to this linear chain 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). The pre-pressure assessment matrix consisted of 4,320 potential impact chains and the threat of each was assessed using the pressure assessment (*sensu* exposure-effect) approach (Robinson et al. In prep).

Impact chains were assessed using five criteria: two criteria were used to describe the *exposure* of the ecological component to a sector-pressure combination*,* one criterion describing the *severity* of the interaction, and two criteria described the time required for the ecosystem components to recover (*recovery lag*) from an impact. Criteria definitions are given in Robinson & Knights (2011) and Robinson et al. (in prep).

Exposure criteria were: (1) the spatial (extent) and (2) temporal (frequency) overlap of a sector-pressure within an ecological component, and the *severity* of the interaction is assessed by (3) the degree of impact criterion. The *exposure* and *severity* criteria were then combined into an aggregate criterion, termed *Impact Risk*, where the greater the Impact Risk score, the greater the threat to that component or combination of components.

Recovery lag was described using a combination of (4) the persistence of the pressure (the number of years before the pressure impact ceases following cessation of the sector introducing it) and, (5) the resilience (recovery time) of the ecological component following cessation of the pressure impact (Table 2). 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 recover back to its pre-impacted state.

The pressure assessment used expert judgment (Cooke and Goossens 2004) to qualitatively assess each impact chain and used categorical descriptions to describe each criterion (Table 2). Each impact chain was assessed under prevailing conditions. We assessed (i) the current extent, frequency of occurrence and degree of impact of each impact chain (including all existing management measure effects), and (ii) the persistence of the pressure and resilience of the ecological component based on its current state.

Each impact chain was assessed at the European regional sea scale, although the pressure assessment approach can be applied at any spatial scale (Robinson et al. In prep). This was done with a view that the outcomes of the assessment could support the objectives of the Marine Strategy Framework Directive (EC 2008), which adopts the ecosystem approach and requires implementation at a regional sea spatial scale (Fig. 1). Experts from 13 countries, each representing one or more regional seas, assessed the impact chain threat using the pressure assessment methodology (the results of the pressure assessment are described in full in Robinson et al. In prep). 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).

Assessing Impact Risk and Recovery Lag in regional sea ecosystems

Risk to an ecological component from a single sector or pressure type was assessed using a numerical score applied to each assessment criterion category (Table 1). As each criterion had a varying number of assessment categories (as many as 5 and as few as 3), scores for each category were standardised using the maximum score of 100 % (the worst case). Our approach builds on a long series of antecedents of productivity susceptibility analysis (e.g. Stobutzki et al. 2001, Hobday et al. 2011) and uses two axes of information to rank each impact chain (Burgman 2005). The first axis was related to the *impact risk* of an ecological component to a particular sector and pressure combination, and the second axis describes the *recovery lag* of the component to that same combination. 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 was calculated as the average of all impact chains aggregated by sector or pressure. Accurate calculation of 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).

Management Scenarios

The potential for management measures to reduce the risk or recovery lag to an ecosystem component or GES descriptor was evaluated using an interactive tool, named the *interactive* Management Strategy Evaluation tool or *i*MSE (see Appendix B for the flyer). Reductions could be implemented using a measure or combination of measures that target impact and/or recovery lag criteria (Table 2).

Table 1. The conversion of the pressure assessment qualitative criteria and categories converted into standardised numeric scores.

Criterion

Extent	**Description**	**Raw value (% overlap)**	**Standardised value (to 100%)**
Widespread	Where a sector overlaps with an ecological component by 50% or more.	75	100%
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	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	3%

Frequency (based on original assessment description)*		**Months per year**	**Standardised value (to 100)**
Persistent	Where a pressure is introduced throughout the year	12	100%
Common	Where a pressure is introduced in 8 months of the year	8	67%
Occasional	Where a pressure is introduced in 4 months of the year	4	33%
Rare	Where a pressure is introduced in 1 month per year	1	8%

Resilience		**Recovery (yr)**	**Standardised value (to 100)**
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	100%
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	55%
Moderate	The population will take between 2 and 10 yrs to recover.	6	6%
High	The population will take between 0 and 2 yrs to recover.	1	1%

Persistence		**Persistence (yr)**	**Standardised value (to 100)**
Continous	The pressure continues to impact the ecosystem for more than 100 yrs	100	100%
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	55%
Moderate	The pressure continues to impact the ecosystem for between 2 and 10 yrs	6	6%
Low	The pressure continues to impact the ecosystem for between 0 and 2 yrs	1	1%

DoI		**Severity per interaction**	**Standardised value (to 100)**
Acute	Severe effects after a single interaction	1	100%
Chronic	Severe effects occur when Frequency of introductions more than common (>8)	0.125	13%
Low	Severe effect not expected. For precautionary reasons, we assume a potential effect after 100 introductions.	0.01	1%

Table 2. The pressure and risk assessment criterion targeted by a specific management measure. Management measure typologies are described in full in Piet et al. (in prep). Impact reducing measures are shown in green and recovery lag reduction measures are shown in blue.

	Management Measure				
	Impact Risk Control			**Recovery Lag Control**	
Pressure/Risk Assessment Criterion	*Spatial distribution control*	*Temporal distribution control*	*Input/output control*	*Restoration*	*Remediation*
Spatial extent	✓				
Temporal frequency		✓			
Degree of Impact			✓		
Pressure persistence				✓	
Ecological component resilience					✓

The potential of a management measure to reduce impact risk or recovery lag was tested using a % reduction in the score allocated to the assessment criterion. For example: if the **spatial extent** of an impact chain “Aggregates-Abrasion-Littoral Sediment” was scored as “Local” (Table 1), then its original score, before management, was 0.3 or 30%[1]. If a management measure dictated a 10% reduction in the spatial extent of the aggregate sector, then the post-management spatial extent score would therefore be as follows:

Original extent score – (10% of the original extent score) = Post-management extent score

= 0.3 – (0.3 x 0.1)

= 0.3 – 0.03

= <u>0.27</u>

In this deliverable, we evaluate the potential of management measures to reduce impact risk using some broad examples of hypothetical management measures recently presented at the ODEMM European Roadshows, but further expanded upon those to consider all possible percentage reductions for each measure. **NB We do not attempt to translate reductions in impact risk to changes in ecosystem state e.g. a 10% reduction in selective extraction in fishing does not correspond to a 10% increase in fish.**

[1] As the impact risk and recovery lag aggregate criteria are calculated as the product of three or two criteria respectively, if a measure is introduced that only targets a single assessment criterion, then an equivalent reduction in impact risk will occur irrespective of the mechanism, i.e. a 10% reduction in spatial extent is the same as a 10% reduction in temporal frequency. However, the simultaneous introduction of a spatial distribution control (5 %) and temporal distribution control (5 %) will have a greater reduction in impact risk as two impact risk criteria will be affected.

The management measures evaluated were as follows:

Table 3. Generic Management Options evaluated at the ODEMM European Roadshows 2013 excluding proposed percentage reductions. Mechanisms through which impact risk reductions are achieved are shown in Table 1.

European Regional Sea	Management Option Description
Baltic Sea	1. Reduce the spatial extent of any activity that contributes physical damage§ or loss to the seafloor; 2. Reduce catch (selective extraction of species) by demersal fisheries using suitable controls (e.g. an input control such as greater gear selectivity); 3. Reduce the input of Nitrogen and Phosphorus enrichment by any sector.
Black Sea	1. Reduce the spatial extent of any activity that contributes physical damage§ or loss to the seafloor; 2. Reduce catch (selective extraction of species) by demersal and pelagic fisheries using suitable controls (e.g. an input control such as greater gear selectivity); 3. Reduce the input of Nitrogen and Phosphorus enrichment by any sector.
Mediterranean Sea	1. Reduce the spatial extent of any activity that contributes physical damage§ or loss to the seafloor; 2. Reduce catch (selective extraction of species) by demersal and pelagic fisheries using suitable controls (e.g. an input control such as greater gear selectivity); 3. Reduce the input of Marine litter from any sector.
North East Atlantic	1. Reduce the spatial extent of any activity that contributes physical damage§ or loss to the seafloor; 2. Reduce catch (selective extraction of species) by demersal and pelagic fisheries using suitable controls (e.g. an input control such as greater gear selectivity); 3. Reduce the input of Marine litter from any sector.

§Pressures causing physical damage or loss include: (1) abrasion; (2) sealing; (3) smothering; (4) changes in siltation; and (5) selective extraction of non-living material. Pressure types are described in Knights et al. (2013) and Robinson et al. (*in prep*).

Management Options (MO) were implemented using the *i*MSE tool and the reduction in impact risk evaluated at a whole ecosystem scale. This includes all impact chains that are linked to the specific MO, and therefore all relevant ecological components. We do not consider each ecological component separately or group components (e.g. by GES descriptor) in these examples, but this type of assessment can easily be done using the *i*MSE tool. We compare the reduction in impact risk for all levels of management, from 0 % to 100 %.

Results

Baltic Sea

Number of Impact Chains (baseline)

In the Baltic Sea, a total of 715 impact chains were identified as posing a threat to the ecosystem and its components (Fig. 2). Demersal fish are exposed to the greatest number of impact chains (94), and the water column the fewest (47). The greatest number of impact chains arises from Tourism and Recreation (65), followed by Aquaculture (62) and the Oil & Gas industry (60) with fewest impact chains introduced by the harvesting and collecting sector (5) followed by aggregates (20) and the waste water sector (24).

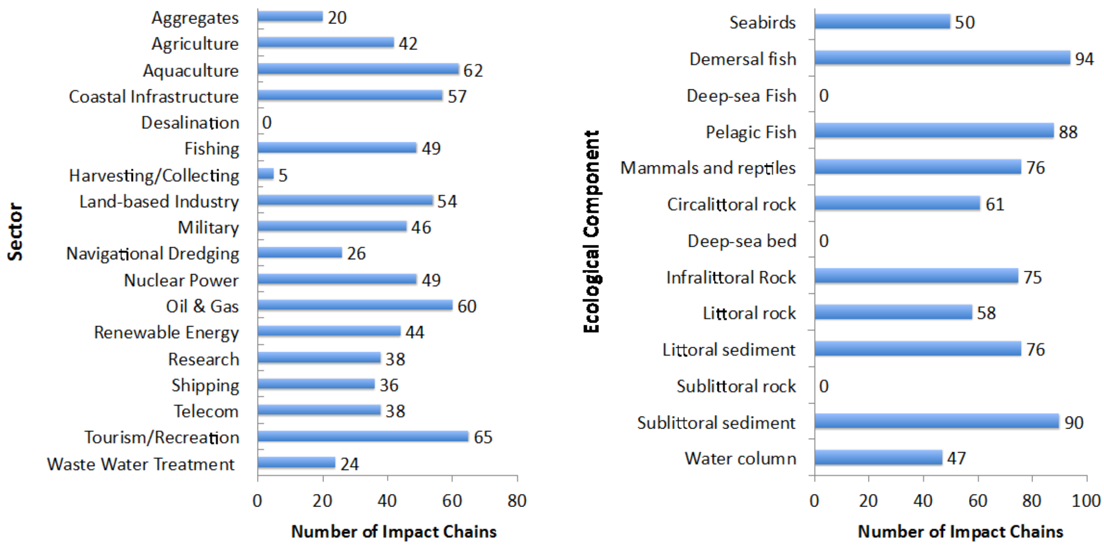


Figure 2. The number of impact chains introduced by sector (all pressure types) and affecting each ecological component of the Baltic Sea ecosystem. A '0' indicates that there are no links i.e. the sector or ecological component does not exist in this region.

Number of Impact Chains affected by the Management Option

The number of impact chains affected by each Management Option (MO) varied greatly (Fig. 3), with the greatest number of chains affected by MO1 (250 impact chains; 15 sectors; 10 ecological components), then MO3 (34 impact chains; 4 sectors; 8 ecological components) followed by MO2 (3 impact chains; 1 sector; 3 ecological components).

