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Reverse the declining course: a risk assessment for marine and fisheries policy strategies in Europe from current knowledge synthesis

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Highlights

- Knowledge integration is key for the Ecosystem Approach to Fisheries Management (EAFM)
- A probabilistic risk assessment framework informed by cases obtained from a review
- We contrast the most and the least-desirable marine ecosystem states by querying the framework
- We discuss performance of marine policies across regional specificities in EU Waters
- Fisheries policy alone is not sufficient for compensating large environmental background changes

Abstract

An ecosystem approach to fisheries management is being developed around the world in an attempt to consider components of marine ecosystems other than just the exploited stocks. While numerous scientific studies on the consequences of fishing on marine ecosystems exist, most of their findings are too uncertain and fail to quantify the magnitude of the effects they describe to be used reliably in an environmental management and marine policy-making realm. To circumvent such a knowledge gap, we built and fitted a Bayesian Network (BN), informed by a review of past studies, which integrates the links and direction of effects between socio-ecosystem components. These effects are represented as conditional probabilities, so that missing magnitudes of some ecosystem effects emerge from the numerous past cases that were reviewed. The Bayesian network is informed by a collection of cases extracted from 246 published scientific studies investigating relationships in marine ecosystems. We find that marine ecosystems are likely to be on a declining course under conjugated pressures of both fishing and changes to environmental conditions, e.g. due to ongoing climate change. By querying the fitted BN to obtain posterior probabilities under different scenarios, we showed that increasing fisheries regulation and environmental

governance could partly mitigate these effects and decrease the risk of biodiversity loss, decreased profit and social inequity; the three pillars of the EU Common Fishery Policy (CFP). We discuss these findings with regard to particular fisheries across EU Waters, specifically: the North Sea, the Baltic Sea, the North Western and the South Western Waters. Furthermore, we discuss how fishing impacts interact with other ecosystem effects and pressures, caused by, or causing possible far-reaching consequences in marine ecosystem dynamics. The Bayesian network has some limitations regarding the ability to handle feedback loops that can occur in natural marine ecosystems. Nevertheless, such an approach helps to take a holistic view and integrate existing knowledge and new findings from future work, in a coherent, probabilistic risk assessment framework, while identifying what leverage and management actions may help nudge the system toward desired states.

Keywords: Bayesian Network, Cumulative impacts, Conditional probability, Ecosystem approach to fisheries management (EAFM), Marine Fishery Policy, Risk assessment framework

1. Introduction

The sustainable management of exploited fish stocks is no longer the only target of fisheries management. There is a demand for implementing an ecosystem approach to fisheries management (EAFM) that requires the consideration of more components of marine ecosystems, than just the exploited stocks (Garcia *et al.* 2003, Francis *et al.* 2007, Cowan *et al.* 2012, Long *et al.* 2015, Tam *et al.* 2017, Trotcha *et al.* 2018). EAFM acknowledges that fisheries are part of the environment and cannot be managed in isolation, while also reflecting the dynamic nature of ecosystem structure and functioning. By accounting for this understanding, EAFM intends to secure the maintenance of healthy, productive, and resilient ecosystems capable of providing the services needed for the wellbeing of human society. Healthy and resilient marine ecosystems are also a prerequisite for ensuring future fishing opportunities, the associated revenues of fishers and their communities. From a more abstracted view, maintaining these fishing opportunities is necessary for the fishing industry to be able to respond to future market demand for seafood (EEA, 2016).

Across fisheries research, oceanography, and environmental management, many scientific studies have investigated the extent to which different pressures affect marine ecosystem structure and functioning, albeit with a bias to single pressures or small subsets of pressures. The overarching challenge when attempting to protect the future of marine ecosystems is to understand the environmental, social and economic consequences of natural resource utilization from that system as a whole. For EAFM specifically, the effect of exploitation in interaction with other pressures (be they natural or anthropogenic) are not well known or are uncertain (Bastardie *et al.* 2020). Such unknowns are blind spots that jeopardize attempts to influence or mitigate undesired ecosystem states through management actions. For example, the long-term effects of fishing on marine food webs may be vastly underestimated when habitat degradation, modifications of the physical properties of the water column or the seafloor sediments, water-sediment chemical exchanges, and sediment fluxes are not taken into consideration (e.g., Torres *et al.* 2013, Johnson *et al.* 2015). The subsequent economic loss that would result from affecting ecosystem functioning is also poorly estimated (Willmann and Kelleher 2009). Including the social dimension of fisheries in an EAFM is also especially challenging, given the gaps in monitoring socioeconomics (STECF 2019b, Varela-Lafuente *et al.* 2019). Therefore, an interdisciplinary approach should support marine

management with monitoring and investigative tools that promote the integration of social, economic, and biological analyses; giving way to a holistic approach in fisheries research (Haapasaari *et al.* 2007).

By developing a mathematical modelling approach of an idealized marine ecosystem, we intend to take a holistic approach and examine the effect of changing marine governance and fishery policy on the accumulated impacts affecting the marine ecosystem. We consider this impact in terms of biodiversity and fishing opportunities, viewed as the expected long-term profit and degree of social equity in accessing these opportunities. We draw relationships between components of the marine ecosystems obtained from a systematic literature review, and the strength of the relationships between components are derived by fitting a Bayesian network (BN) with a set of cases extracted along with our literature review (Bastardie *et al.* 2020). From each published study, the review extracted the impacted and the pressure impacting socio-ecosystem components, together with the direction of the impacts. While the direction of the impact is well identified, in most cases, the magnitude of the impact is either not quantified or too uncertain to be of use, as frequently acknowledged by the authors of the studies. In such cases it is, therefore, logical to apply a powerful approach, such as a BN, to incorporate the scientific knowledge in an overarching framework in spite of the lack of accurately detailed quantification (see Kaikkonen *et al*. 2020 for a recent review of the use of BNs for conducting Environmental Impact Assessment, and in a fisheries-related context, e.g., Lee *et al.* 1997, Levontin *et al.* 2011, Stelzenmuller *et al*. 2015, Trifonova *et al.* 2017, Raoux *et al.* 2018, Carriger *et al.* 2019, Gacutan *et al.* 2019). Integrating causal information by linking all components together from the individual pieces of evidence, as in a BN, is useful to help weigh uncertainties between management decisions, risks arising from ecosystem drivers and controls, and the corresponding delivery of ecosystem services (Carriger *et al.* 2019). BNs as knowledge synthesis tools provide the ability to decompose a risk problem into chains of interrelated events and variables and therefore avoid quantifying probabilities in isolation (Fenton and Neil, 2013). Taking the big picture view is undoubtedly an advantage, especially given that many of the ecology studies reviewed discussed possible far-reaching consequences of changing input pressures on the ecosystem structure and functioning, without being able to document them, or account for small subsets of these relationships only, and in isolation, unable to represent or perceive larger scale changes and impacts. Some of these variables also provide controls points for different decisions to aid the adoption of integrated approaches for considering uncertainties in the marine ecosystems and their management, e.g. in an EAFM context.

