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Identifying common pressure pathways from a complex network of human activities to support ecosystem-based management

Antony M. Knights,[1] Rebecca S. Koss, and Leonie A. Robinson

School of Environmental Sciences, University of Liverpool, Nicholson Building, Liverpool L69 3GP United Kingdom

Abstract. The marine environment is heavily exploited, but unintentional consequences cause wide-ranging negative effects to its characteristics. Linkage frameworks (e.g., DPSIR [driver–pressure–state–impact–response]) are commonly used to describe an interaction between human activities and ecological characteristics of the ecosystem, but as each linkage is viewed independently, the diversity of pressures that affect those characteristics may not be identified or managed effectively. Here we demonstrate an approach for using linkages to build a simple network to capture the complex relationships arising from multiple sectors and their activities. Using data-analysis tools common to ecology, we show how linkages can be placed into mechanistically similar groups. Management measures can be combined into fewer and more simplified measures that target groups of pressures rather than individual pressures, which is likely to increase compliance and the success of the measure while reducing the cost of enforcement. Given that conservation objectives (regional priorities) can vary, we also demonstrate by way of a case study example from the Marine Strategy Framework Directive, how management priorities might change, and illustrate how the approach can be used to identify sectors for control that best support the conservation objectives.

Key words: ecosystem approach; European regional seas; human activities; linkage framework; marine management; pressure; sustainability.

Introduction

The marine environment and its coastal margins are heavily exploited for a wide range of ecosystem goods and services (Ban et al. 2010). Unintentional habitat loss, habitat fragmentation, and disturbance resulting from this resource exploitation can affect ecosystem structure and functioning, with unforeseen consequences for nontarget species and ecosystem services (Eastwood et al. 2007, Halpern et al. 2008, 2010). Measures to limit the harmful effects of human activities have typically attempted to protect a specific habitat, species or other feature of interest through management of a single sector (Commission of the European Communities (EC) 2009, Khalilian et al. 2010). Implementation of management measures on an industry-by-industry basis has caused some sectors to be subject to strict licensing controls (e.g., the offshore oil and gas is licensed in UK waters under the Petroleum Act [1998] and Continental Shelf Act [1964]). Although several single-sector management programs have been successful in mitigating the impacts of their target industry (see the Quality Status Report 2010 [OSPAR Commission 2010]), this type of management cannot control the full range of detrimental pressures on ecosystems that arise from diverse industry activities, and other insufficiently regulated sectors continue to have widespread effects across the ecosystem.

Ecosystem-wide improvements will often require a combination of measures to control the whole suite of pressures introduced by the full range of human activities that impact the marine ecosystem; i.e., an ecosystem approach to management is needed. The link between human activities and impact on the ecosystem can be described using a simple hierarchy (Fig. 1). This hierarchy follows the form of a sector (e.g., fishing) undertaking an activity (e.g., trawling) that generates a pressure (e.g., selective extraction of fish), which impacts the environment (e.g., by physically removing fish) and changes the quality (state) and quantity of the resource (e.g., by reducing the standing stock biomass (SSB) of fish). In recent years there has been a major shift in focus within environmental policy toward an ecosystem approach to management (Hassan et al. 2005). Although the underlying concepts and potential benefits of the ecosystem approach are recognized, its practical implementation has been rare (FAO 2005). Early efforts were made at a relatively small scale, concentrating on the conservation of a single species but considering multiple activities or impact pathways (Ruckelshaus et al. 2008). These have gradually been replaced by larger-scale planning and policy mechanisms incorporating multiple environmental, societal, and economic objectives (Samways et al. 2010) that use increasingly complex

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[1] Present address: Marine Environment Laboratory, Ryan Institute, National University of Ireland, University Road, Galway, Ireland. E-mail: antony.knights@nuigalway.ie

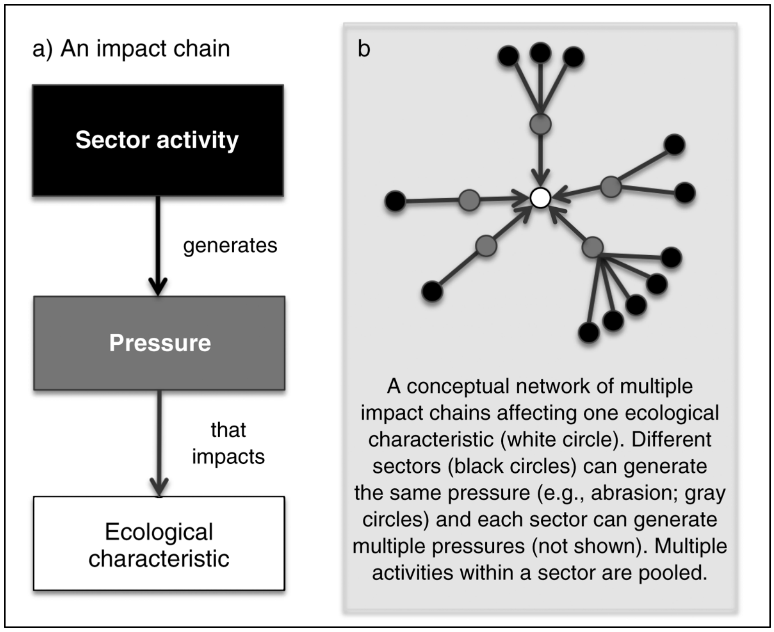

FIG. 1. Impact chains. (a) A generic hierarchical impact chain linking sectors and activities to an ecological characteristic via a specific pressure. A *sector* is a distinct industry, such as fishing or shipping, that undertakes specific activities (e.g., benthic trawling) during its exploitation of marine resources. Each sector activity can generate many different pressures that impact one or more ecological characteristics or cause harm to the environment (e.g. benthic trawling extracts fish species). An *ecological characteristic* (a habitat, species, or interest feature of an ecosystem, e.g., demersal fish) 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 characteristic (central white circle).

concepts such as ecological networks to enhance ecosystem health (Oberle and Schaal 2011).