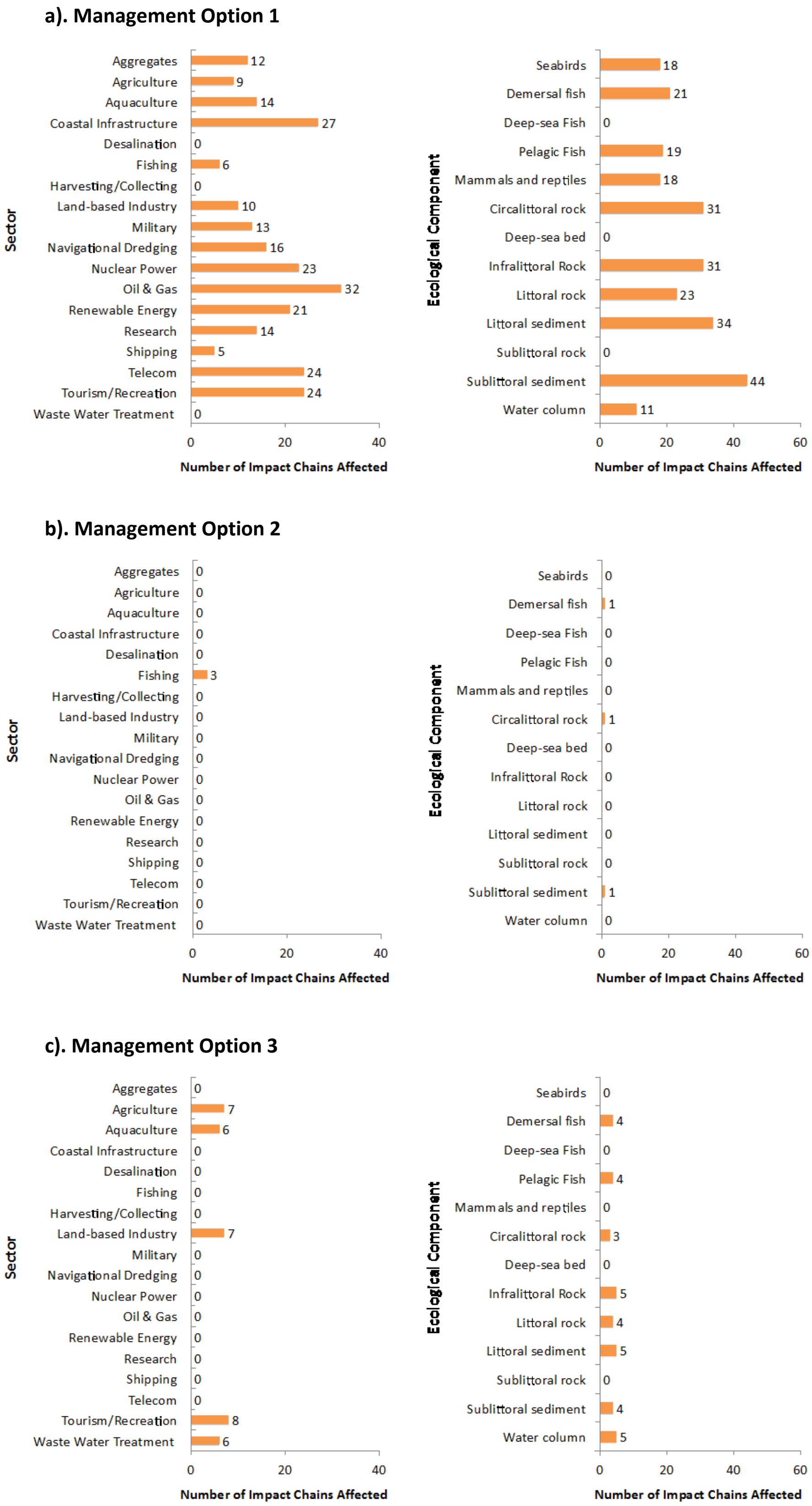


Figure 3. The number of sector-pressure combinations (impact chains) affected by the management option (MO1 [a], MO2 [b], MO3 [c]) specified by sector (left column) and ecological component impacted (right column). The reduction in impact risk is not specified and the contributing pressure types (impact mechanism) are not shown.

Reduction in Impact Risk following Management Option introduction

The number of impact chains alone cannot be used to predict the potential reduction in impact risk following the introduction of a Management Option. Comparisons of the reduction in impact risk for the ecosystem (all ecological components considered) under each management option revealed that despite greater number of impact chains being targeted by an option (e.g. MO1 targets 250 impact chains), the reduction in impact risk may be similar to a Management Option targeting fewer impact chains if the impact risk of those chains differ. In this example, MO1 and MO2 result in broadly similar reductions in impact risk, especially when the MO implementation strategy is less severe (e.g. up to a 20% reduction in criterion score)(Fig. 3). The impact chains targeted by MO2 therefore present a disproportionately large impact risk to the Baltic Sea ecosystem in comparison to those impact chains targeted by MO1 and 3.

Outstanding Impact Risk

The total exclusion of impact chains (100% reductions in criterion scores) indicates that a significant impact risk is outstanding following the implementation of all Management Options (between 87 and 96 %) despite, in some cases, a large number of impact chains being targeted. The greatest reduction in impact risk is expected to occur from MO1 (12.4 %), followed by MO2 (11.1 %) then MO3 (3.9 %)(Fig. 3).

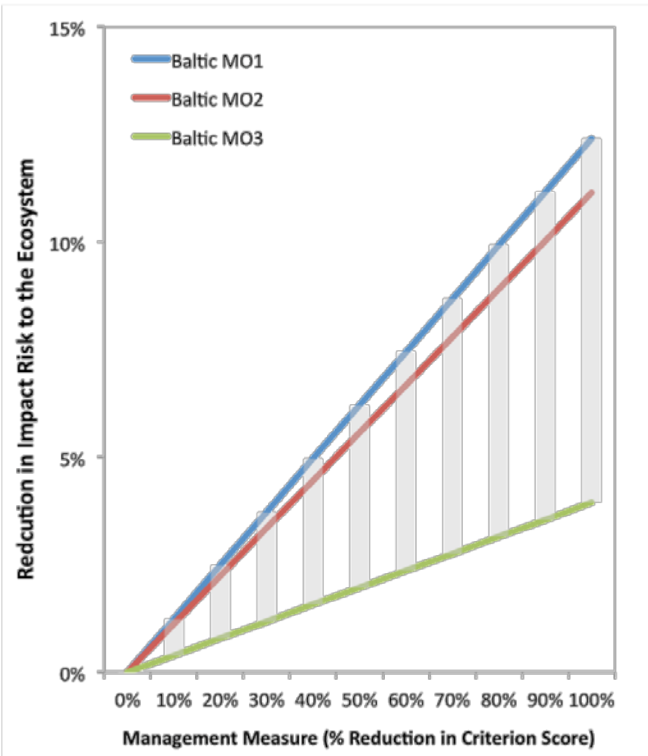


Figure 3. Reductions in impact risk to the ecosystem (all ecological components) following the introduction of 3 different management options (see Table 3). Reductions are shown with changes in the severity of the measure, where 100% equates to the total removal of an impact chain.

Identifying which sectors and pressures to manage

The risk assessment methodology enabled different sectors and pressures to be compared and ranked in terms of the impact risk they pose (the severity of the sector or pressures and its ecological implications) and the time required (*recovery lag*) for the pressure impact to dissipate and recovery of the ecosystem component(s) to occur. In the Baltic Sea, the impact risk varied greatly between sectors, and the recovery lag less so. Fishing was identified as having the greatest impact risk, its score nearly 4x greater than the next highest scores attributed to shipping and agriculture (Fig. 5). This high score is driven by the widespread and frequent occurrence of the sector and the severity of its pressure impacts often being high. The lowest impact risk was attributed to navigational dredging, largely driven by the small spatial footprint of the sector, rare or occasional frequency of occurrence and the relatively low severity of many of its pressures.

The recovery lag between sectors varied little, primarily because many of the sectors generate a similar suite of pressures (see Knights et al. 2013 for discussion). Nevertheless, distinctions could be made between the recovery lags of sectors. Results suggest that ecosystem recovery largely falls within intermediate (values between 0.01 and 0.1) time frames (Fig. 5), indicating recovery would take between 17 - 62 yr for intermediate recovery lag sectors (Figs. 4 and 5). For long recovery lag sectors, namely coastal infrastructure and renewable energy, long-term infrastructure, such as groynes and turbine foundations, are features of the sectors operational requirements, which invariably are not removed and can result in prolonged pressure persistence and slow or no reduction in risk associated.

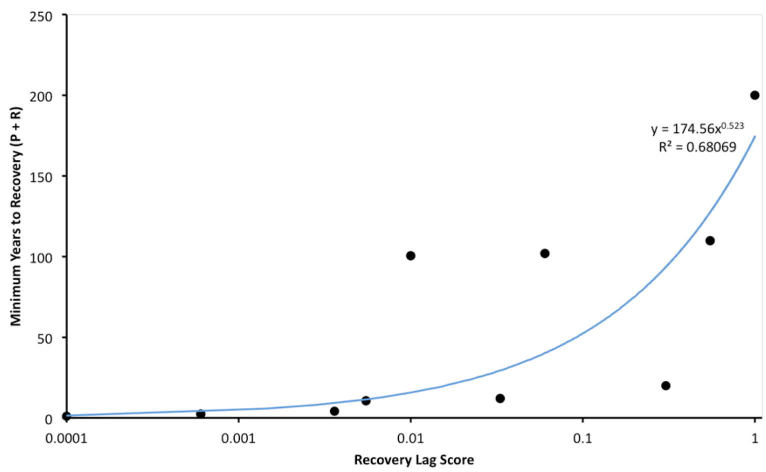


Figure 4. The relationship between recovery lag score and the minimum number of years to recovery. Significant regression is shown ($y = 174.56x^{0.523}$, $R^2 = 0.68$). P = persistence; R = Resilience. Outliers occur when persistence is continuous.

The distribution of pressure types in the index was far wider, with impact risk and recovery lag varying greatly between pressure types (Fig. 4). In several cases, the recovery lag is relatively low (< 0.001) indicating that recovery would require a minimum of 1 yr (e.g. Salinity), whereas other pressures may take considerably longer (e.g. Abrasion = ~11 yr). Differences in recovery lag are driven by the combination of pressure persistence and the recovery rate of the ecological component being impacted. In the cases described here, changes in salinity tend to impact the water column and thus, recovery to pre-impacted conditions can be exceptionally fast. In contrast, benthic communities being impacted by abrasion may require several years to recover despite the persistence of the pressure itself being short-lived.

In some cases, recovery rates are expected to be in excess of 60 yr where recovery lag values > 0.1 (Figs. 4 and 5). Selective extraction of living resources (e.g. the act of fishing) was identified as the pressure type posing the greatest impact risk (Fig. 5); the impact risk associated with that pressure type was considerably higher than for any other pressures, highlighting the reason for the disproportionate reduction in impact risk seen in MO2 in comparison to MO1 (above) given the number of impact chains targeted. This was in contrast to the other well-known pressure sources in the Baltic, such as Nitrogen & Phosphorus enrichment (N&P), which has less of a direct impact risk, but that have a considerably longer recovery lag period (Fig. 5) (61 yr in comparison to ~7 yr required for selective extraction) due to high residence (persistence) times.