Whether induced by fisheries management measures (including technical measures such as selective fishing from special gears specifications),spatial management measures (closed areas or seasons to fishing, or marine parks), or by a change in fishing opportunities (following quotas or effort regimes), an optimal fishing effort allocation in space and time is expected to benefit fish stocks managed in the CFP context. These benefits may be derived from obvious direct effects but also from less conspicuous indirect effects, for example by protecting vulnerable life stages (e.g., juveniles, spawning aggregations, or migratory corridors) and most vulnerable periods. However, in most cases, these mitigation tools and spatial plans are not protecting benthic habitats (e.g., EC 2019). Therefore, the overall level of displaced effort is likely to induce adverse environmental effects on other socio-ecosystem components, and the net outcome at the overall ecosystem scale is generally uncertain. Hence, it appears that the sustainable use of exploited fish stocks, as an objective of the CFP, does not equate to preserving the integrity of the exploited marine ecosystems in the long term. A coherent marine environmental EU policy would therefore seek to ensure that both

the CFP and environmental policies are integrated and evaluated in a joint environmental impact assessment. In this study, we describe the cumulative pressures of fishing effort and environmental conditions on the bentho-pelagic marine ecosystems. We investigate these effects on the marine ecosystem by reporting on changes in long-term fishing opportunities in parallel with other ecosystem indicators such as the ecosystem inherent biodiversity, fisheries economics, and changes in social equity arising from distributional economic effects. We calculate the effect on the size of the risks (or its counterpart i.e. the opportunities) of changing the probabilities of drivers and controlling variables that cause subsequent changes (the impacts) and propagate across the causal chains into the marine ecosystems, to finally change the pre-categorized overall impact into social, environmental and economic consequences. In a scenario analysis, the risk assessment is therefore able to rank different options from the more risky ones against the ones decreasing the overall risk. Our study seeks to inform policy makers of emergent, broad-scale impacts of changes in European marine ecosystems and their management by integrating existing knowledge on fishing – ecosystem impacts in a holistic context. This approach advances our understanding by working toward a healthier and more resilient marine ecosystem, beyond the management of direct exploitation alone.

2. Methods

2.1. The systematic review

We made a systematic review of the ecosystem challenges that marine ecosystems are facing in EU Waters by searching among the last two decades' peer-reviewed scientific literature with search determinants listing impacted components, impacting pressures and the framing conditions for these impacts. The review (described in detail in Bastardie *et al.* 2020) resulted in the retention of 246 papers (see the list of references in Supp. Mat. Annexe 1). From these results, we extracted information on the impacting components, impacted components, and the direction of the impact. Note that the magnitudes of the impacts were not used as they were unavailable, or deemed unreliable, for most of the studies we reviewed. The search of primary literature was augmented by including the last three years' (2017-2019) of the Scientific, Technical and Economic Committee for Fisheries (STECF) plenary reports, where valuable information on fisheries, fisheries management and the economic and institutional context for fisheries is collected in Europe.

2.2. Bayesian Network modelling

2.2.1. Building the Bayesian Network (BN)

A BN model is made of components (named variables or nodes) of a network that define a directed acyclic graph. A Bayes net, also known as a belief network or probabilistic causal network, captures believed relations, which may be uncertain between the set of nodal components and are relevant to some problem (examples in Kaikkonen *et al.* 2020). Such a network is comprised of both the influence diagram and the probabilities describing strength of the connections. In a BN, the set of random variables and their relations are relative and are based on some measure of concurrent change; be that a direct cause-effect relationship or some correlative relationship.

Our BN is an abstracted representation of the European marine ecosystem with fisheries at its core, interacting with sociological and environmental ecosystem components. These components are represented as one of three types of nodes: The first are input (or "control") nodes, which represent the influence of the input on other nodes. The second are output (or "consequence") nodes, which represent the response predictions for each of the components

of interest. Finally, there are intermediary (or "risk") nodes, which represent the influence of perturbations on the system through the input variables and the interactions among themselves. In this study, the input nodes selected are predominantly governance components of the system, to investigate system responses to different regulatory impacts or *vice versa*. The output nodes were chosen to reflect the goals of the CFP and are namely biodiversity (environmental), fisheries profit (economic), and the relative split of profit between pelagic and benthic fisheries (equity). The intermediary nodes are relationships between all other socio-ecosystem components identified in the literature review.

From the review materials of section 2.1, we were able to build a conceptual marine ecosystem consisting of the identified socio-ecosystem components and relationships that link them. One key finding from the review, which carried over into the current study, was the persistent, clear delineation between the responses of pelagic and benthic fisheries to and from the ecosystem; therefore, we have retained this differentiation in our conceptual models described below. The combinations of socio-ecosystem components and the links between were identified and described in Bastardie *et al.* (2020) and are summarized here in Table 1.

Table 1. Description of the deterministic relationships that make the causal links and chains in the Bayesian Network (BN) framework derived from the literature review undertaken by Bastardie et al. (2020).

Link between components (BN nodes)	**Description of the effect**
Benthic fishing effort → Benthic habitat	Direct or indirect effect of changing the fishing pressure on the benthic biotope and living benthic communities
Benthic fishing effort → Benthic catch	Direct removals of commercial species specimen living in the benthic communities
Benthic catch → Benthic exploited animals	Direct depletion of the population numbers, density and species diversity of the benthic communities
Benthic fishing effort → Benthic non-exploited animals	Direct depletion of the population numbers, density and species diversity of species with no commercial interest, i.e. including unmarketable invertebrate
Pelagic fishing effort → Pelagic catch	Direct removals of commercial species specimen living in pelagic water column being retained on board of fishing vessels to be later sold
Pelagic catch → Pelagic exploited animals	Direct removals of commercial species specimen living in pelagic water column retained on board of fishing vessels to be later sold
Pelagic fishing effort → Pelagic Catch	Direct depletion of the population numbers, density and species diversity of the marine species living in the water column
Pelagic fishing effort → Pelagic non-exploited animals	Direct depletion of the population numbers, density and species diversity of marine species with no commercial interest, i.e. including marine mammals, seabirds, or unmarketable fish
Environmental conditions → Pelagic habitat	Effect of Change in temperature, salinity, from warming waters, acidification, eutrophication etc.