Describing and understanding the complex network of human activities and their pressures is key to successfully implementing an ecosystem approach. Linkage-based frameworks have commonly been used to describe the relationships between human activities and ecological characteristics (Elliott 2002, La Jeunesse et al. 2003, Odermatt 2004, Scheren et al. 2004, Holman et al. 2005). There are several widely used frameworks including the pressure–state–response (PSR) framework (Rapport and Friend 1979) and the more recent derivation, Driver–Pressure–State–Impact–Response (DPSIR) framework (EEA 1999). Linkage frameworks tend to be based on a concept of causality, i.e., human activities exert pressures on the environment changing the quality (state) and quantity of its natural resources. An advantage of linkage frameworks is that key relationships are captured and displayed in a relatively simple way (Rounsevell et al. 2010), but a disadvantage is that linkages tend to be viewed independently of each other without consideration of the interplay with linkages arising from other sectors, the range of pressures generated by specific activities, or the variety of ecosystem components that are impacted by a particular pressure. These shortcomings may explain the limited evidence for improvement following adoption of the ecosystem approach (Ruckelshaus et al. 2008, Tallis et al. 2010). In an analogous way that single-species or single-sector fisheries management under the Common Fisheries Policy of the European Union (CFP; *available online*)[2] has been limited by a failure to account for nontarget sector(s) impacting on a resource (Khalilian et al. 2010), the ecosystem approach can also be undermined by a failure to account for the multiple unmanaged sectors and activities that could impact an ecosystem and its characteristics as a whole (Smith et al. 2007).

Here we illustrate an approach for using these “simple” linkages (impact chains) to build an integrated network that captures the diverse and complex range of sector activities that impact marine ecosystems (a simplified network is shown in Fig. 1). Using common ecological data-analysis tools, such as network topology metrics and cluster analyses, we demonstrate how mechanistic similarities between linkages can be identified, allowing development of improved management measures in support of conservation or restoration objectives. We also illustrate how differences in policy objectives could affect management priorities using case-study examples from the Marine Strategy Framework Directive (MSFD) (EC 2008). We focus on the MSFD as it is the policy mechanism through which ecosystem-based marine management will be implemented in European regional seas. The overarching aim of the

[2] http://ec.europa.eu/fisheries/cfp/index_en.htm

MSFD is to ensure that natural resources are exploited in a sustainable manner so that biodiversity is maintained and that its regional seas are clean, healthy, and productive (Article 3(5); EC 2008). When this goal is achieved, the regional sea is considered as being at "Good Environmental Status" (GES). In the MSFD, 11 underlying qualitative descriptors were developed (Annex I; EC 2008) to allow differentiation between structure and functional processes of the ecosystem. The descriptors are not objectives per se. Rather, they describe features of the ecosystem that are widely considered as important, either from a conservation (e.g., biodiversity, food web) or threat (e.g., nonindigenous species, marine litter) perspective that may be useful in developing a specific set of objectives.

In this paper we consider two of the descriptors developed for the MSFD, namely, Descriptor 1: Biodiversity, and Descriptor 4: Food webs. The choice of descriptor has a direct effect on the number/type of impact chains requiring consideration. By definition, the *biodiversity descriptor* includes all aspects of the ecosystem and therefore, all impact chains are relevant to its assessment. In contrast, the *food-web descriptor* as developed is focused on some key species, and on whole trophic groups, including fish, marine mammals, seabirds, benthic flora and fauna, and plankton (see Commission Decision 2010/477/EU for further details). As such, only those impact chains relevant to these ecological characteristics were considered (see Appendix: Table A3 for the relevant links). Under both descriptor scenarios, we illustrate the management priorities as a result of changes in the impact chains.

Approach and Methods

Assessing ecosystem complexity: linking sectors and pressures to ecological characteristics of the ecosystem

Understanding the hierarchical pathways through which sector activities affect descriptor indicators is an essential first step in the process of managing their impact (see Fig. 1 and definition of the hierarchy in *Introduction*, paragraph two). This description is complicated by the fact that specific impacts can result from activity associated with numerous sectors (Soto et al. 2006, Ban et al. 2010). If the impact of a sector and its activities is to be reduced or mitigated so that no detrimental effects to the ecological characteristics of the ecosystem are seen, we must make clear and definitive links between sectors, the pressures they generate and the effects those pressures have on components of the ecosystem.

There are numerous human activities with the potential to impact marine ecosystems (Halpern et al. 2007), many of which are common to several sectors functioning in Europe's regional seas. Using a wide range of sources including peer-reviewed literature, gray literature, and regional expertise, we identified 19 sectors, and their effect on the ecosystem was assessed. While the sectors were chosen for evaluation based on their predominance in one or more of Europe's regional seas, they are also common to marine ecosystems globally (Halpern et al. 2007) (see Appendix: Table A1 for a full list of sectors). Sectors in an early stage of development (e.g., carbon sequestration) or increasing in prevalence (e.g., renewable energy) were also included. Sectors are defined broadly (e.g., fishing), encompassing a range of activities associated with that industry (e.g., benthic trawling, pelagic trawling, long-lines or fixed nets). In total, 105 activities were identified and assessed (see Appendix: Table A1 for a comprehensive list). Although not presented here, the assessment can easily be modified to illustrate similarities between linkages at the activity scale rather than at the sector scale.