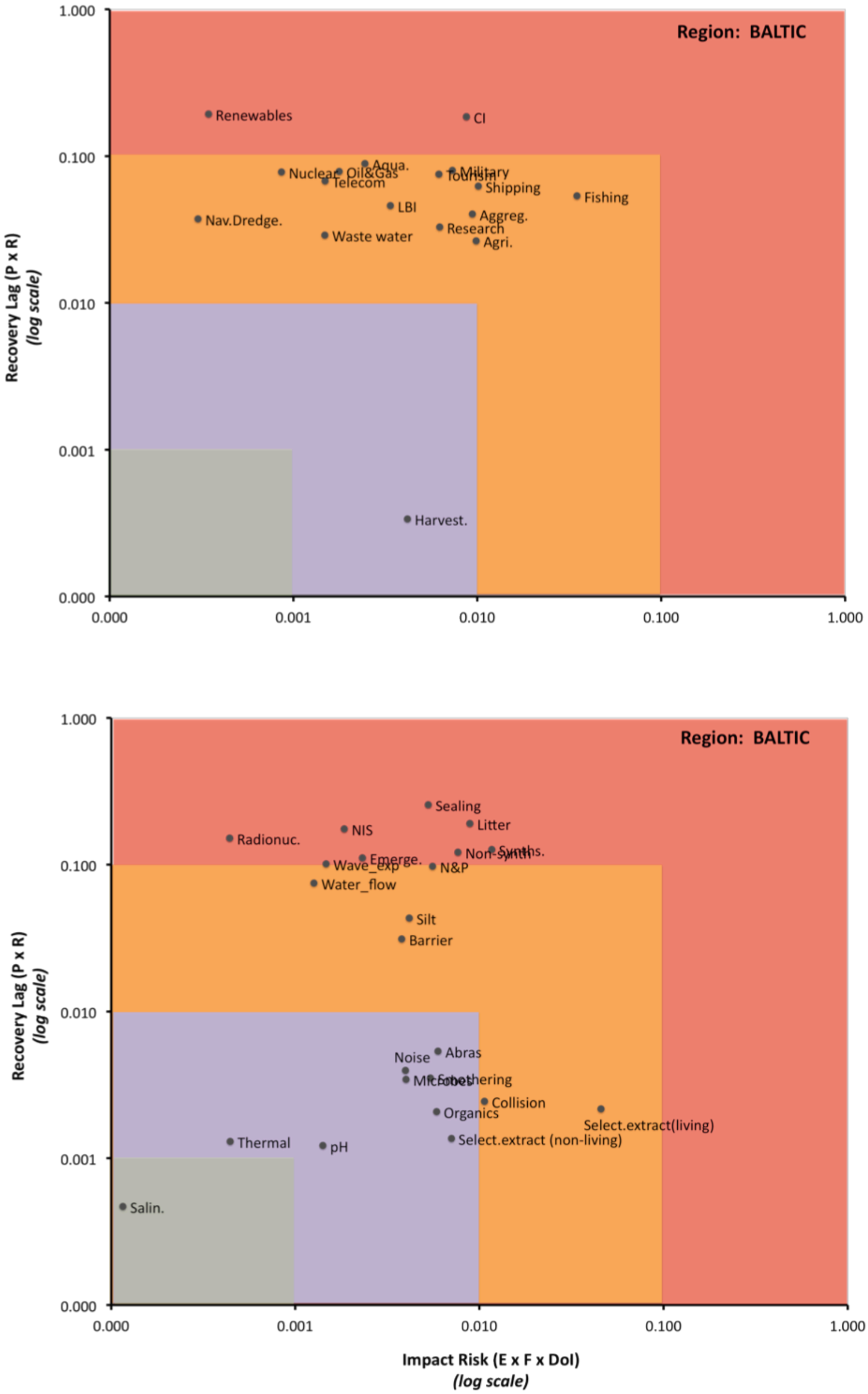


Figure 5. Average of *Impact risk* and *Recovery lag* indices plots by *log*-sectors (top) and *log*-pressure types (bottom) in the Baltic Sea. **NB** Max score on either axis is 1.0.

Black Sea

Number of Impact Chains (baseline)

In the Baltic Sea, a total of 578 impact chains were identified as posing a threat to the ecosystem and its components (Fig. 6). The greatest number of impact chains arises from Tourism and Recreation (65), followed by Oil & Gas (62) and Aquaculture (51) with fewest impact chains introduced by the harvesting and collecting sector (13) followed by the waste water sector (21) and navigational dredging (27). Sublittoral sediments are exposed to the greatest number of impact chains (84), and seabirds the fewest (34).

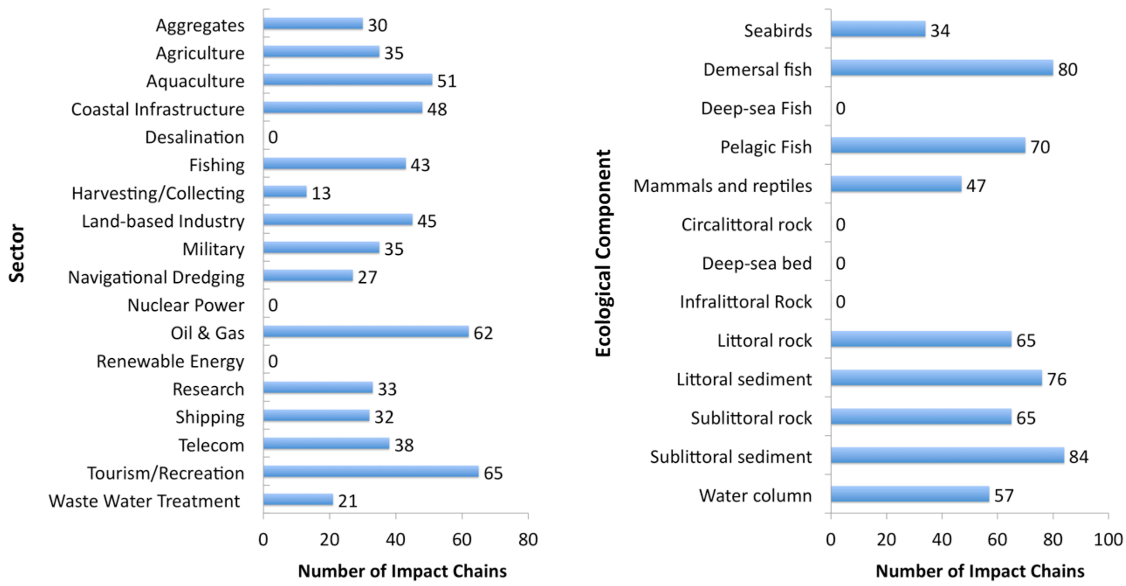


Figure 6. The number of impact chains introduced by sector (all pressure types) and affecting each ecological component of the Black Sea ecosystem. A '0' indicates that there are no links i.e. the sector or ecological component does not exist in this region.

Number of Impact Chains affected by the Management Option

The number of impact chains affected by each Management Option (MO) varied greatly (Fig. 7), with the greatest number of chains affected by MO1 (182 impact chains; 14 sectors; 9 ecological components), then MO3 (30 impact chains; 5 sectors; 7 ecological components) followed by MO2 (7 impact chains; 1 sector; 7 ecological components).

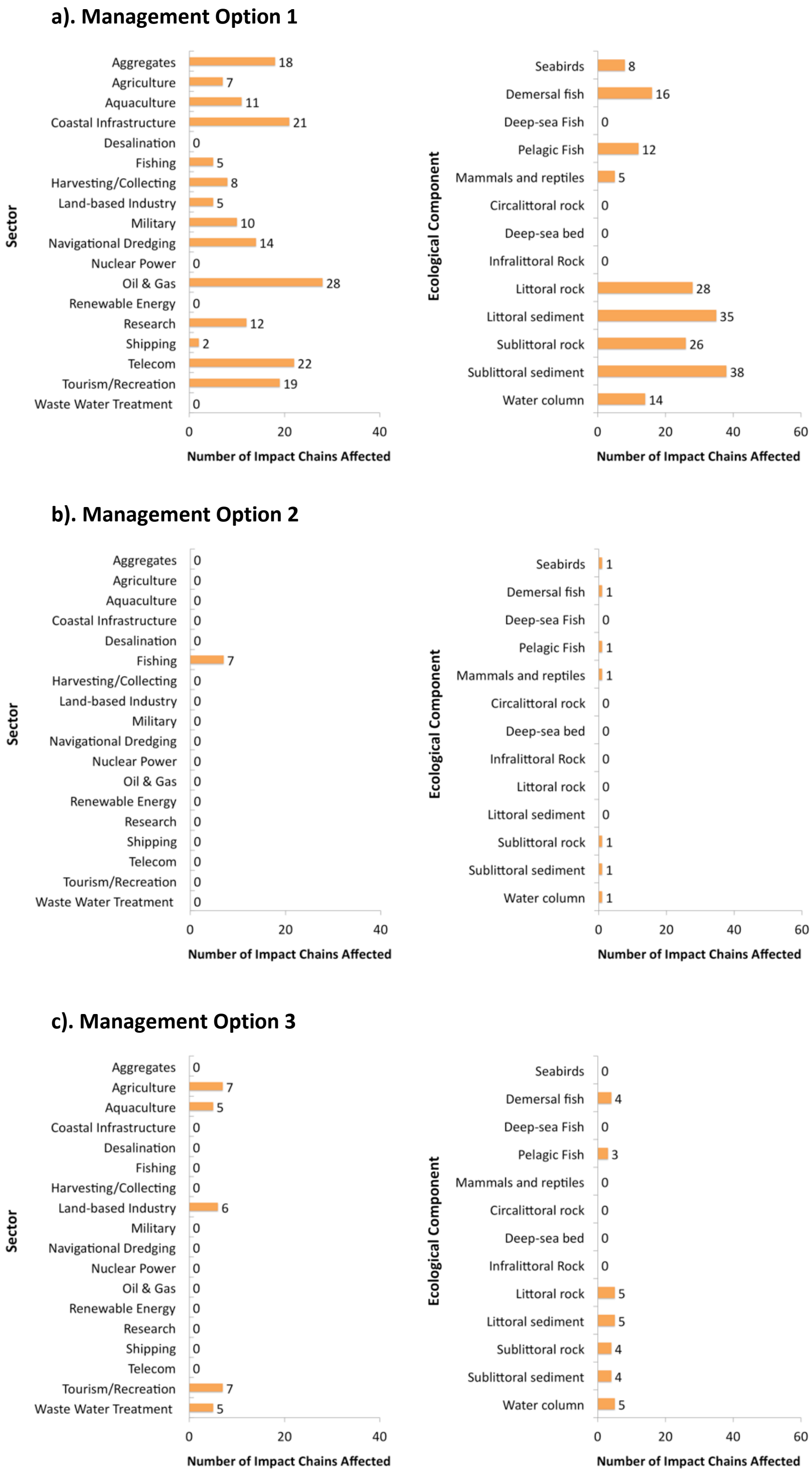


Figure 7. The number of sector-pressure combinations (impact chains) affected by the management option (MO1 [a], MO2 [b], MO3 [c]) specified by sector (left column) and ecological component impacted (right column). The reduction in impact risk is not specified and the contributing pressure types (impact mechanism) are not shown.

Reduction in Impact Risk following Management Option introduction

There were marked differences in the reduction in impact risk following the introduction of each Management Option. The greatest reduction in impact risk was achieved with MO1, followed by MO2, with smallest reductions in impact risk with MO3 (Fig. 8). The amount of impact risk reduced by each MO's differed, with differences apparent even when a 'low severity' option (e.g. a 10% reduction in risk criterion score) was implemented. This indicates that physical pressures (MO1) are a greater source of risk in the Black Sea ecosystem than, in this case, fishing (selective extraction) pressures (MO2) or N&P enrichment (MO3), although the density of impact chains is greater than MO2 and MO3 (Fig. 7) indicating the severity of each chain is lower than that of fishing.

Outstanding Impact Risk

The total exclusion of impact chains (100% reductions in criterion scores) indicates that a significant impact risk is outstanding following the implementation of all Management Options (between 76 and 96 %) despite, in some cases, a large number of impact chains being targeted. The greatest reduction in impact risk is expected to occur from MO1 (23.5 %), followed by MO2 (17.7 %) then MO3 (3.7 %)(Fig. 8).

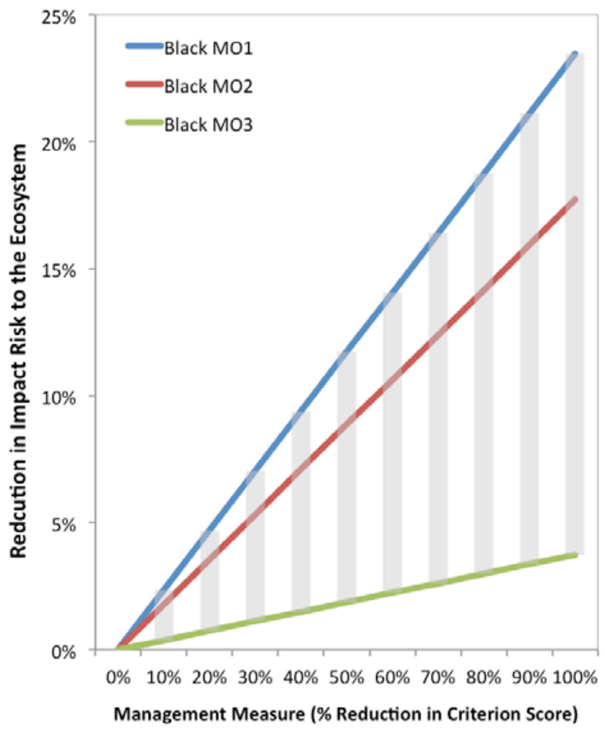


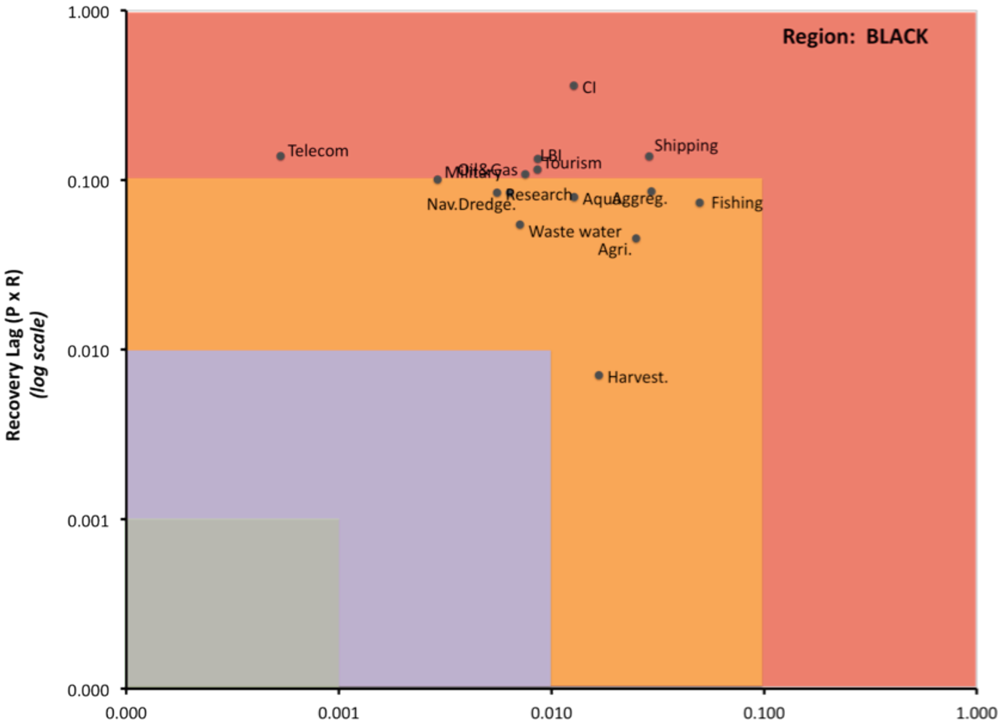
Figure 8. Reductions in impact risk to the ecosystem (all ecological components) following the introduction of 3 different management options (see Table 3). Reductions are shown with changes in the severity of the measure, where 100% equates to the total removal of an impact chain.