Environmental conditions → Benthic habitat	Effect on the seafloor integrity of a change in water stratification, deoxygenation, hypoxia etc.
Other Uses → Benthic habitat	Direct or indirect effect of the other sectors than fishing in affecting the seafloor integrity positively or adversely
Benthic habitat → Benthic exploited animals	Effect of a change in physical habitats or the associated living communities on the abundance and density of the exploited species
Benthic habitat → Benthic non exploited animals	Effect of a change in physical habitats or the associated living communities on the abundance and density of the non-exploited species
Pelagic habitat → Pelagic exploited animals	Effect of a change in physical habitats or the associated living communities on the abundance and density of the exploited species
Pelagic habitat → Benthic non exploited animals	Effect of a change in physical habitats or the associated living communities on the abundance and density of the non-exploited species
Pelagic non exploited animals → Pelagic exploited animals	Predation by the top predator in the food web, e.g. marine mammals and sea birds
Pelagic non exploited animals → Benthic exploited animals	Predation by the top predator in the food web, e.g. marine mammals and sea birds
Benthic non exploited animals → Benthic exploited animals	Effect of changing the abundance, density and body condition of the components the benthic communities on the exploited benthic species that predate on them
Pelagic or Benthic non exploited animals → Biodiversity	Effect of changing the occurrence of species without commercial interest on the framing biodiversity of the marine ecosystems
Pelagic or Benthic exploited animals → Fishing opportunities	Effect of changing the occurrence of species with commercial interest on opening fishing opportunities
Governance → Environmental conditions	Effect of management measures and actions taken to promote a mitigation of changing climate
Governance → Fisheries policy	Effect of the ensemble of actions taken to install a legislative and institutional framing of the fisheries management and policy
Governance → Other uses	Effect of the ensemble of actions taken to install a legislative and institutional framing and spatial plans for arranging the utilization of the seas by other sectors than fisheries
Fisheries Policy → Pelagic or Benthic fleet fishing effort	Effect of the fisheries management regulating the allowance of the fishing effort deployed at sea with technical measures, and catch quotas

Fisheries Policy → fishing opportunities	Effect of the fisheries management regulating the catch opportunities by capping the amount of catch allowed with catch quotas, and landing obligation in EU
Other Uses → Pelagic (or Benthic) fishing effort	Effect of the competition for marine space in limiting the space available for fishing
Pelagic or Benthic Catch and Effort → Profit	Effect of changing the catch revenue and operating costs on the profit
Fishing opportunities → Profit	Effect of changing the fishing opportunities on possible future profit
Fishing opportunities → Equity	Effect of changing the profit on the balance of distributional economic effects among the fishing communities or fleet-segments

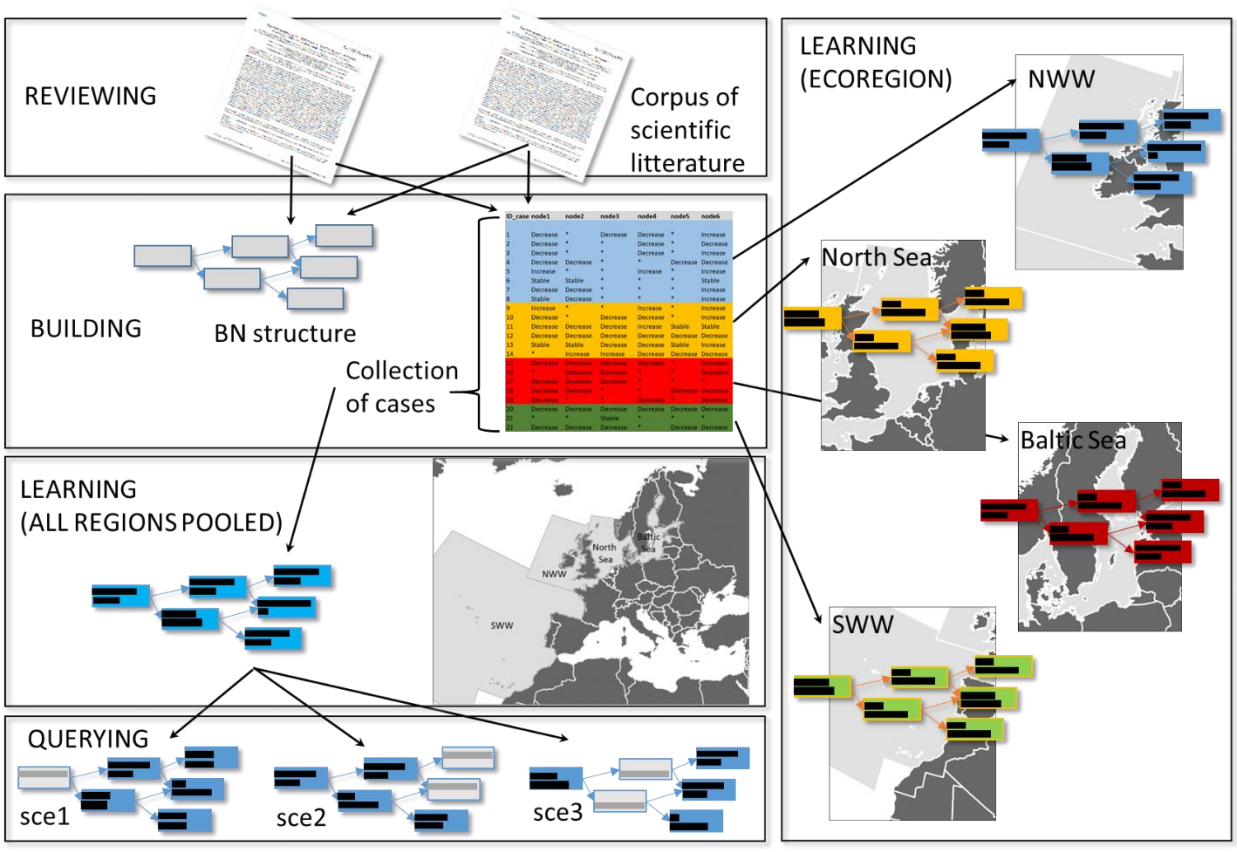

Figure 1. Conceptual diagram for a stepwise approach in building the probabilistic risk assessment framework for answering scenario-based queries.

All these components (nodes) are further arranged according to a set of links derived from the relationships extracted from the reviewed literature. These links influence the state of each node according to the direction of the reported relationship in the literature. In our case, node states are not informed by, and hence do not provide information on, the magnitude of

change, only a probability for each of the three possible directions of change ("increase", "decrease", "stable"). This limitation exists because information on the magnitude of relationships between socio-ecosystem components was found to be too scarce, inaccessible, or too uncertain in the reviewed studies.

2.2.2. Learning in Bayesian Networks

The conditional probabilities of the nodes being some state are then derived by learning with probability revision that iteratively subsample the data (or evidence) that informs the links between nodes. Hence, the probability data consist of the number of cases addressing a specific connection and the direction of the link identified from the reviewed literature. We used the software Netica (version 6.07, http://www.norsys.com, Spiegelhalter and Dawid 1993) for the Bayesian computation of conditional probabilities and the probabilities of node states. Hence, we treated all the relationships extracted from the reviewed literature as evidence within the BN. The importance of these bits of evidence were weighted according to a quality score assigned to the study during the extraction phase of the literature review. This scoring was derived from independent assessments of data resolution and scale, in time and space, as well as method design used in each of the screened studies (e.g. BACI vs post-hoc comparisons, see Methratta, 2020). Once the cases were listed and weighted, the BN learning process (an iterative subsampling routine) determined the conditional probability table CPT at each node, between each parent and child nodes, given the preexisting link structures and the evidence. The CPT is simply a table that has one probability for every possible combination of parent and child states.