The Marine Strategy Framework Directive (MSFD; EC 2008) identified 18 specific pressures, which could be placed into one of eight general pressure groupings based on their shared impact characteristics such as whether the pressure caused physical damage (e.g., abrasion or selective extraction), physical loss (e.g., smothering or sealing) or contamination (e.g., introduction of synthetic compounds) (see Annex III of the Directive [EC 2008] for the full list of pressures and impacts). We expanded this to 21 specific pressures as the list was not exhaustive; e.g., changes in wave exposure and their effects on intertidal communities (Dayton 1971) were not included, nor did it include pressures that could arise from new but increasingly prevalent activities such as barriers to species movement arising from renewable-energy installations (Aprahamian et al. 2010). Additional pressures and their link to sectors and ecological characteristics were identified using a combination of peer-reviewed literature, gray literature (e.g., The Marine Life Information Network, *available online*),[3] and expert judgment. See Appendix: Table A3 for a full list of pressure types together with a short description of each pressure.

Sixteen ecological characteristics of the marine environment were identified in the MSFD (Annex III; EC 2008). However, we exclude "listed habitats" and "habitats meriting special reference" from the analysis as they can be included within the "predominant habitat" category in terms of the mechanism(s) through which pressures act on them. The 14 ecological characteristics can be classified into four broad categories: (1) physical and chemical features (i.e., temperature, salinity, topography, nutrients and oxygen, pH); (2) predominant habitat types (e.g., sublittoral sediment, deep sea, littoral rock); (3) biotic characteristics (fish, birds, mammals, benthic flora and fauna, plankton, listed species), and (4) other notable chemical features of the ecosystem (e.g., presence or absence of hotspots for eutrophication). The impact of a pressure on an ecological characteristic is not specified but could range from

[3] www.marlin.ac.uk/human-activity.php

changes in biomass, demography, or abundance (for biotic characteristics) to ones that cause a change in the salinity or temperature profile (for physical and chemical features).

Evaluating impact chains of the ecosystem

We evaluated the links between sectors, pressures, and ecological characteristics by constructing impact chains using three matrices. The first contains *i* rows of sectors and *j* columns of pressures (Appendix: Table A2) and the second contains *i* rows of pressures and *j* columns of ecological characteristics (Appendix: Table A3). The third matrix combines Appendix: Tables A2 and A3 into a matrix of impact chains (i.e., a table of all potential sector–pressure–ecological characteristic interactions). This third "impact-chain" matrix is not shown for brevity as it contains >7000 impact chains. Each cell in the impact-chain matrix is a qualitative and deterministic assessment of the presence (X) or absence (blank cell) of a link, which was assessed using a combination of published literature and expert judgment. Matrices were combined in Netica (*available online*),[4] resulting in an integrated ecosystem model that describes all potential linkages among all sectors, pressure types, and ecological characteristics.

The complexity of the ecosystem impact-chain network was measured using three properties of network topology (Dunne et al. 2002): (1) complexity/linkage density (the number of links between sectors, pressures, and ecological characteristics), (2) links per ecological characteristic (connectance) (Gardner and Ashby 1970), and (3) linkage similarity (clustering) (Allen and Starr 1982). In addition, agglomerative hierarchical cluster analysis (Dubes and Jain 1988) was used to group similar impact chains. This allowed sectors to be grouped by similarity of pressure types they introduce (e.g., does Sector A introduce the same pressure types as Sector B? If so, Sector A is similar to Sector B in terms of its impact pathways). Similarity of pressure types also enabled the likelihood of pressure co-occurrence to be determined. For example, when a sector activity causes a "change in temperature", should we also expect a "change in salinity"? Finally, different ecological characteristics were grouped by the similarity of impact chains that affect them, indicating where wider (indirect) ecosystem benefits might be achieved beyond those envisioned under a particular management measure or suite of measures. For example, if a measure was introduced to limit impacts on plankton, are these benefits likely to be indirectly conferred to pelagic fish species as a result of the restriction(s)?

Food-web model

To evaluate how management might change when the conservation priority is different, we truncated the ecosystem model to include only those linkages relevant to the ecological characteristics representative of a marine food web. Food webs are networks of connections between a diversity of consumers and resources (Polis and Strong 1996). The species composition of a food web can vary by habitat and region, but the principles of energy transfer from sunlight to plants and successive trophic levels are the same. Functional aspects and a specific focus on the levels of productivity of key components can be used to describe a food web. In the Marine Strategy Framework Directive, GES (good environmental status) of a food web is described as when "all elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity" (Annex I; EC 2008). A task group further defined generic functional indicators as: (1) biological groups with fast turnover rates (e.g., phytoplankton, zooplankton, bacteria) that respond quickly to system change; (2) groups targeted by fisheries; (3) habitat-defining groups; and (4) charismatic or sensitive groups often found at the top of the food web, such as marine mammals and seabirds (ICES 2010). Here we specifically refer to the ecological characteristics: bottom flora and fauna (habitat-forming species), fish, marine mammals, plankton, and seabirds. Food-web-specific ecological characteristics were selected within the deterministic model to indicate the impact chains only relevant to them.