Identifying which sectors and pressures to manage

Fishing was identified as having the greatest impact risk, its score 1.5x greater than the next highest scores attributed to shipping and agriculture (Fig. 9). This high score is driven by the widespread and frequent occurrence of the sector and the severity of its pressure impacts often being high. The lowest impact risk was attributed to telecommunications, largely driven by the small spatial footprint of the sector, rare or occasional frequency of occurrence and the relatively low severity of many of its pressures to the ecological components of this system.

Differences between the recovery lag of sectors, in the most part, did not vary greatly, primarily because many of the sectors generate a similar suite of pressures (see Knights et al. 2013 for discussion). Results suggest that ecosystem recovery largely fell within intermediate (values between 0.04 and 0.13) time frames (Fig. 9), indicating recovery would on average take between 34 - 62 yr for intermediate recovery lag sectors (Fig. 9). For long recovery lag sectors, such as coastal infrastructure, long-term infrastructure is a feature of this sector and is invariably not removed such that its pressures are prolonged in persistence automatically resulting in longer periods of recovery. If the impacted component is also slow to recover, the recovery lag can be extended further.

The distribution of pressure types in the index was far wider, with impact risk and recovery lag varying greatly between pressure types (Fig. 9). There are numerous pressures where the recovery lag is relatively low (between 0.003 and 0.007) indicating that recovery would require a minimum of 8-13 yr (e.g. barriers to microbes). In some cases, recovery rates are expected to be in excess of 50 yr where recovery lag values > 0.1 (Figs. 4 and 9). Selective extraction of living resources (e.g. the act of fishing) and the selective extraction of non-living resources (e.g. aggregates removal) were identified as the pressures posing the greatest impact risk (Fig. 9); the impact risk associated with those pressures was at least 6x higher than for any other pressure. These pressures, as well as other physical pressures, appear to have a significant role in impacting the seafloor habitats of the Black Sea, and to a greater extent than some other pressures.



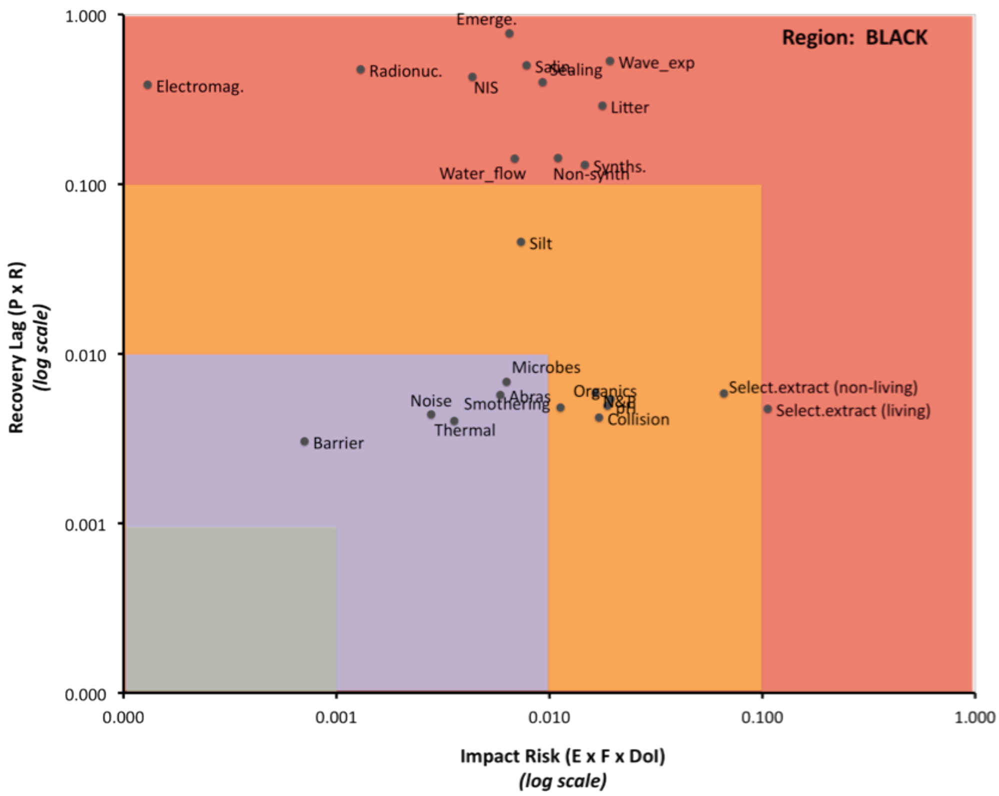


Figure 9. Average of *Impact risk* and *Recovery lag* indices plots by *log*-sectors (top) and *log*-pressure types (bottom) in the Black Sea. **NB** Max score on either axis is 1.0.

Mediterranean Sea

Number of Impact Chains (baseline)

In the Mediterranean Sea, a total of 547 impact chains were identified as posing a threat to the ecosystem and its components (Fig. 10). The greatest number of impact chains arises from Tourism and Recreation (63), followed by Fishing (54), then Aquaculture and Oil & Gas (52) with fewest impact chains introduced by the harvesting and collecting sector (8) followed by the Desalination sector (15) and aggregates (20). Demersal fish are exposed to the greatest number of impact chains (77), and the deep-sea bed the fewest (17).

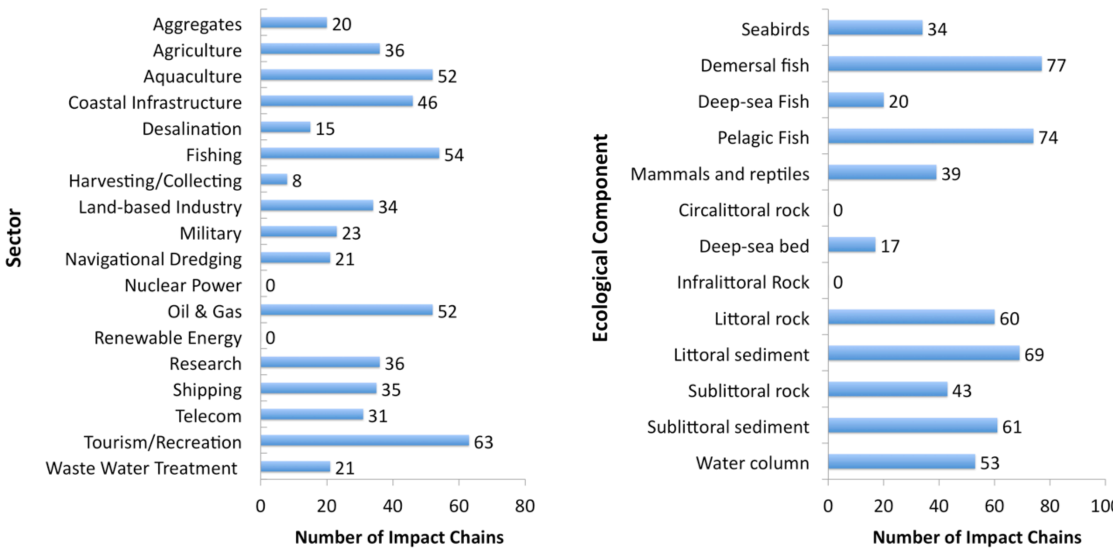


Figure 10. The number of impact chains introduced by sector (all pressure types) and affecting each ecological component of the Mediterranean Sea ecosystem. A '0' indicates that there are no links i.e. the sector or ecological component does not exist in this region.

Number of Impact Chains affected by the Management Option

The number of impact chains affected by each Management Option (MO) varied greatly (Fig. 11), with the greatest number of chains affected by MO1 (185 impact chains; 15 sectors; 11 ecological components), then MO3 (79 impact chains; 9 sectors; 11 ecological components) followed by MO2 (10 impact chains; 1 sector; 10 ecological components).

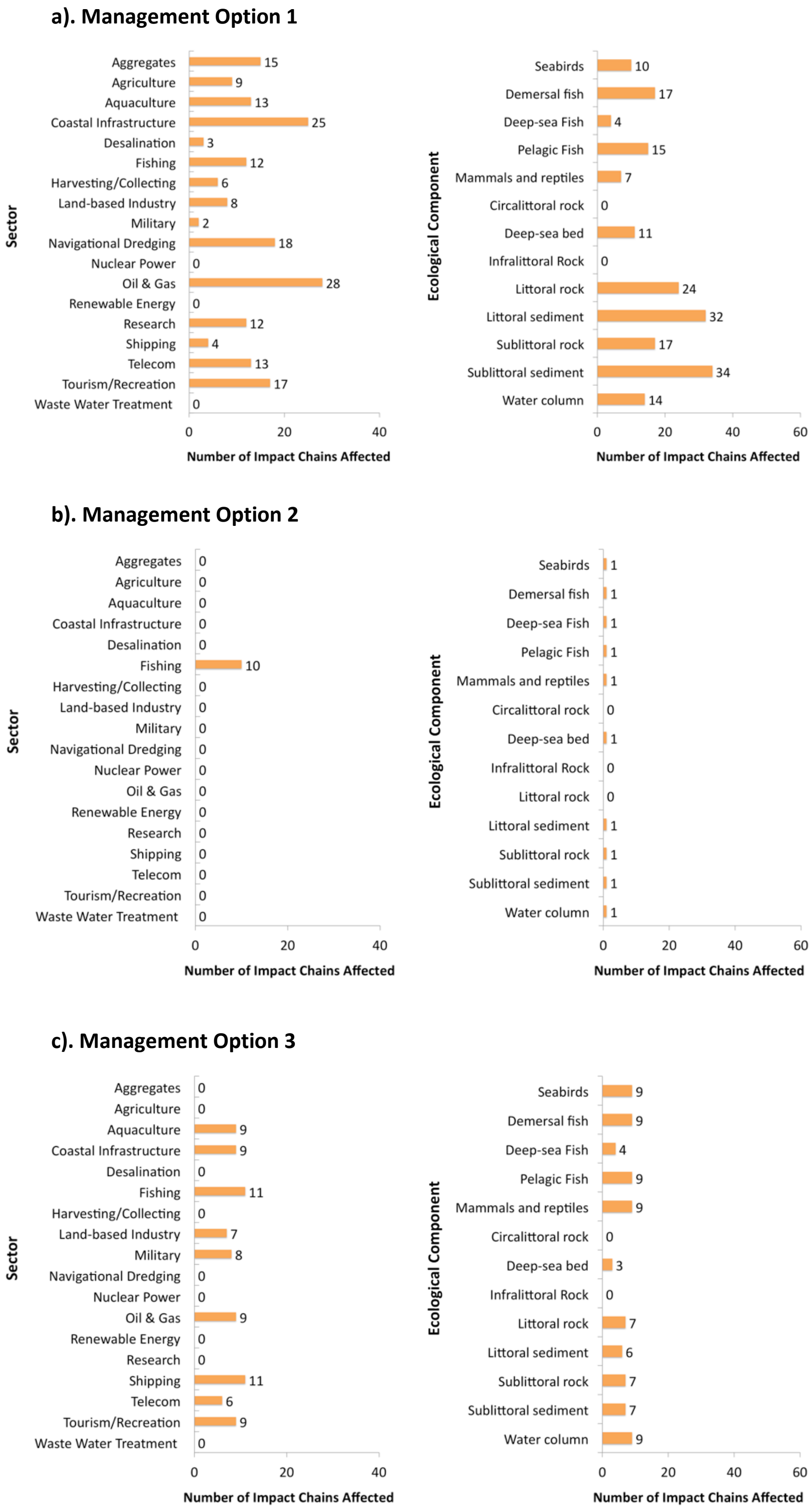


Figure 11. The number of sector-pressure combinations (impact chains) affected by the management option (MO1 [a], MO2 [b], MO3 [c]) specified by sector (left column) and ecological component impacted (right column). The reduction in impact risk is not specified and the contributing pressure types (impact mechanism) are not shown.