The resultant network of nodes and associated CPTs based on all evidence from the review is the baseline BN and determines the posterior probability that each variable/node is in a certain state, in our case a direction of change under these current conditions. This baseline BN can be manipulated and re-analysed to explore the effect of possible scenarios of change in the system (Figure 1). The manipulation (also called a query) is the estimation of the posterior probabilities given new evidence, which in scenario testing is applied by changing the likelihood of different states of select nodes in the network, in other words modifying the priors. The re-analysis that follows is again a Bayesian probabilistic inference and uses the baseline CPTs to propagate the effects of these manipulated state-likelihoods through the rest of the network. The resulting changes in the probable states of nodes of interest can then be compared between the query and the baseline to determine expected responses to change across the network / ecosystem.

BNs of the same structure as the overall baseline were also learnt for some EU ecoregions, individually. While this reduced the number of cases, or evidence, available for each regional BN, this was important for three key reasons: Because it is likely there is no universal solution to improve the status of degraded marine ecosystems, because local governance is now required by the CFP (EC, 2013), and because regionalisation is needed to contextualize to local problems (Meek et al. 2011). We, therefore, split the collection of cases in the four ecoregions for which we had observations, namely: the North Sea (149 cases), the Baltic Sea (77), the North-Western Waters (47) and the South Western Waters (58) (Figure 1).

2.2.3 Querying the Bayesian Networks for scenario evaluation

In parallel we also applied three queries, or “what-if” scenarios, to the all-regions baseline BN to investigate both outcomes and required changes to achieve desired outcomes. These scenarios are outlined below:

Scenario 1. A plausible path

We set the probabilities of increased fishery regulation, increased other marine activities and degraded environmental conditions to 100%. This is a probable scenario in the context of a call for increased fisheries management in an EAFM, together with a strong signal of background change that is not perceived to stop in the short term, i.e., trends for changing climate (Frölichter et al 2018), and for increased utilisation of marine resources through the EU "blue growth" agenda (EC 2017).

Scenario 2. Most-desirable state (with back-casting)

To investigate what changes are required to achieve the desired outcome of maximizing fisheries profits and restoring lost biodiversity (in the framed context), we set these two output variables to 100% certain. This is seen to be the best situation, coming closest to the goals of the EU CFP.

Scenario 3. Least-desirable fishing effort

For this scenario we ran nine different BN scenarios representing the different possible combinations of change in the two fishing effort variables. From these nine different BNs, we selected the one in which fishing profits were at the highest risk of decreasing.

All of these scenarios are queried on the BN and reported on relative to the baseline scenario. Hence, with the BN causal perspective of risk, a risk is therefore actually characterized not by a single event but by a set of events. These events each have a number of possible outcomes (Degrade/Improve, Increase/Decrease). The uncertainty associated with a risk is not a separate notion as every event has uncertainty that is characterized by the event's probability distribution. In our scenario analysis, we imposed a 100% certainty on certain event outcomes to explore the extreme bounding the effects.

3. Results

3.1. Baseline likelihood trends

The Bayesian network informed by the full collection of cases extracted from the literature review show the posterior probabilities of variable states (Figure 2) that result from the conditional probabilities revealed by the interdependency links between the socio-ecosystem components. The baseline BN (Figure 2) represents an idealised European marine ecosystem with fisheries as the core that binds human and environmental components. The resultant variable state probabilities indicate that if this idealised system should continue on the same trends as those identified in the literature review, there is a relatively high chance that profit (44.4%) and social equity (64.2%) will decrease, primarily as a result of the high probability that fishing opportunities will decrease (53.8%). Concurrently, the probability that biodiversity will decrease is the greatest (68%) of our selected output variables. This baseline situation is linked to a likely decrease in the abundance of exploited animals but, to an even greater extent, it is linked to a probable decrease in the abundance of non-exploited animals (66.1% for pelagic animals and 69.1% for benthic animals). These results occur in a situation where the overall fishing effort remains relatively unchanged, albeit slightly more likely to increase in the pelagic realm and slightly more likely to decrease in the benthic. Another likely factor driving a high probability of decreasing biodiversity appears to be habitat degradation, where both of the benthic and pelagic habitat ecosystem components have high probabilities of being degraded (77.2% and 69.9%, respectively). The reviewed literature, as reflected in the baseline BN fit, broadly assumes that this negative situation for both fisheries

and biodiversity results from fisheries and environmental governance remaining stable. With stable governance, management actions are not taken or cannot counteract the environmental changes, even if a slight increase in fisheries regulation, which limits fishing effort, occurs.

By looking at the outcomes per ecoregion, we found that the likelihood of the trends described so far, i.e. higher probability of decreased fishing opportunities, social equity, profit, and biodiversity, are more pronounced for the North Sea (Table 2 and Figure S2.1 in Supplementary Materials). On the contrary, these degraded states are less probable in the Baltic Sea than in the pooled baseline (Figure S2.2 in Supplementary Materials). In the Baltic Sea, the state of profit from fisheries is also less conclusive, partly because the environmental conditions are more likely to improve compared to the pooled baseline (22% vs 8.1%). In the North-Western Waters (Figure S2.3 in Supplementary Materials), even while the likelihood is that fishing effort will increase (54.1% and 44.7% for benthic and pelagic fisheries, respectively), the benthic habitat is less likely to be in a degraded state (56.2%) than across all ecoregions combined (77.2%). This reduced probability of habitats being in a degraded state contributes to the reduced probability of decreased biodiversity, and higher probability of increased biodiversity in the NWW compared to the overall baseline (baseline to NWW, decrease: 68% to 46.2%, increase: 18.1% to 26.9%). However, it must be noted that the overall likelihood remains that biodiversity will decrease for the NWW. Finally, in the South Western Waters (Figure S2.4 in Supplementary Materials) there is a marked difference in the likely state of fisheries policy. For all regions combined, an increase in regulation was much more likely than a decrease (48.5% and 22.1%, respectively), whereas in SWW an increase in regulation was less likely than a decrease (40.9% and 44.4%, respectively) A less stringent set of policies makes the fishing effort more likely to increase for both pelagic fleet (52.6% vs 44.4%) and benthic fleet (48.4% vs 36.3%). In this ecoregion, non-exploited pelagic animals are less likely to be declining than over all regions (56.6% vs 65.1%), with flow-on effects reducing the probability of a decreasing state of biodiversity (48.9% vs 68.0%)