Data analysis

Linkage similarities were assessed using cluster analysis (Clarke 1993). All analyses were undertaken using the open-source software R (R Development Core Team 2008) and the package Pvclust (Suzuki and Shimodaira 2006). Clusters were calculated as the Euclidean distance of the sector, pressure, or ecological characteristic from the origin, and the clustering method used was average distance. Statistically significant clusters were calculated as approximate unbiased (au) and bootstrap probabilities (bp) (see Suzuki and Shimodaira [2006] for full details).

Results

The ecosystem model

We evaluated 7066 impact chains and, based on the 19 sectors included in the model, 1462 individual impact chains were identified as having the potential for detrimental effects on the ecosystem and its characteristics.

Connectance of sectors, pressures, and ecological characteristics

The five sectors identified from the ecosystem model as those contributing the greatest number of impact chains were coastal infrastructure, renewable energy, oil and gas, tourism/recreation, and fishing. Sectors intro-

[4] www.norsys.com

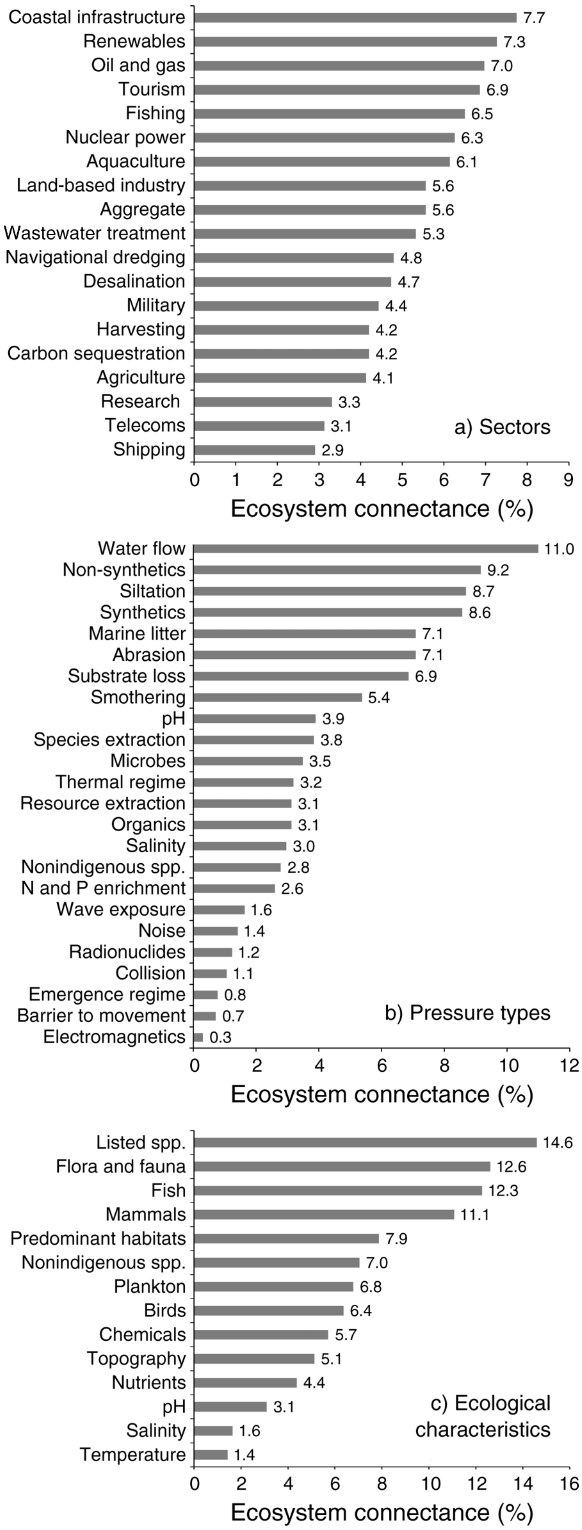

FIG. 2. The number of linkages (proportional connectance) associated with (a) the sectors, (b) the pressure types, and (c) the ecological characteristics of the ecosystem in European regional seas. Proportional connectance is calculated as the number of linkages associated with each sector/pressure type/ecological characteristic divided by the total number of linkages in the ecosystem model ($N = 1692$ impact chains). Absolute proportional connectance values are shown at the end (right side) of each bar.

ducing the fewest impact chains were shipping, telecommunications and scientific research (Fig. 2).

The five most common pressures (Fig. 2b) were changes in water flow rate, introduction of non-synthetic compounds, changes in siltation, introduction of synthetic compounds, and marine litter. The most infrequent pressures were electromagnetic energy, barriers to species movement, and change in emergence regime (Fig. 2b).

The five ecological characteristics with the greatest number of impact chains affecting them were listed species, bottom flora and fauna, fish, marine mammals and predominant (seafloor) habitats. Physio-chemical characteristics, namely, temperature, salinity, and pH were the least threatened (Fig. 2b).

Clustering sectors, pressures, and ecological characteristics by impact-chain similarity

We identified 17 different groups of sectors. The average distance (height) among clusters was generally low, indicating a relatively high degree of similarity between the impact chains introduced by different sectors (Fig. 3). Two clusters of sectors with statistically similar impact chains were identified. The first included land-based industry, agriculture, desalination, and waste-water treatment (percentage similarity of 100) and the second included fishing, aquaculture, and tourism and recreation (percentage similarity of 96) (Fig. 3b).