Reduction in Impact Risk following Management Option introduction

There were marked differences in the reduction in impact risk following the introduction of each Management Option. The greatest reduction in impact risk was achieved with MO1, followed by MO2, with smallest reductions in impact risk with MO3 (Fig. 12). The amount of impact risk reduced by each MO differed, with differences apparent even when a 'low severity' option (e.g. a 10% reduction in risk criterion score) was implemented. This indicates that physical pressures (MO1) present more than double the impact risk to the Mediterranean Sea ecosystem than fishing (selective extraction) (MO2), and more than 5x the impact risk of marine litter (MO3).

Outstanding Impact Risk

The total exclusion of impact chains (100% reductions in criterion scores) indicates that a significant impact risk is outstanding following the implementation of all Management Options (between 69 and 94 %) despite, in some cases, a large number of impact chains being targeted. The greatest reduction in impact risk is expected to occur from MO1 (30.7 %), followed by MO2 (12.1 %) then MO3 (5.6 %)(Fig. 8).

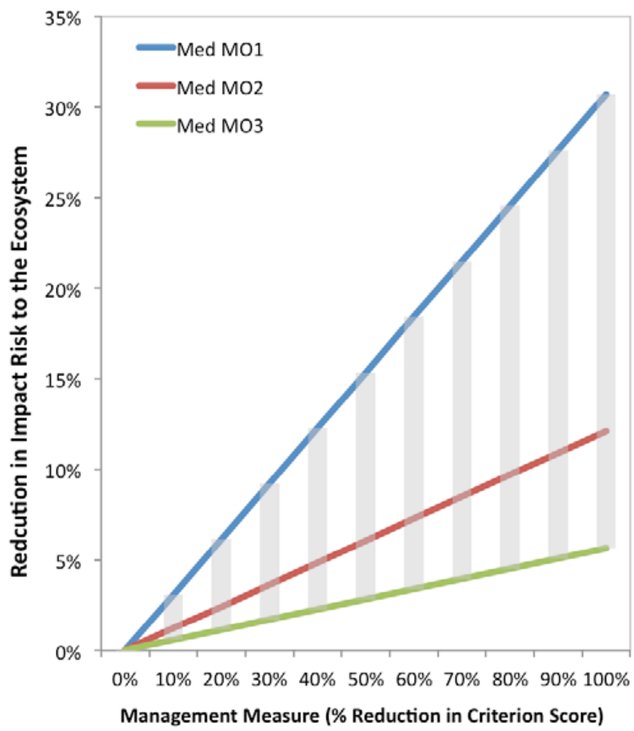


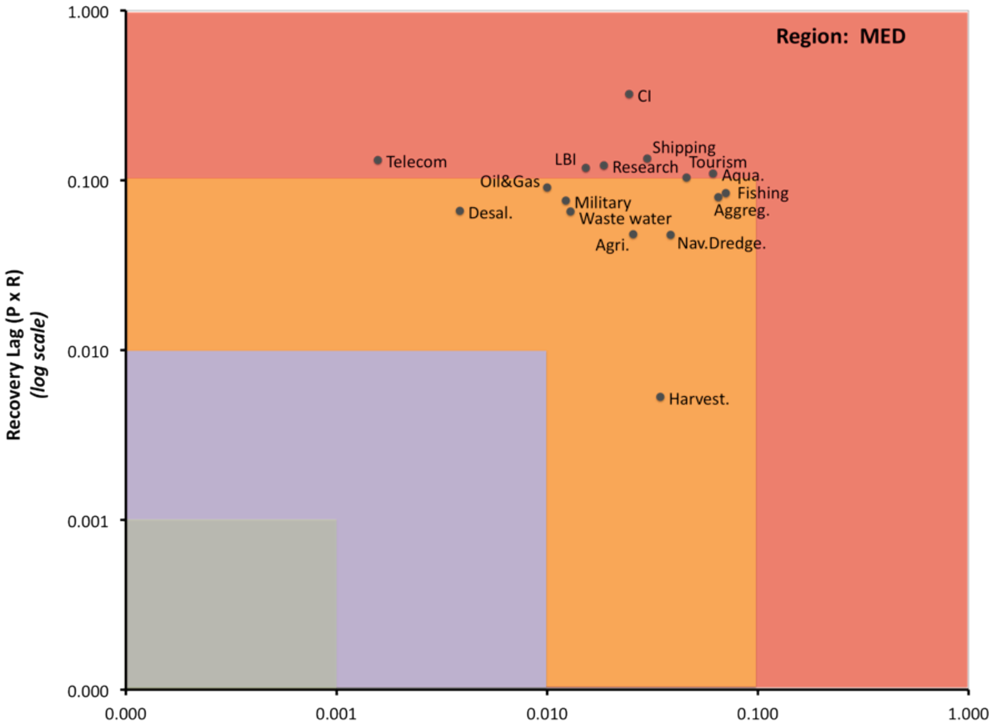
Figure 12. Reductions in impact risk to the ecosystem (all ecological components) following the introduction of 3 different management options (see Table 3). Reductions are shown with changes in the severity of the measure, where 100% equates to the total removal of an impact chain.

Identifying which sectors and pressures to manage

Fishing was identified as having the greatest impact risk, but many of the sectors were clustered closely together, both in terms of impact risk and recovery lag scores (Fig. 13), once again indicating the similarities in the types of pressure, impact risk and ecological components affected. As per the Black Sea, the telecommunications sector has the lowest impact risk associated with its activities.

Differences between the recovery lag of sectors, in the most part, did not vary greatly, primarily because many of the sectors generate a similar suite of pressures (see Knights et al. 2013 for discussion). Results suggest that ecosystem recovery largely falls within intermediate (values between 0.048 and 0.12) time frames (Fig. 13), indicating recovery would, on average, take between 36 - 58 yr (Fig. 13). Coastal infrastructure, is again the sector with the longest recovery lag, here predicted to require ~97 yr for recovery from all pressures (Fig. 13).

The distribution of pressure types in the index was far wider, with impact risk and recovery lag varying greatly between pressure types (Fig. 13). There are primarily two distinct groups; low recovery lag (< 0.01) and high recovery lag (> 0.10) pressures. Lower recovery lag pressures (between 0.003 and 0.007) would require a minimum of 8-13 yr (e.g. smothering to organics), where as high recovery lag pressures would likely require >69 yr for recovery (Fig. 13). Pressure impact risk was once again highly variable, with the selective extraction of living resources (e.g. the act of fishing) and physical pressures, the selective extraction of non-living resources (e.g. aggregates removal) and sealing posing the greatest risks (Fig. 13). Electromagnetic changes and emergence regime were considered of lowest impact risk, limited by their spatial extent and low severity effects.



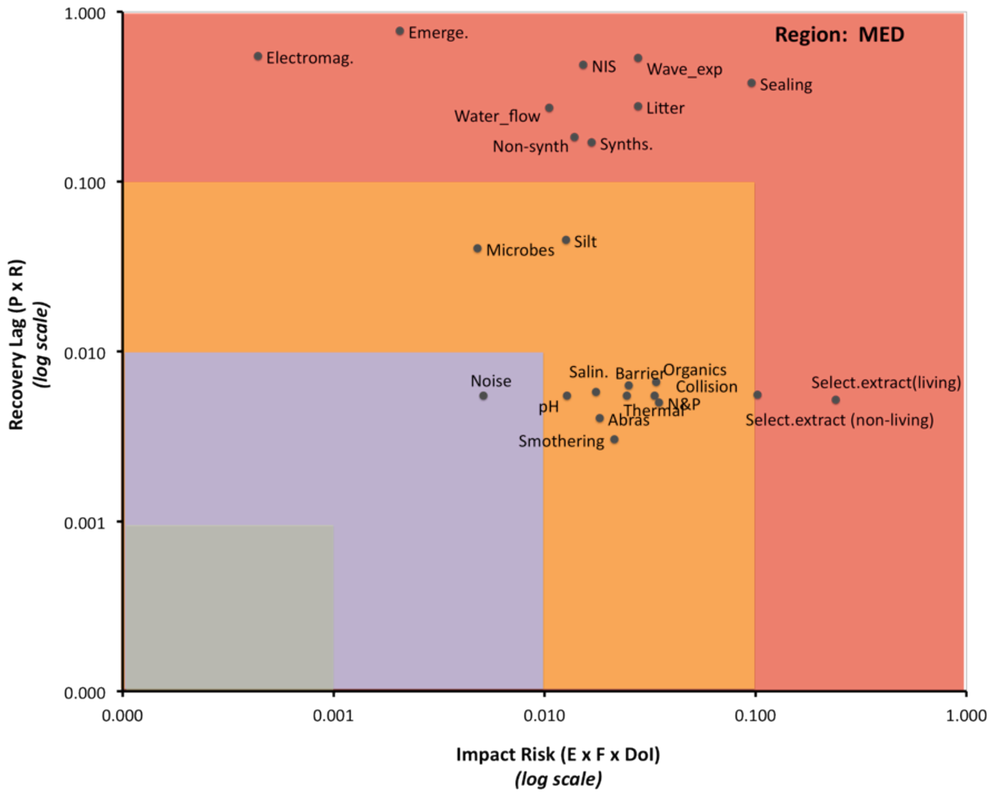


Figure 13. Average of *Impact risk* and *Recovery lag* indices plots by *log*-sectors (top) and *log*-pressure types (bottom) in the Mediterranean Sea. **NB** Max score on either axis is 1.0.

North East Atlantic

Number of Impact Chains (baseline)

In the NE Atlantic, a total of 788 impact chains were identified as posing a threat to the ecosystem and its components (Fig. 14). The greatest number of impact chains arises from Oil & Gas (70), followed by Coastal Infrastructure and Tourism (both 66) with fewest impact chains introduced by the harvesting and collecting sector (8) followed by the waste water sector (20) and navigational dredging (30). Demersal fish are exposed to the greatest number of impact chains (110), and deep-sea fish the fewest (16).

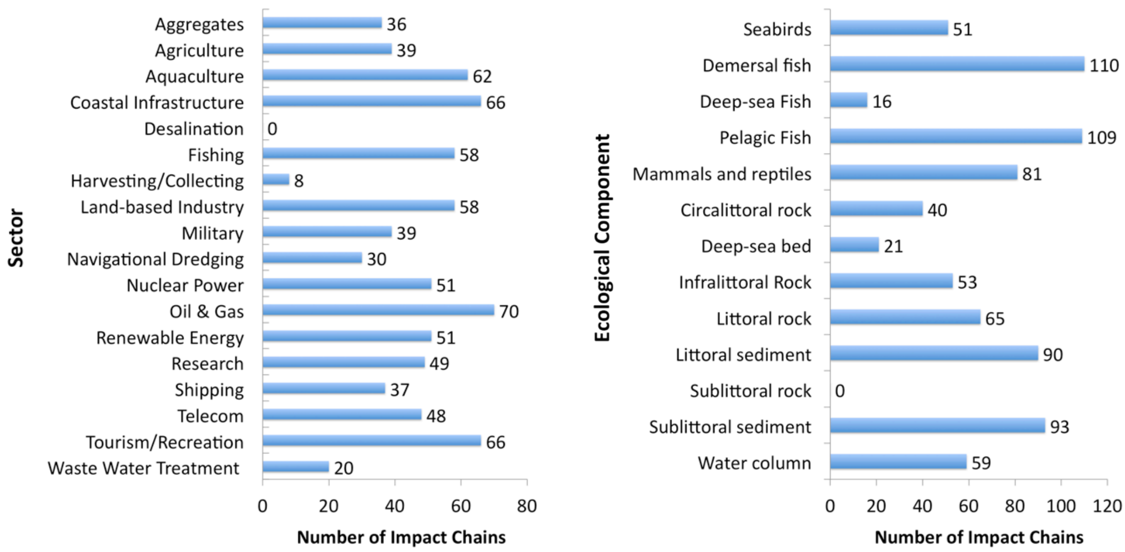


Figure 14. The number of impact chains introduced by sector (all pressure types) and affecting each ecological component of the North East Atlantic ecosystem. A '0' indicates that there are no links i.e. the sector or ecological component does not exist in this region.