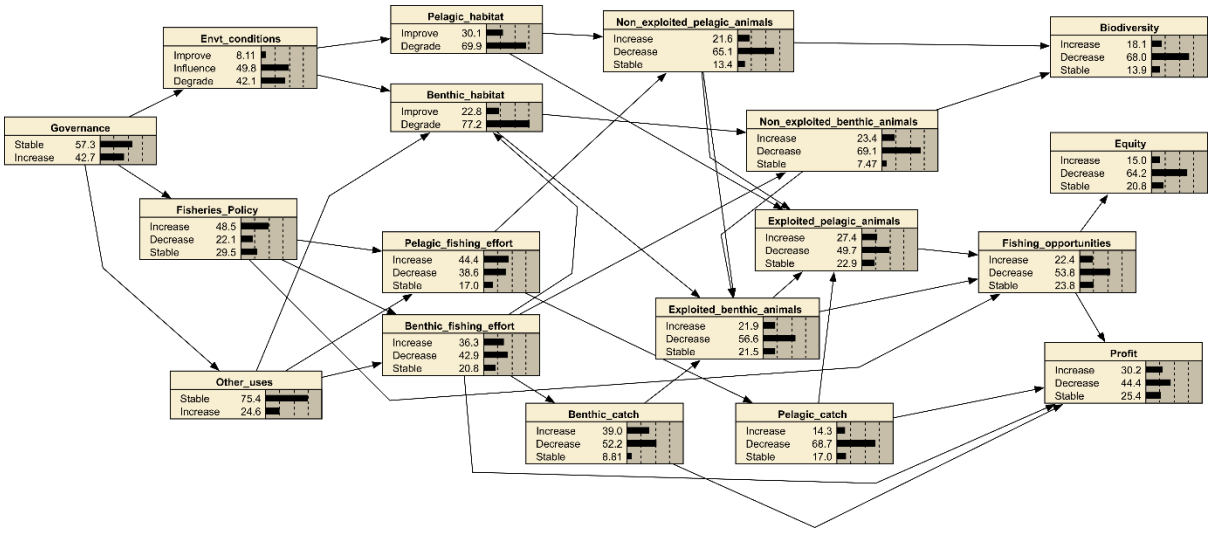

Figure 2. Bayesian Belief Network structure and probabilities on nodes (likelihoods of variable states) obtained after learning from the collection of cases provided by the the literature review including all ecoregions. Also referred to as the all regions baseline BN in this manuscript.

Table 2. Synopsis of the probability per state for the main nodes across ecoregions (the BN representation per ecoregion are given in the Supplementary Materials)

Node	All regions	North Sea	Baltic Sea	NWW	SWW
Governance					
Stable	57.3	57.5	67.3	81.0	56.8
Increase	42.7	42.5	32.7	19.0	43.2
Envir. Conditions					
Improve	6.11	10.8	22.0	18.8	30.7
Influence	49.8	42.9	54.6	40.6	32.3
Degrade	42.1	46.3	23.4	40.6	37.0
Fisheries Policy					
Increase	48.5	41.7	48.4	17.0	40.9
Decrease	22.1	27.7	25.8	62.8	44.4
Stable	29.5	30.6	25.8	20.2	14.7
Other uses					
Stable	75.4	66.7	94.1	69.3	83.9
Increase	24.6	33.3	5.86	30.7	16.1
Biodiversity					
Increase	18.1	23.4	24.0	26.9	27.4
Decrease	68.0	56.5	52.0	46.2	48.9
Stable	13.9	20.1	24.0	29.6	23.7
Equity					
Increase	15.0	12.3	33.6	23.7	33.5
Decrease	64.2	63.8	48.4	52.5	51.4
Stable	20.8	23.9	17.9	23.7	15.1
Profit					
Increase	30.2	30.9	33.2	29.3	30.0
Decrease	44.4	41.4	33.7	41.4	39.9
Stable	25.4	27.7	33.2	29.3	30.0

3.2. Perturbation scenarios

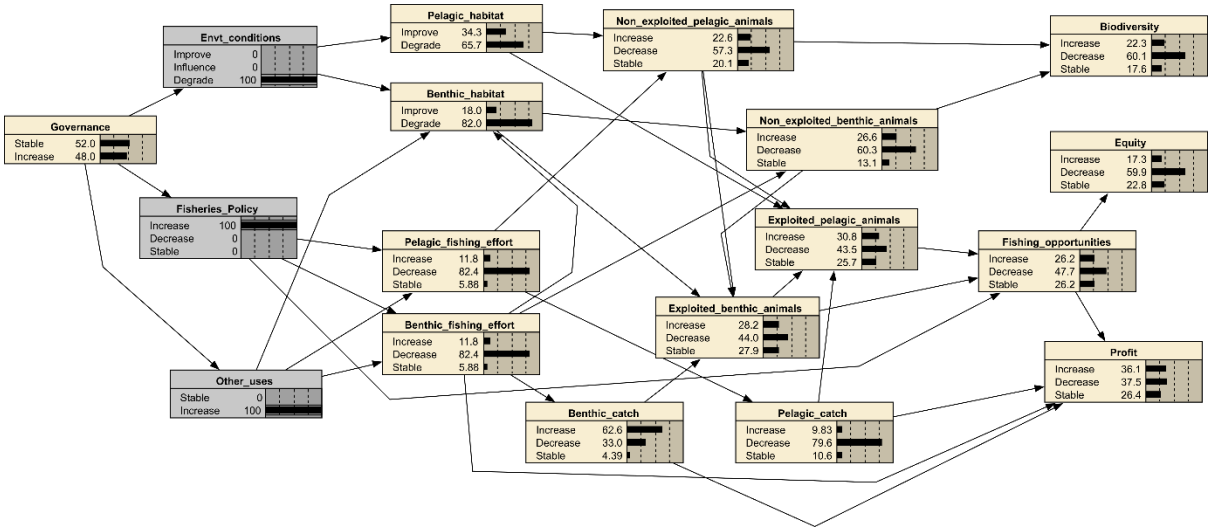

Figure 3. Change in probabilities of variable states for a plausible future, i.e., a combination of increased fishery policy, degraded environmental conditions and intensification of marine space uses from other sectors, all ecoregions confounded. This query corresponds to scenario 1.