There was less similarity in terms of the combination of sectors introducing a pressure type. With the exception of changes in salinity and changes in thermal regime (Fig. 3c; percentage similarity of 99), there were no statistically significant groupings, indicating that each pressure type is introduced by a different combination of sectors. However, combining mechanistically similar pressure types, such as substrate loss, abrasion, and smothering into their broader typologies (i.e., physical loss and physical damage), revealed some similarities (Fig. 3b).

Ecological characteristics could be grouped into distinct clusters and the average distance (dissimilarity) among clusters was more than three times greater than found in the sector and pressure comparisons, indicating clear differentiation between the combination of sectors and pressures that impact different ecological characteristic groups (Fig. 3c, height ~10). Twelve clusters were identified, four of which consisted of statistically similar ecological characteristics. Group 1 was comprised of the physical/chemical features (1) salinity and (2) temperature (100% similarity). These fell within a larger cluster (9) that includes chemicals, nutrients and pH. The second group (2) consisted of bottom flora and fauna and listed species (97% similarity), which themselves fell within the larger group of "Biological features" including marine mammals and fish (cluster 8). Group 3 consisted of predominant-habitat types and topography (97% similarity), and the final group was comprised of nonindigenous species and plankton (group 6; 98% similarity), which are subject to a similar group of impact chains as the physical and chemical characteristics (Group 10) (Fig. 3c).

The food-web model

Of the 1462 impact chains identified, 704 chains were relevant to indicators of food-web status, with the greatest number of impact chains affecting bottom flora and fauna and the fewest affecting plankton (Fig. 4). There was a change in the ranking of sectors when considering only those characteristics relevant to food-web GES ("good environmental status" of the marine environment). Ten sectors increased in rank, two did not change, and seven decreased in rank (Fig. 5), although the predominant sectors (most connected) did not change from the ecosystem model. The prevalence of a pressure type changed to a greater extent: 12 pressure types increased in rank, one did not move, and 11 pressure types decreased in rank (Fig. 5). Greatest changes were to the rankings of agriculture (+3) and nonindigenous species (NIS; +7).

The greatest number of impact chains arose from Renewable energy (Fig. 4), which contributed 56 different chains and affected all five ecological characteristics of food webs, in particular, fish and bottom flora and fauna. The most common pressures were the introduction of synthetic and non-synthetic compounds, and changes in siltation and water flow (Fig. 4).

Discussion

One of the greatest challenges of transforming ecosystem-based management (EBM) from a conceptual approach into an operational framework that supports sustainable use is identification and management of the impact chains that are detrimental to ecosystem structure and functioning (Leslie and McLeod 2007). As illustrated here, impacts derive from a number of sectors and activities, which contribute a range of threats to form a complex network of impact chains that affect multiple aspects of the environment. Using a simple framework approach, we have shown how the complex network of impact chains introduced by multiple sectors can be placed into mechanistically similar groups so that programs of management measures could be developed to address the diverse range of threats to the ecosystem and its components, but in a simplified, more efficient and effective way.

We evaluated 19 sectors for their potential to introduce up to 21 different pressure types. Over 1460 impact chains were identified indicating the scale and complexity of the issues that EBM faces. Despite this, five predominant sectors could be identified: coastal infrastructure, renewable energy, oil and gas, tourism/recreation, and fishing, which contribute ~35% of all impact chains and are predominant features of both the ecosystem and food-web frameworks (Figs. 2 and 4). However, the similarity of the impact chains arising from multiple sectors (Fig. 3) underscores the limited efficacy of single-sector management in mitigating all potential impacts (Khalilian et al. 2010) and highlights the need for either a single management measure that addresses the pressure(s) of interest, or a suite of management measures that target multiple sectors and the pressures they introduce (i.e., cross-sectoral management). For example, aquaculture and tourism and recreation introduce a similar suite of pressures, suggesting that management of both sectors would be required to effectively mitigate the detrimental pressures they introduce (Fig. 3).

Grouping sectors by the suite of pressures they introduce is on its own unlikely to support EBM. Several sectors and their activities can introduce the same pressure types, so that even if one sector was restricted—for example using a spatial management program to limit the area of impact by that sector's activities—impacts may still occur as a result of the unmanaged sector. This is further complicated by the potential for spatial and/or temporal overlap between different sectors and activities, which can lead to 'repeated' introductions of a pressure that can increase its intensity and the severity of its impact (Zhao and Newmann 2004, Eastwood et al. 2007, Stelzenmüller et al. 2010). Growing demand for marine resources has led to an increase in the spatial extent of sectors and, in turn, a greater likelihood of overlap between different sector activities (Eastwood et al. 2007). Linking specific