Number of Impact Chains affected by the Management Option

The number of impact chains affected by each Management Option (MO) varied greatly (Fig. 7), with the greatest number of chains affected by MO1 (182 impact chains; 14 sectors; 9 ecological components), then MO3 (30 impact chains; 5 sectors; 7 ecological components) followed by MO2 (7 impact chains; 1 sector; 7 ecological components).

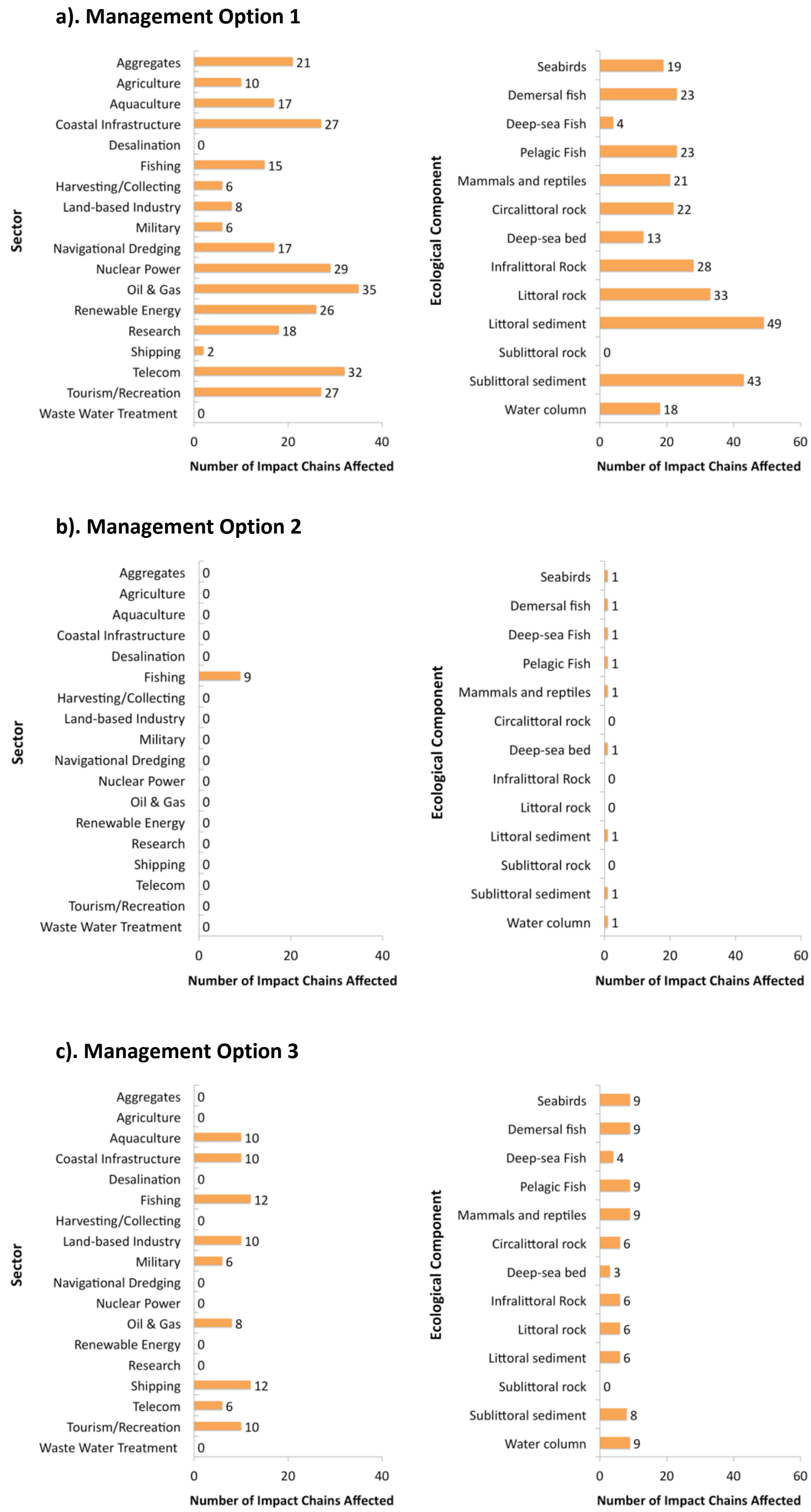


Figure 15. The number of sector-pressure combinations (impact chains) affected by the management option (MO1 [a], MO2 [b], MO3 [c]) specified by sector (left column) and ecological component impacted (right column). The reduction in impact risk is not specified and the contributing pressure types (impact mechanism) are not shown.

Reduction in Impact Risk following Management Option introduction

There were marked differences in the reduction in impact risk following the introduction of each Management Option. The greatest reduction in impact risk was achieved with MO1, although the improvement was only marginally better than MO2 (100^{th} of a % impact risk reduction per 10 % reduction in criterion score). As with all other regions, the smallest reductions in impact risk were achieved with MO3 (Fig. 16). The similarity in impact risk reduction indicates that selective extraction of species by fishing is far greater than the physical pressures impacting the NE Atlantic seafloor, especially considering the number of impact chains targeted by each measure (Fig. 15).

Outstanding Impact Risk

The total exclusion of impact chains (100% reductions in criterion scores) indicates that a significant impact risk is outstanding following the implementation of all Management Options (between 84 and 94 %) despite, in some cases, a large number of impact chains being targeted. The greatest reduction in impact risk is expected to occur from MO1 (23.5 %), followed by MO2 (17.7 %) then MO3 (3.7 %)(Fig. 8).

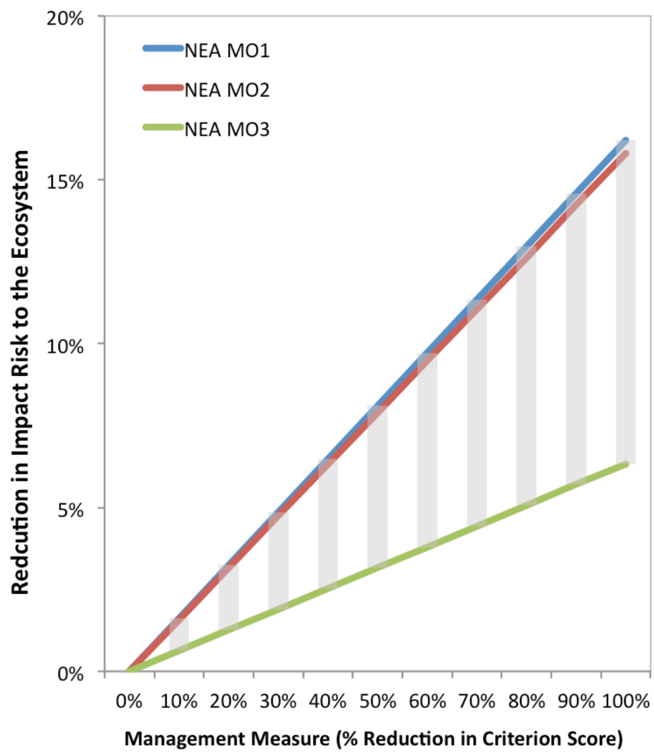


Figure 16. Reductions in impact risk to the ecosystem (all ecological components) following the introduction of 3 different management options (see Table 3). Reductions are shown with changes in the severity of the measure, where 100% equates to the total removal of an impact chain.

Identifying which sectors and pressures to manage

As in all other regional sea areas, fishing was identified as having the greatest impact risk, its score 2.3x greater than the next highest scores attributed to shipping and agriculture (Fig. 17). Again, this high score is driven by the widespread and frequent occurrence of the sector and the often high severity of its pressures. The lowest impact risk was attributed to nuclear power, largely driven by the small spatial footprint of the sector, relatively rare occurrence and often low severity of this sector's pressures.

As in other regions, differences between the recovery lag of sectors, in the most part, did not vary greatly. Results suggest that the ecosystem recovery largely fall within intermediate to high (values between 0.045 and 0.304) time frames (Fig. 17), indicating recovery could take at least 34 - 94 yr, with long recovery lag sectors being those such as coastal infrastructure and renewable energy.

The distribution of pressure types in the index was far wider, with impact risk and recovery lag varying greatly between pressure types (Fig. 17). Again, pressures could broadly be separated into two groups: lower recovery lag with values between 0.005 and 0.008 (11 – 14 yr) and high recovery lag values of > 0.1 (>52 yr). Selective extraction of living resources (e.g. the act of fishing) was again the pressure of greatest impact risk (0.14), 2.8x greater than the next greatest, risk of collision (0.05). Other physical pressures had considerably lower impact risk scores (abrasion [0.009]; sealing [0.009]; siltation [0.005]; selective extraction of non-living resources [0.03]; and smothering [0.007]) highlighting the reason for the performance of MO2 in reducing impact risk (Fig. 16) despite targeting far fewer impact chains (Fig. 15a and 15b).

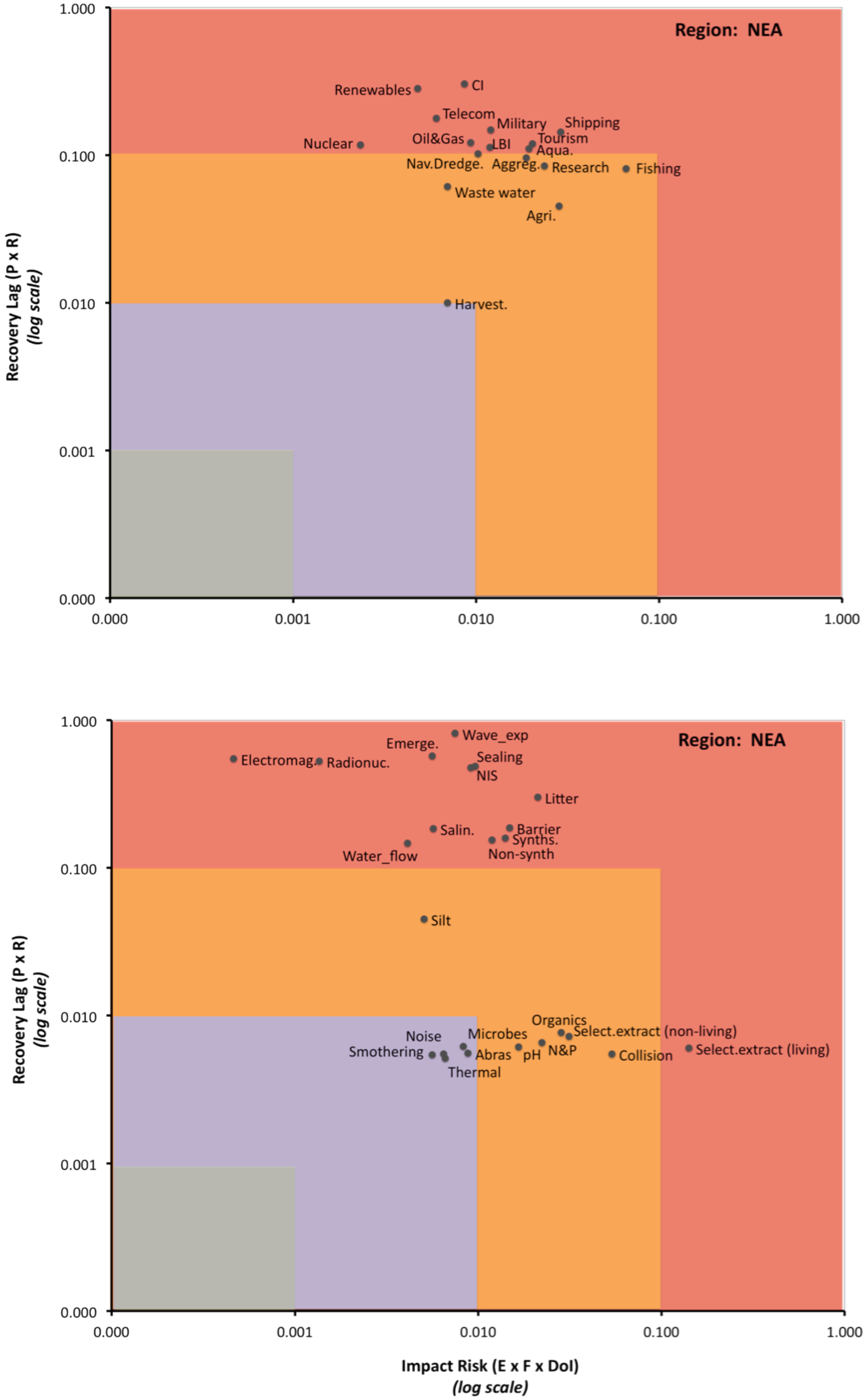


Figure 17. Average of *Impact risk* and *Recovery lag* indices plots by *log*-sectors (top) and *log*-pressure types (bottom) in the North East Atlantic. **NB** Max score on either axis is 1.0.