Scenario 1. A plausible path

In scenario 1 we queried the BN to investigate plausible future trends, namely degraded environmental conditions, increased fishery policy and increased other uses of the seas. In this scenario there was a modest reduction in the risk of decreased biodiversity and profit compared to the baseline trends (Scenario 1, Figure 3, 68.0 to 60.1% for a decreased biodiversity, 44.4 to 37.5% for a decreased profit). By making certain that fisheries regulation and competition for marine space both increase, there is a large likelihood that fishing effort, both in the pelagic and the benthic fleets, would reduce (38.6% and 42.9%, respectively, to 82.4%, both). The likely reduction in fishing effort propagates through to catches in different ways, with the probability that benthic catch increases, increasing (39% to 62.6%) while the probability that pelagic catch decreases, increasing (68.7% to 79.6%) compared to baseline. While the likely reduction in effort and catch in the pelagic realm leads to an intuitive increase in the probability of increased abundance of exploited pelagic animals (27.4% to 30.8%), the opposite occurs in the benthic realm. The probable increase in benthic catch under a likely regime of reduced effort, appears to be driven by a reduction in the probability that exploited benthic animals decrease (56.6% to 44%). However, this combined mediating effect on the two realms of exploited animals (reduced risk of decreasing) appears to reduce the probability that fishing opportunities will decrease, relative to baseline (53.8% to 47.7%). In addition to this, non-exploited animals from both realms are less likely to decrease driving a lower probability of biodiversity loss (68.0% to 60.1%) in this scenario compared to baseline.

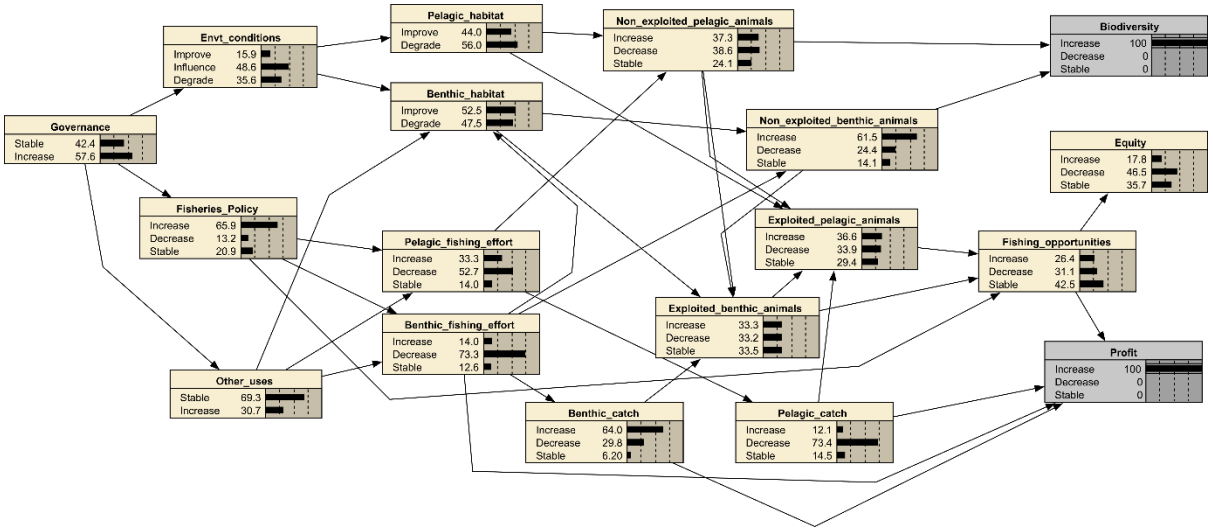

Figure 4. Change in probabilities of variable states for an imposed ideal situation where a simultaneous increase in biodiversity and profit is made certain, all ecoregions confounded. This query on the initial BN corresponds to scenario 2.

Scenario 2. Most-desirable state (with Back-casting)

To achieve a certain increase in both fisheries profit and biodiversity, scenario 2 (Figure 4) shows that a massive, concurrent rise in the probabilities of increased non-exploited benthic animals (21.6% to 61.5%) and the benthic catch (39% to 64%) is required. To a lesser extent, it would also require the probability that exploited and non-exploited pelagic animals are decreasing is reduced (49.7 to 33.9% for exploited, 65.1 to 38.6% for non-exploited pelagics). The change in posterior likelihood in the BN shows that achieving such a target would require significantly lowering the probabilities that each of the benthic and pelagic habitats degrade (77.2% to 47.5% for the benthic habitat, 59.9% to 56.0% for the pelagic habitat). This reduction in the probability of habitat degradation is likely derived from the high probability that fishing effort decreases compared to baseline (42.9% to 73.3% for the benthic effort, 38.6% to 52.7% for the pelagic effort). In this scenario, an increased probability of the environmental conditions improving (8% to 15.9%) via a higher level of governance (42.7% to 57.6%) is likely brought about by increasing fisheries regulations (48.5% to 65.9%), especially those that increase the probability of reduced benthic fishing effort (42.9% to 73.3%). The increased chances of a reduction in benthic fishing effort is likely to also be driven by the rise in probability of an increase in other uses of the seas (from 24.6% to 30.7%).

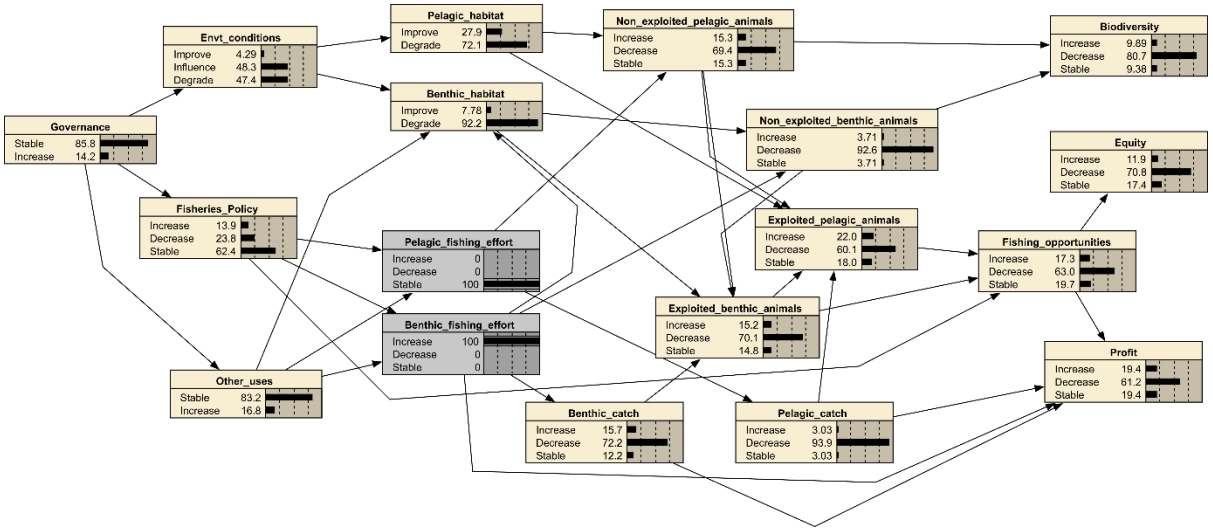

Figure 5. Change in probabilities of variable states for a plausible future, leaving the profit to decrease the most, all ecoregions confounded. This query to the BN corresponds to scenario 3.