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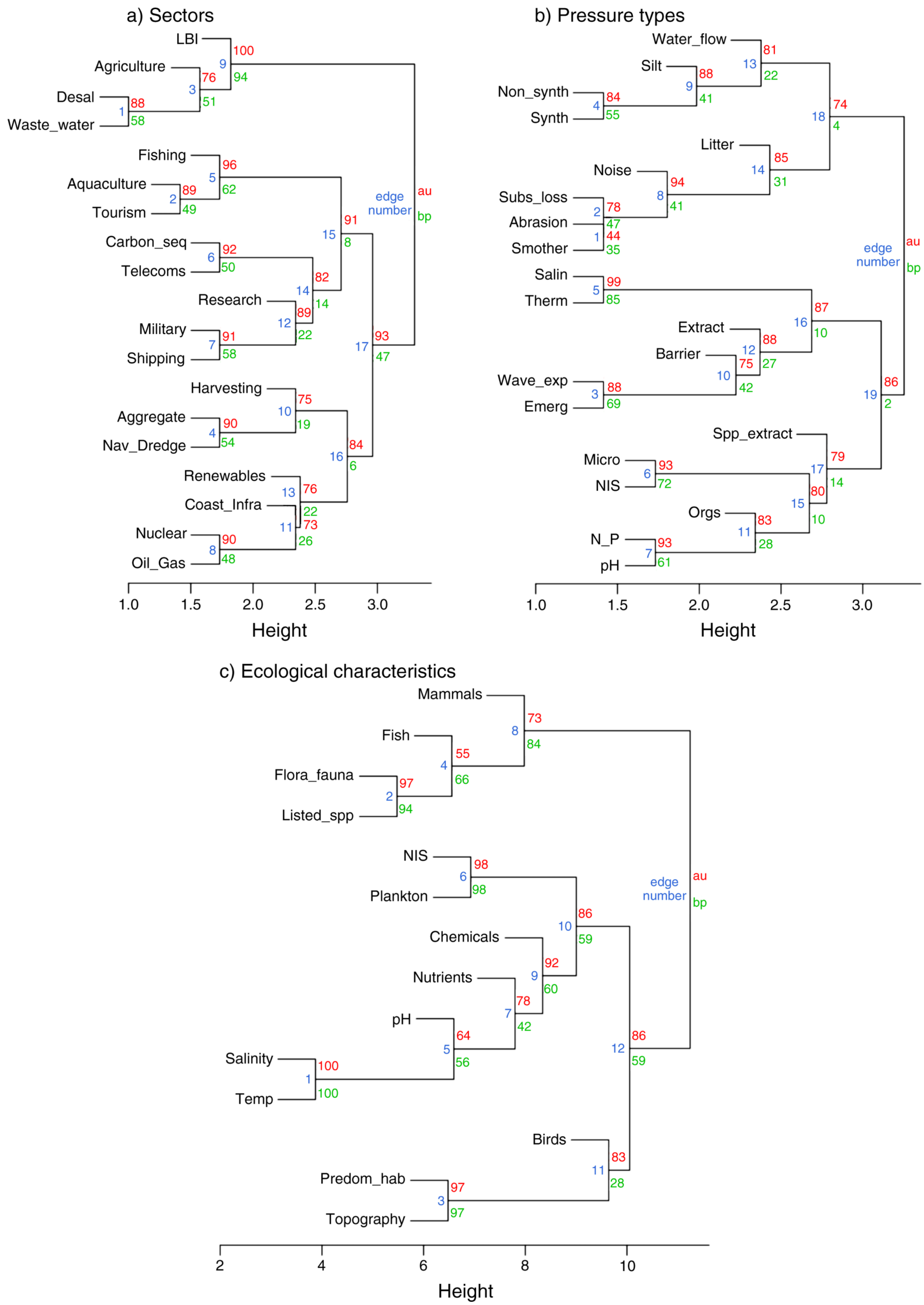
Fig. 3. Agglomerative hierarchical cluster analysis comparing the similarity of impact chains for (a) sectors, (b) pressure types, and (c) ecological characteristics. Height indicates percentage dissimilarity where 1 = no dissimilarity, and values shown above each cluster indicate the approximate unbiased (au; red) and bootstrap probabilities (bp; green, percentage similarity) for that cluster. The blue numbers indicate the cluster ranking (edge number); the lower the number (e.g., 1), the more similar the cluster. Hierarchical clusters were calculated by average Euclidean distance. Abbreviations (in alphabetical order): Barrier, barriers to species movement; Carbon_seq, carbon sequestration; Coast_Infra, coastal infrastructure; Desal, Desalination; Emerg, emergence regime; Extract, extraction of nonliving organisms; Orgs, introduction of organic matter; LBI, land-based industry; Mammals, mammals and reptiles; Micro, microbes; Nav_Dredge, navigational dredging; N_P, nitrogen and phosphorus enrichment; NIS, nonindigenous species; Non-synth, non-synthetic compounds; Predom_hab, predominant habitats; Salin, salinity; Silt, siltation; Smother, smothering; Spp_extract, species extraction;Subs_loss, substrate loss; Synth, synthetic compounds; Therm, thermal regime; Waste_water, wastewater treatment; Wave_exp, wave exposure.