Conclusions

- The risk assessment was able to identify threats in Europe's regional seas and could separate those threats by their impact risk and the recovery lag. The impact risk between sectors varied greatly in all regions, ranging from low impact risk sectors, such as telecommunications, renewable energy (where present) and navigational dredging, to high impact sectors of fishing, shipping, aggregates, and agriculture. In contrast, recovery lag between sectors was generally less variable, with the majority of sectors displaying intermediate to high recovery lag scores suggesting that, on average, recovery would take between 35-100 yr if all pressures associated with those sectors were stopped.

- Comparison of separate pressure types revealed more notable differences, in particular, the recovery lag associated with each pressure type which could be separated into two distinct groups; those of low to intermediate lag (e.g. NE Atlantic scores of between <0.01 [<16 yr to recovery]) and high recovery lag pressures (values >0.1 [> 50 yr to recovery]). In general, recovery from any sector pressure combination is not predicted to be quick. This can be explained by the fact that even where ecological components might have high recovery rates, the persistance of the pressure they are being impacted by might be long even when all activities introducing it are prohibited (and vice versa).

- Impact risk scores for pressures were also more varied than the recovery lag scores, with a range of high impact risk pressures, such as the selective extraction of species, to relatively low impact risk pressures, such as electromagnetic changes. High impact risk pressures are predicted to cause widespread and severe impacts and require fewer occurrences to impact the ecosystem in comparison to low impact risk pressures. However, this does not mean that we should not be concerned with pressures of lower impact risk. Changes in the frequency or spatial extent of pressure introductions could lead to those pressures becoming of greater impact risk and sectors introducing those pressures should be controlled such that impact risk does not increase.

- The performance of 3 management options (MO) was assessed in terms of their effectiveness in reducing impact risk, where greater effectiveness is defined as an MO that reduces risk to a greater degree than another MO. The effectiveness of MO did not differ between European regions with MO1 most effective, MO3 of intermediate effectiveness, and MO2 the least effective. However, the extent to which each MO reduced risk did vary between regions indicating differences in the impact risk associated with sector/pressure combinations in the region as well as illustrating the capability of the approach to resolve regional differences. The greatest reduction in risk from any one MO were achieved in the Mediterranean Sea (up to a maximum of ~30% following MO1), and least effective in the Baltic Sea (a maximum reduction of ~12 %) if the most severe derivation of the measure was implemented.

- Here, we assessed only 3 MO's with broad objectives. There is, however, a wide range of possible MO's that could be adopted by managers, using mechanisms such as remediation, restoration, spatial and temporal distribution controls and input/output controls to reduce risk and improve ecosystem health (Piet et al. In prep). We developed an integrated Management Strategy Evaluation (*i*MSE) tool to combine the pressure assessment outcomes (Robinson et al. In prep) from each regional sea with the risk assessment framework (see Knights et al. in prep). This tool allows the range of management options to be assessed and adopts the linkage framework (Koss et al. 2011, Knights et al. 2013) to describe the relationship between sectors and the ecosystem components (via their pressures) and allows management options to be designed based on the identified relationships.

- We present the risk assessment results at an ecosystem level, whereby all ecological components are included in the analysis. The analysis can be modified to consider specific sectors, pressures or ecological components or grouped in such a way that the reduction in risk to GES descriptors (e.g. seafloor integrity) can be determined. We will demonstrate grouping data in this way in an upcoming paper (Knights et al. *in prep*).

- The impact risk and recovery lag scores per linkage or group of linkages as calculated by the *i*MSE tool can be used to prioritise management toward impact chains posing the greatest risk to the ecosystem – the overview of these data shown in this report. Management could be prioritised by a combination of the impact of the sector/pressure and the time period expected for benefits to be realised. Using a simple matrix, we can place sectors or pressures into arbitrary management groups (Fig. 18 below), whereby each group gives an indication of the impact associated with a particular sector or pressure and an expectation of when ecosystem state benefits are likely to be seen. For example, if the focus is simply that we wish to improve ecosystem health, then sectors or pressures in quadrants 2b and 3 should be prioritised for management given they have the greatest impact, irrespective of the time required for recovery. However, if time is a factor in the decision-making process, for example, improvements need to be seen within 15 yr, then management should focus on the sectors or pressures that occur in quadrants

1 and/or 2b, but with recognition that reductions in risk and thus, changes in state, following the management of sectors/pressures in quadrant 1 are likely to be the least.

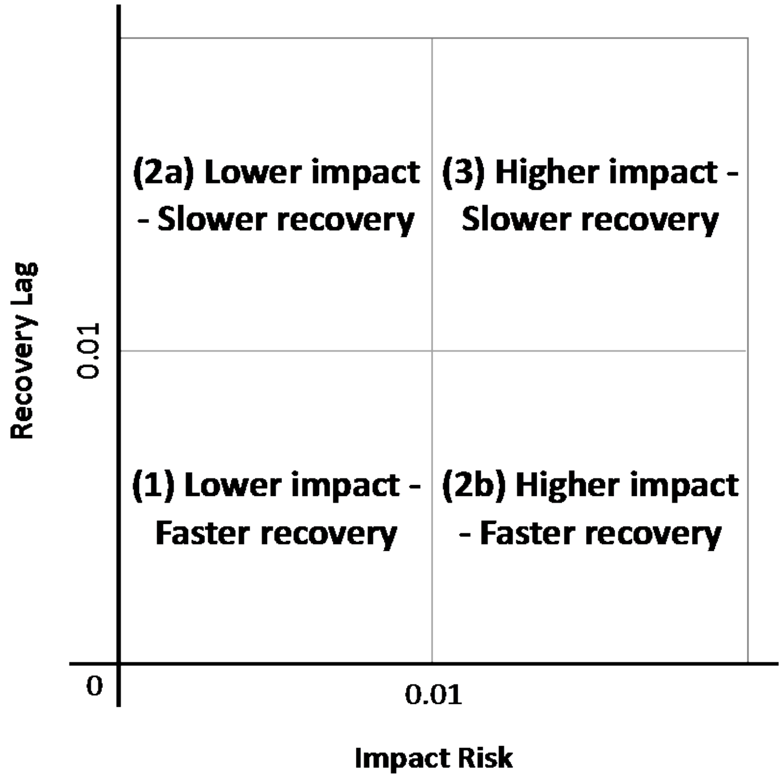


Figure 18. Management quadrants: Prioritising management based on impact risk and recovery lag scores. Tipping points are abitrary and occur at 0.01 scores on both impact risk and recovery lag axes for illustration purposes. These can be altered based on a managers requirements e.g. a recovery lag score of 0.004 equates to a recovery of 10 yr. Minimum and maximum scores on each axes are 0 and 1.

References

Airoldi, L. and M. W. Beck. 2007. Loss, status and trends for coastal marine habitats of Europe. Oceanography and Marine Biology, Vol 45 45:345-405.

Astles, K. L., M. G. Holloway, A. Steffe, M. Green, C. Ganassin, and P. J. Gibbs. 2006. An ecological method for qualitative risk assessment and its use in the management of fisheries in New South Wales, Australia. Fisheries Research 82:290-303.

Ban, N. C., H. M. Alidina, and J. A. Ardron. 2010. Cumulative impact mapping: Advances, relevance and limitations to marine management and conservation, using Canada's Pacific waters as a case study. Marine Policy 34:876-886.

Bax, N. J. and A. Williams. 2001. Seabed habitat on the south-eastern Australian continental shelf: context, vulnerability and monitoring. Marine and Freshwater Research 52:491-512.

Bottrill, M. C., L. N. Joseph, J. Carwardine, M. Bode, C. N. Cook, E. T. Game, H. Grantham, S. Kark, S. Linke, E. McDonald-Madden, R. L. Pressey, S. Walker, K. A. Wilson, and H. P. Possingham. 2008. Is conservation triage just smart decision making? Trends in Ecology & Evolution 23:649-654.

Breen, P., L. A. Robinson, S. I. Rogers, A. M. Knights, G. Piet, T. Churlova, P. Margonski, K. N. Papadopoulou, E. Akoglu, Z. Finenko, V. Fleming-Lehtinen, B. S. Galil, F. Goodsir, M. Goren, F. Kremena, O. Krivenko, J. Leppanen, V. Markantonatou, S. Moncheva, T. Oguz, L. Paltriguera, F. Timofte, and F. Thomsen. 2012. An environmental assessment of risk in achieving good environmental status to support regional prioritisation of management in Europe. Marine Policy doi: 10.1016/j.marpol.2012.02.003.

Burgman, M. 2005. Risks and Decisions for Conservation and Environmental Management. Cambridge University Press, Cambridge, UK.

Campbell, M. L. and C. Gallagher. 2007. Assessing the relative effects of fishing on the New Zealand marine environment through risk analysis. ICES Journal of Marine Science 64:256-270.

CENR. 1999. Ecological risk assessment in the federal government. CENR/5-99/001., Committee on Environment and Natural Resources, National Science and Technology Council, Washington, DC, USA.

Cooke, R. M. and L. H. J. Goossens. 2004. Expert judgement elicitation for risk assessments of critical infrastructures. Journal of Risk Research 7:643-656.

EC. 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). Pages 19-40 Official Journal of the European Union.

Elliott, M. 2002. The role of the DPSIR approach and conceptual models in marine environmental management: an example for offshore wind power. Marine Pollution Bulletin 44:Iii-Vii.

Fletcher, W. J. 2005. The application of qualitative risk assessment methodology to prioritize issues for fisheries management. ICES Journal of Marine Science 62:1576-1587.

Fletcher, W. J., J. Shaw, S. J. Metcalf, and D. J. Gaughan. 2010. An ecosystem-based fisheries management framework: the efficient, regional-level planning tool for management agencies. Marine Policy 34:1226-1238.

Francis, R. I. C. 1992. Use of risk analysis to assess fishery management strategies - a case-study using orange roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. Canadian Journal of Fisheries and Aquatic Sciences 49:922-930.

Halpern, B. S., S. Walbridge, K. A. Selkoe, C. V. Kappel, F. Micheli, C. D'Agrosa, J. F. Bruno, K. S. Casey, C. Ebert, H. E. Fox, R. Fujita, D. Heinemann, H. S. Lenihan, E. M. P. Madin, M. T. Perry, E. R. Selig, M. Spalding, R. Steneck, and R. Watson. 2008. A global map of human impact on marine ecosystems. Science 319:948-952.

Hobday, A. J., A. D. M. Smith, I. C. Stobutzki, C. Bulman, R. Daley, J. M. Dambacher, R. A. Deng, J. Dowdney, M. Fuller, D. Furlani, S. P. Griffiths, D. Johnson, R. Kenyon, I. A. Knuckley, S. D. Ling, R. Pitcher, K. J. Sainsbury, M. Sporcic, T. Smith, C. Turnbull, T. I. Walker, S. E. Wayte, H. Webb, A. Williams, B. S. Wise, and S. Zhou. 2011. Ecological risk assessment for the effects of fishing. Fisheries Research 108:372-384.

Holman, I. P., R. J. Nicholls, P. M. Berry, P. A. Harrison, E. Audsley, S. Shackley, and M. D. A. Rounsevell. 2005. A regional, multi-sectoral and integrated assessment of the impacts of climate and socio-economic change in the UK: II Results. Climatic Change 71:43-73.

Hope, B. K. 2006. An examination of ecological risk assessment and management practices. Environment International 32:983-995.

Knights, A. M., R. S. Koss, and L. A. Robinson. 2013. Identifying common pressure pathways from a complex network of human activities to support ecosystem-based management. Ecological Applications 23:755-765.

Koss, R. S., A. M. Knights, A. Eriksson, and L. A. Robinson. 2011. ODEMM Linkage Framework Userguide. ODEMM Guidance Document Series No.1. University of Liverpool, Liverpool.

La Jeunesse, I., M. Rounsevell, and M. Vanclooster. 2003. Delivering a decision support system tool to a river contract: a way to implement the participatory approach principle at the catchment scale? Physics and Chemistry of the Earth 28:547-554.