Scenario 3. Least-desirable fishing effort

Querying the BN by imposing hard pieces of evidence for an increase in benthic fishing effort and simultaneously a stable pelagic effort is the combination of different fishing pattern scenarios, that leads to the highest probability of decreasing the profit compared to the baseline situation (Scenario 3, Figure 5, 44.4% to 61.2%). Such risk for profit loss is the likely outcome of the risk for reducing the catches (68.7% to 93.9% for the pelagic catch, 52.2% to 72.2% for the benthic catch), causing a more considerable risk for reduced fishing opportunities (53.8 to 63%). Imposing an increase in fishing effort will further increase the probability that habitats will degrade (77.2 to 92.2% for benthic habitat, 69.9 to 72.1% for pelagic habitat), that non-exploited benthic species will be negatively impacted (69.1% to 92.6%), and that the system's overall Biodiversity will decrease (68% to 80.7%). This combination of fishing effort increase for the benthic fleet and stable fishing effort for the pelagic fleet, would likely result from a fishery policy remaining stable.

4. Discussion

We present a knowledge synthesis tool that combines all documented states and trends of socio-ecosystem components interacting with fisheries and presents outcomes in terms of how likely they are to occur. The framework is instrumental in investigating far-reaching consequences of diverse pressures applying to marine ecosystems. Given the many uncertainties inherent to ecosystem dynamics, by resorting to priors accumulated over the long term, the application of a Bayesian Network allows combining and valuing existing knowledge in an integrative way. A scenario evaluation enables exploring how drivers of change (controls) can mitigate pressures applying to marine ecosystems in the long-run and sheds light on the sectoral trade-offs likely to be faced by policy-makers. Such a probabilistic tool is therefore of suitable help to develop further the ecosystem approach to fisheries in Europe. In Europe, the overarching aim of the revised Common Fisheries Policy (CFP; EC, 2013) is now aligned with the EAFM to ensure that fishing is environmentally, economically and socially sustainable. Our findings show that action is required now to implement and operationalize the EAFM, as it appears from evidence accumulated over the last two decades that European marine ecosystem health and resilience are on a declining course. Marine ecosystems in EU waters are at risk from the conjugated effects of fishing, the changes in

environmental conditions, and the pressures from other uses of the seas. These pressures accumulate to make overall biodiversity loss, loss of fishing opportunities for both pelagic and benthic fishing fleets, loss in long-term fisheries profit, and an erosion of social equity among stakeholders a likely future situation. The background degradation of both the benthic and the pelagic habitats is the most substantial cause of these risks and is eroding the natural capital available to support future natural resource production. It appears that maintaining the current level and/or structure of governance is not sufficient to reduce or counteract the environmental changes. Even so, more stringent fisheries policies may be able to limit fishing effort and its adverse effects, without reversing the overall declining trends.

We found that looking at specificities per ecoregion does not change the overall outcome. However, investigating the per-ecoregion scale does refine the diagnosis of which direct effects or foodweb-propagated effects intervene with far-reaching consequences on fish dynamics and marine habitats. In the North Sea, the dependence of seabirds, marine mammals, and predatory fish species on these forage fish make them all sensitive to variations in forage fish population size and productivity (Engelhard *et al.* 2014). The pelagic fleet is geared to catch massive volumes of fish (sprat, mackerel, herring, Norway Pout), which sometimes results in a large volume of juvenile fish of demersal fish species being caught as by-catch (STECF, 2017b). Forage fish as well as pelagic and demersal North Sea stocks are hence under cumulative threat from different fishing activities alone. Many other anthropogenic pressures accumulate, especially in coastal areas (Brown *et al.*, 2018). For example, coastal spawning and juvenile habitats of herring, which are under threat from increased competition for space, particularly with sand and gravel extraction operations but increasingly from wind farms (ICES 2020).

Changing climate, ocean stratification and other environmental conditions affect ecosystem functions independent of fisheries. These natural pressures act directly on exploited populations via changes in abundance, density and vital rates but also indirectly by modifying the make-up and function of marine communities. In the Baltic Sea, a change in environmental conditions can affect fish and benthos distributions as they shift or disperse along with their preference of certain environmental conditions. The variable nature of the hydrography in this system means that populations can rapidly decline both locally and across the system, as environmental conditions change outside of their tolerance limits and could have lowered the ecosystem's resilience (Tomczak *et al*. 2013). Deep oxygen concentrations have been found important for sprat egg survival, especially in the northern Baltic, while recruitment dynamics of Baltic herring and sprat are primarily restricted by temperature-dependent processes and the availability of key zooplankton prey (Lindegren *et al*. 2014). As the mean water depth is only 54 m, temporal variation in stratification and currents are large compared to other seas, making the Baltic Sea relatively more vulnerable to global change (Meier *et al.* 2012). Hence, change in conditions can also open the gate to some invasive species, and the invasion of round goby (*Neogobius melanostomus*), with low commercial value, in coastal areas is now a big issue in the Baltic Sea (Ramírez-Monsalve *et al*. 2016, Ojaveer *et al*. 2018).

The main issue in EU North-Western Waters is obtaining MSY in practice, given the multiple interactions of species, ecosystem dynamics, and characteristics of individual fisheries. Achieving MSY for an individual stock can hamper the achievement of MSY for other stocks, as it is a stock-specific property. Given that the majority of NWW European fisheries can be considered mixed, i.e. they catch a range of species even when targeting specific

species, implementing MSY inevitably generates compromises in fishing practices and outcomes (Rindorf et al., 2016). The issue is exceptionally accurate in situations where this would lead to premature closure of the fishery, like in the Celtic Sea (STECF 2017a). The implementation of the landing obligation makes the technical interactions potentially more harmful with risk for massive quota underutilization. Some species restrict (choke) fishing effort, which significantly reduces fishing opportunities. An ongoing striking example due to technical interactions is haddock being caught together (along with other species) in demersal trawl fisheries targeting cod. In the situation where haddock TAC does not increase but that of the target species, cod, does increase then it is likely that fishing activity will increase and with it so too will the mortality of haddock (among other) (Borges *et al.* 2018).

Finally, in the EU South Western Waters, increased effort, lower risk to profits and little change in the risk to other socio-ecosystem components appears to be a favorable outcome of decreased regulation. However, the overall fishing capacity may increase more dramatically over slightly longer timescales due to a preference for maximizing short term economic profits with myopic investment behaviour (Mullon *et al.* 2016). The focus of management efforts should be on the design of institutions that are goal-oriented, to maximize the chance of finding solutions that improve outcomes in all three sustainability dimensions simultaneously (Burgess *et al.* 2018, Bellanger *et al.* 2018). While some evidence focusses on the effect of seasonal environmental variability, it is also on longer time scales that environmental changes will act to affect fish condition, which is important in fisheries production. This has been shown for the anchovy and sardine in the Bay of Biscay (Gatti et al. 2018). In the SWW's narrow area of continental shelf, the risk for technical interactions and social conflicts increases, where each fleet or gear has negative impacts on the efficacy of other fleets or gears, as in the different bottom fisheries on the narrow shelf of the Cantabrian Sea (Sánchez and Olaso 2004).