a) Sectors
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Agriculture
Desal
Waste_water
Fishing
Aquaculture
Tourism
Carbon_seq
Telecoms
Research
Military
Shipping
Harvesting
Aggregate
Nav_Dredge
Renewables
Coast_Infra
Nuclear
Oil_Gas
edge number
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Abrasion
Smother
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Barrier
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Micro
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c) Ecological characteristics
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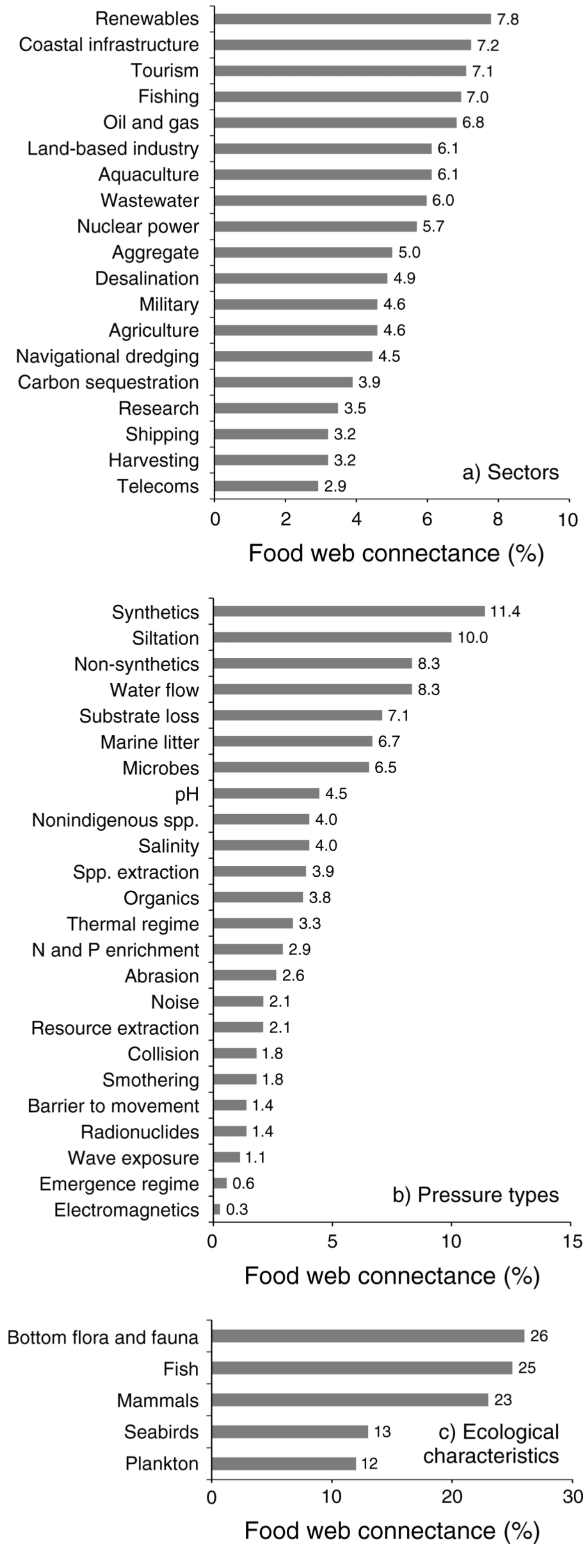

FIG. 4. The number of linkages (proportional connectance) associated with the sectors, pressure types, and ecological characteristics of the food web in European regional seas. Proportional connectance is calculated as the number of linkages associated with each sector/pressure type/ecological characteristic divided by the total number of linkages in the food-web model ($N = 704$ impact chains).

pressures to those sectors and their activities is a critical step that underpins our efforts to mitigate their harmful effects. While our framework does not attempt to evaluate the extent of overlap nor attempt to evaluate how pressure severity might change if sector activities do co-occur, it does indicate the potential for combined or cumulative impacts (Fig. 3) and can be used to highlight two things. First, where EBM should consider including multiple sectors (and activities) within its management strategies, and second, it identifies which sectors should be included in those strategies given current usage.

Comparison of the pathways of pressure introduction revealed some similarities, but also the need for quite different controls for dissimilar pressure types (Fig. 3). Grouping pressure types in this way allows indirect benefits of management to be identified. For example, management of sector activities that cause changes in salinity (e.g., freshwater discharge into coastal oceans; Davila et al. 2002) is also likely to limit changes in thermal regime (Fig. 3). The approach could therefore be used to develop management measures that confer wider benefits than simply affecting the targeted single pressure type. There are several benefits to this. First, management measures can be combined into fewer and more simplified measures, leading to greater compliance (Tallberg 2002). Second, assuming the measure itself is well designed and is linked to clear and realistic targets, the likelihood of success will increase and the cost of enforcement will decrease (Sutinen and Soboil 2003). However, as shown here, the number of potential impact chains is great and it is unlikely that all impacts can be managed. Policy makers must make trade-offs in terms of which ecological characteristics they are prepared to support—a decision often driven by the societal and economic value of the goods and services the ecosystem provides rather than the health of the ecosystem itself (Altman et al. 2011). Thus, identifying management measures that provide the greatest (direct and indirect) benefits at the lowest cost will make the choice of measure(s) for implementation simpler, while addressing a wider range of threats and satisfying societal and economic objectives.

Under the Marine Strategy Framework Directive (MSFD; EC 2008), EU Member States are legally obligated to implement management measures where a risk to GES is identified (Article 13(1); EC 2008). However, funding constraints are likely to limit the capacity for national, international or regional stakeholders to implement and enforce management measures at the level required to mitigate all impact chains introduced by sectors and their activities (Article 14(1d); EC 2008). Implementation decisions will therefore likely depend on the interests of the stakeholder. As our results