Leslie, H. M. and K. L. McLeod. 2007. Confronting the challenges of implementing marine ecosystem-based management. Frontiers in Ecology and the Environment 5:540-548.

Odermatt, S. 2004. Evaluation of mountain case studies by means of sustainability variables - A DPSIR model as an evaluation tool in the context of the North-South discussion. Mountain Research and Development 24:336-341.

Piet, G. J., R. H. Jongbloed, A. M. Knights, J. E. Tamis, A. Paijmans, M. van der Sluis, P. de Vries, and L. A. Robinson. In prep. A framework for integrated ecosystem-based management based on risk assessment.

Robinson, L. A., G. J. Piet, T. Churlova, P. Margonski, K. N. Papadopoulou, V. Abaza, E. Akoglu, P. Breen, A. Eriksson, Z. Finenko, V. Fleming-Lehtinen, B. S. Galil, F. Goodsir, M. Goren, R. Jongbloed, F. Kremena, O. Krivenko, J. Leppanen, V. Markantonatou, S. Moncheva, T. Oguz, J. Rogers, C. Smith, J. Tamis, F. Timofte, F. Thomsen, and A. M. Knights. In prep. A pressure assessment to identify the major threats to marine ecosystems, using information on ecological footprints, sensitivity and management potential.

Rounsevell, M. D. A., T. P. Dawson, and P. A. Harrison. 2010. A conceptual framework to assess the effects of environmental change on ecosystem services. Biodiversity and conservation 19:2823-2842.

Samhouri, J. and P. S. Levin. 2012. Linking land- and sea-based activities to risk in coastal ecosystems. Biological Conservation 145:118-129.

Scheren, P. A. G. M., C. Kroeze, F. J. J. G. Janssen, L. Hordijk, and K. J. Ptasinski. 2004. Integrated water pollution assessment of the Ebrie Lagoon, Ivory Coast, West Africa. Journal of Marine Systems 44:1-17.

Smith, A. D. M., E. J. Fulton, A. J. Hobday, D. C. Smith, and P. Shoulder. 2007. Scientific tools to support the practical implementation of ecosystem-based fisheries management. ICES Journal of Marine Science 64:633-639.

Stobutzki, I., M. Miller, and D. Brewer. 2001. Sustainability of fishery bycatch: a process for assessing highly diverse and numerous bycatch. Environmental Conservation 28:167-181.

Williams, A., J. Dowdney, A. D. M. Smith, A. J. Hobday, and M. Fuller. 2011. Evaluating impacts of fishing on benthic habitats: A risk assessment framework applied to Australian fisheries. Fisheries Research 112:154-167.

Appendix A: List of Sectors, Pressures and Ecological Components (after Robinson & Knights, 2011 and Robinson et al. *in prep*)

Table A1. The list of broad Sectors that contribute at least one pressure to at least one of Europe's regional sea ecosystems

Sector	Code	Type
Aquaculture	1	Fin-fish
		Macro-algae
		Shellfisheries
Fishing	2	Benthic trawls
		Fixed nets
		Pelagic trawls
		Potting/creeling
		Suction (hydraulic dredging)
Shipping	3	Cargo vessels/tankers
		Transport (ferries/liners)
Renewable Energy	4	Tidal
		Wave
		Wind
Oil & Gas	5	Offshore prospecting and operations
		Land-based power stations
Nuclear Power	6	Land-based power stations
Telecommunications	7	Communication cables
Aggregates	8	Inorganic mine and particulate waste
		Maerl
		Rock/Minerals (coastal quarrying)
		Sand/gravel (aggregates)
Navigational Dredging	9	Capital dredging
		Maintenance dredging
Coastal Infrastructure	10	Seawalls/Breakwaters/Groynes

		Artificial reefs Beach replenishment Culverting lagoons Dock/port facilities Land claim Marinas Urban dwellings, i.e. housing and other buildings.
Land-based Industry	11	Industrial sites with discharges into the marine environment
Agriculture and Forestry	12	Coastal farming and/or forestry where discharges and runoff reach the marine environment from the catchment area
Tourism/Recreation	13	Angling Boating/Yachting Diving/Dive sites Public beaches Tourist Resorts Water sports
Military	14	Military (ships, munition)
Research	15	Animal Sanctuaries Marine Archaeology Marine Research
Desalination	16	Desalination plants with abstraction of seawater
Waste Water Treatment	17	Wastewater discharges that reach the marine environment
Collecting/Harvesting	18	Bait digging Bird Eggs Shellfish hand collecting Peels Curios

Table A2. List of human pressures associated with sectors operating in Europe's regional seas.

Pressure Code	Pressure Name	Pressure Definition	Listed in the MSFD
1.	Smothering	Cover habitat surface with materials falling to the seafloor from activities in the water column (e.g. waste substances from aquaculture cages), on land (e.g. in runoff or effluent), or around activities (e.g. around trawling gear), or from disposal of materials onto the seafloor (e.g. disposal of materials from dredging). Smothering may lead to reduced functioning (e.g. feeding) or mortality of benthic animals living on, or in, the seafloor.	Yes
2.	Sealing	Physical loss of habitat from sealing by permanent construction (e.g. Coastal defences, wind turbines)	Yes
3.	Changes in siltation	Change in the concentration and/or distribution of suspended sediments in the water column from runoff, dredging etc.	Yes
4.	Abrasion	Physical interaction of human activities with the seafloor and with seabed fauna/flora causing physical damage and/or mortality (e.g. from trawling or anchoring).	Yes
5.	Selective extraction of non-living resources	Includes sand and gravel (aggregates) extraction, removal of surface substrates for exploration of seabed and subsoil, or removal of seawater for e.g. cooling industrial plants or for desalination	Yes
6.	Underwater noise	Underwater noise created from shipping, acoustic surveys, etc.	Yes
7.	Marine litter	Litter originating from numerous sources but entering the marine environment and consisting of different materials including: plastics, metal, glass, rubber, wood and cloth	Yes
8.	Thermal change	Change in temperature of the water (average, range or variability) e.g. due to outfalls from industrial plants	Yes
9.	Salinity change	Change in salinity (average, range or variability), e.g. due to outfalls from industrial plants or alterations in coastal structures affecting mixing	Yes
10.	Introduction of synthetic compounds	Introduction of manmade compounds such as pesticides, antifoulants and pharmaceuticals into marine waters	Yes

11.	Introduction of non-synthetic compounds	Introduction of heavy metals and hydrocarbons into marine waters	Yes
12.	Introduction of radionuclides	Introduction of radionuclides into marine waters	Yes
13.	Nitrogen and Phosphorus enrichment	Input of fertilisers, and other Nitrogen and Phosphorous rich substances, including any subsequent associated deoxygenation	Yes
14.	Input of organic matter	Organic enrichment and any subsequent deoxygenation, e.g. from industrial and sewage effluent into rivers and coastal areas, or from the waste from aquaculture or from fishing discards	Yes
15.	Introduction of microbial pathogens	Introduction of microbial pathogens into marine waters	Yes
16.	Introduction of non-indigenous species and translocations	Introduction of non-indigenous species and translocations by the activities of a particular sector (e.g. through exchange of ballast waters by shipping or from release of individuals from aquaculture)	Yes
17.	Selective extraction of species	Extraction (and subsequent mortality) of any marine fauna (vertebrate or invertebrate) from their natural habitat, including incidental non-target catch (e.g. by commercial fishing, recreational angling and collecting/harvesting).	Yes
18.	Death or injury by collision	Death or injury of marine fauna due to impact with moving parts of a human activity, e.g. marine mammals with ships/jet skis, seabirds with wind turbines etc.	No
19.	Barrier to species movement	Preventing the natural movement of motile marine fauna along a key route of travel (e.g. a migration route) due to barrages, causeways, wind turbines, and other man-made structures.	No
20.	Emergence regime change	Changes to natural sea level regime (average, range or variability) due to barrages or other manmade structures such as coastal defences	No
21.	Water flow rate changes	Changes in currents (speed, direction or variability) due to barrages or other manmade structures such as coastal defences	No
22.	pH changes	Changes in pH (average, range or variability) e.g. due to run off from land-based industry	No
23.	Electromagnetic changes	Change in the amount and/or distribution and/or periodicity of electromagnetic energy emitted in a marine area (e.g. from electrical	No

		sources such as underwater cables)	
24.	Change in wave exposure	Change in the size, number, distribution, and/or periodicity of waves along a coast due to installation of coastal structures	No

Table A3. List of Ecological Components used in the ODEMM linkage framework

Number	Ecological Component
1.	Seabirds
2.	Marine Mammals & Reptiles
3.	Fish Deep Sea
4.	Fish Pelagic
5.	Fish Demersal
6.	Pelagic Water Column (inc. plankton)
7.	Deep Sea Habitat (inc. benthos)
8.	Littoral Rock (inc. benthos)
9.	Littoral Sediment (inc. benthos)
10.	Sublittoral Sediment (inc. benthos)
11.	Sublittoral Rock (inc. benthos)

Appendix B: *i*MSE Advertising Flyer

(full details available to download from www.odemm.com)

interactive MANAGEMENT STRATEGY EVALUATION

An ODEMM decision-support tool

Introduction

Ecosystem-based management (EBM) is a concept central to several environmental policies. Implementation requires an understanding of how the wide variety of human activities that occur day-to-day interact with the environment. To this end, DPSIR (Driver-Pressure-State-Impact-Response) has been promoted as *the* environmental management framework by forming structured, mechanistic descriptions ('impact chains') of how human activities interact with different environmental features (Fig. 1). When coupled with up-to-date threat and risk assessments, the likelihood and consequence of harm to the environment from one or multiple activities can be determined and approaches to mitigate risk identified.

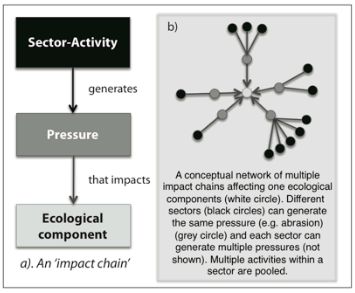


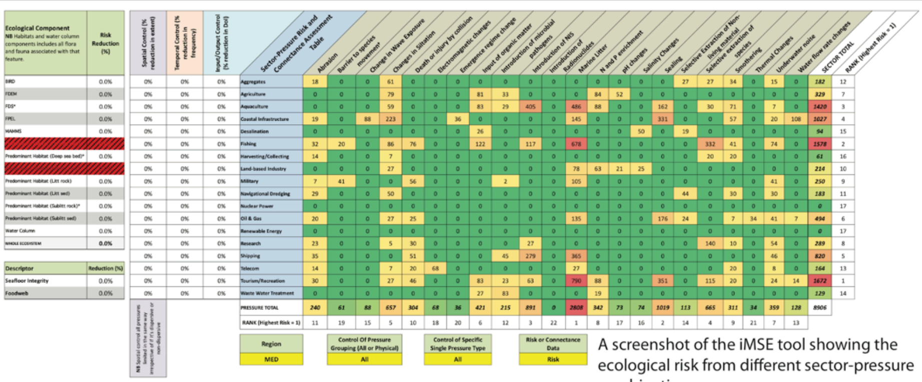
Figure 1. Impact chains. (a) A generic hierarchical impact chain linking sectors and activities to an ecological components via a specific pressure. Each sector activity can generate many different pressures that impact one or more ecological components or cause harm to the environment. An ecological component can be impacted by multiple sectors and multiple pressures, forming (b) a complex network of sector–pressure impact chains. A separate impact chain is generated for every combination of sector (black circles), pressure (gray circles), and ecological component (central white circle). Redrawn from Knights et al. (2013) Ecol. Apps. 23(4).

iMSE tool: Key features

- Comprehensive framework linking human activities to impacts on ecological components of marine ecosystems
- Expert-judgement driven threat assessment of current pressures acting on Europe's regional seas
- State-of-the-art ecological risk assessment analysis of sector-pressure combinations describing their severity and ecosystem recovery timeframe
- Includes a range of tools for evaluating the effectiveness of management measures in reducing risk
- Design, develop and test innovative Management Options against environmental policy objectives
- Interactive, GUI-interface with "traffic light" system gives instantaneous results

Support for Decision-makers

- Robust, evidence-base developed using best available knowledge by regional scientists to provide decision-support
- Structured approach with transparent outcomes allowing rationale for a decision to support a specific management option or strategy to be readily demonstrated
- Outcomes easily interpreted by a range of stakeholders, irrespective of background



A screenshot of the iMSE tool showing the ecological risk from different sector-pressure combinations

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