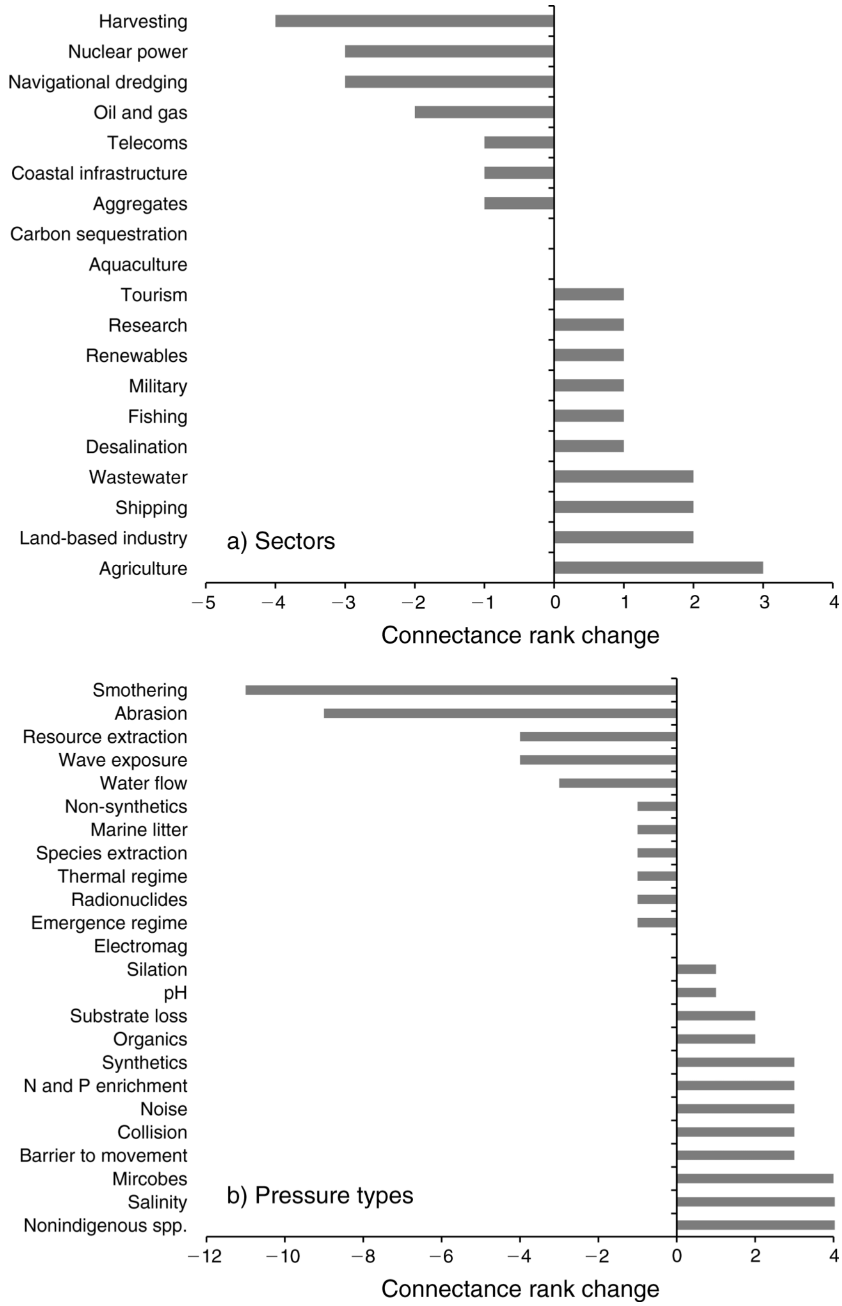

FIG. 5. Change in the connectance ranking of (a) sectors and (b) pressure types in the food-web model in comparison to the ecosystem model. A positive change in ranking value indicates a proportional increase in connectance of a sector or a pressure type.

show, the chosen objective can greatly influence the impact chains that management measures must address, insofar as the pressure type varied greatly between the ecosystem and food-web models, but the relative connectance of sectors did not. This suggests that all sectors broadly affect the ecosystem and its characteristics, but the mode of action through which an impact occurs might change. Our approach illustrates how different impact chains can be identified, following which the institutional capacity required to implement relevant measures can then be determined (Carlsson and Berkes 2005). We have demonstrated the approach using a whole-ecosystem and food-web example, but the approach can easily be modified to assess another objective by limiting the model to the impact chains relevant to the feature of interest, e.g., fish species or a specific habitat. The approach can therefore be applied in a different context (e.g., ecosystem-based fisheries management) and can help support decision making based on the specific priorities of that context.

The development of management measures to support EBM will be challenging, perhaps more so for biological characteristics of the ecosystem, which are subject to over 70% of the total pressure (Fig. 2). Impact chains affecting the physical and chemical properties of the ecosystem are less complex and may indicate why management measures that relate to the physical and chemical environment, such as the Nitrates Directive (EEC 1991) have been so successful. The considerable number of chains affecting biological characteristics highlights the difficulties facing EBM, in particular, how to manage sectors and their activities to account for all impact chains (whether direct or indirect) affecting ecological characteristics. In this study, we did not consider the links between ecological characteristics, so we cannot evaluate how reductions in pressure on one characteristic might affect another, but the role of complexity and interdependencies in food-web stability has been long debated in ecology (Polis and Strong 1996). Until recently (Berlow et al. 2009), it was suggested that interdependencies among species were so complex that it would be impossible to predict how one species affects another (Yodzis 1988). Advances in food-web modeling (Berlow et al. 2009) will likely provide support for valuing the contribution of different ecological characteristics in ecosystem structure and functioning and may enable prioritization of management toward the impact chains most detrimental to the ecosystem and its biotic components. However, until that time, our results suggest that EBM is likely to face difficult challenges in successfully mitigating the vast number of impact chains that affect the characteristics of the ecosystem so that the objective of sustainable use is achieved.

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Supplemental Material

Appendix

Three tables listing the sectors and activities that were considered, the pressure types that are generated by each sector, and indicating which ecological characteristics of the ecosystem are impacted by specific pressure types. Short descriptions of sectors, activities, and pressure types are also given (*Ecological Archives* A023-038-A1).