The scenarios explored in this paper cover an expected "business as usual" future, together with a best-case and a worst-case scenario. Each of these scenarios provides insight into the potential outcomes of regulatory actions. The overarching conclusion is that there are ways in which the probability of declines in the three key ecosystem components (biodiversity, equity and profit) can be reduced, primarily through action taken at the level of policy. In the first scenario, despite further environmental degradation and competition for space from other marine industries, a regulated and subsequently reduced effort fishery can probably improve catches for benthic fisheries. This comes with a high risk of decreased pelagic catches and hence an increased risk of a reduction in equity with regard fishing profit distribution. Should other, non-fisheries, regulations be installed to reduce the risk of environmental degradation, then the reduced fishing effort may act to improve both habitats and species diversity. However, this is not borne out in our scenario testing.

In the second scenario, which seeks to investigate the changes necessary to make certain an increase in biodiversity and profit, the BN indicates that a low-effort, highly productive benthic fishery is key. The back-casting inference based on the current literature suggests that a reduction in pelagic catch and a decreased effort in benthic fisheries will lead to higher catches of high value benthic/demersal species, thus increasing profit. This same change in fishing patterns increases the chances of improved habitat quality and decreases by-catch associated risks; both of which act to increase system biodiversity. To enable such a shift in

fishing behaviour would likely require strong regulatory intervention, which is reflected in this BN's high probability of an increase in fisheries policy. The changes in fishing patterns and repercussions through the rest of the network are similar in this best case scenario as to the "BAU" scenario 1; the main difference being that a strong policy intervention is required to drive the change in fishing practices further to achieve the goals of improved profit and biodiversity.

Our third and final scenario identified the fishing patterns under which profits were most likely to decline. The identified combination reflects that the current effort exerted in harvesting pelagic stocks will likely lead to reduced catches and fishing opportunities, while an increase in benthic fishing pressure will drive catches of these high value species down even further. Although a different approach was utilised to find the fishing pattern with the highest risk to profit (scenario 3) compared to that used to identify the pattern with the lowest risk (scenario 2), both approaches identified increased benthic fishing effort as a risk to industry wide profit (or vice-versa). While the BN selected in this scenario was based solely on worst profits, it also resulted in the highest risk to system wide biodiversity. This finding, combined with those from scenario 2, indicate that the profit maximising goals of fishers need not be in conflict with biodiversity goals of conservationists and that sensible but strong fisheries policy can simultaneously benefit both of these goals.

Fisheries management in Europe has been using long-term management plans over a couple of decades. The EU CFP is now implementing multiannual management plans that should ideally include EAFM features. However, there is a persisting risk of mismanagement when predator-prey relationships between exploited stocks create a link of dependency altering relative abundance levels and biological reference points being used to manage them. Nevertheless, some upcoming EU multiannual management plans (MAP) consider the difficulties of achieving MSY simultaneously for multiple species and taking into account the trade-offs that result from interactions between species, mixed fisheries, and the multiple objectives of stakeholders. Beside species interactions, the biological reference points should not ignore environmental determinants and methods for estimating reference points which integrate the effects of environmental changes on recruitment and stock productivity should be developed (e.g., Brunel and Boucher 2007, Casini *et al.* 2011). However, even the best management driven by biological reference points is ineffective in the face of persistent stock-recruitment failure, such as that of North Sea herring in the early 2000s (Dickey-Collas *et al.* 2010, Goti-Aralucea *et al.* 2018).

A fishery policy that does not address conservation issues will continue to contribute to the degradation of non-target ecosystem components supporting the exploited stocks productivity. Such degradation is occurring via non-selective fishing practices causing bycatch or habitat modification induced by the exploitation of targeted, commercial species, and can lead to species extirpation or even extinction. TACs are not sufficient as the principal management tool to reduce such pressures (Reiss *et al.* 2010). Spatial management measures, such as fishing bans in certain areas, could fail to include a variety of different benthic biotopes, thus neglecting to account for potential linkages and interactions between those biotopes (STECF 2019a). Management of fisheries and nature conservation has historically been separated although both healthy fish populations and marine habitats are central elements for maintaining a good status of the coastal environment and continued provision of

fish for the fishery. The degradation will continue if the limited integration of broader environmental concerns persists as the result of lack of coordination between fisheries and environmental policies, at both national and EU levels. The absence of clear guidance on how to combine the Marine Strategy Framework Directive MSFD and CFP and their associated governance systems does not help (Meek et al. 2011, Ramírez-Monsalve *et al.* 2016). Hence, the European network of marine parks (marine Natura 2000 sites, EEA 2018) is only located and enforced within territorial waters while the protection of sensitive habitats requires designing cross-boundary areas, which is allowed for under the CFP. Not all of the Good Environmental Status (GES) objectives of the MSFD have defined quantitative targets and, therefore, it is for example not possible to measure the performance of fisheries' technical measures (EC, 2020) in relation to reaching the environmental goals on benthic habitats (MSFD Descriptor 6). Indeed, while methods for estimating the impacts exist, it appears that there are still no methods available to set thresholds to define whether GES can be achieved. EU Member States are required to define certain threshold values at Union level rather than through regional structures (EC, 2020). Progress in setting threshold values for determining good environmental status has so far been slow, and there seems to be a reluctance to set ambitious levels, as that would prevent EU Member States from reaching good environmental status within the deadline established in the Directive (EC, 2020).

We have shown that the effects of management actions throughout the causal links that the network represents could not propagate well i) in the idealized ecosystem we built, but ii) nor could these links in the real ecosystem. There are many uncertainties, both naturally and due the knowledge gaps in our idealised system, that capture the signals and make the outcome of policy under changing environmental conditions uncertain and underdetermined (i.e., multiple interacting causes). Concerning the point i), it is apparent that the idealized ecosystem model we designed here may be refined to include more variables in place of the ones we used, for now aggregating several underlying aspects. For example, disaggregating the fisheries policy into different types of management actions could be beneficial in identifying useful tools for managers to use in an attempt to reverse the declining trend (e.g., Bastardie *et al.* 2020). We were limited in our study by the need for supporting the causal links with data. The evidence extracted from the corpus of studies we reviewed did not provide enough resolution to refine model nodes to such a detailed level. Concerning point ii), in the natural system this can be discussed in light of our findings from the literature stressing that the direction of causality is sometimes unclear (e.g., Selim et al. 2016). The effect may be additive or multiplicative, and each may aggravate or mitigate the direction of ecosystem responses. This is also because fishing effort typically increases during periods of high fish stock abundance and availability, such that effort responds to ecosystem processes as well as driving them. Hence, fishing adversely affects future fishing opportunities if the indicators used to manage them do not relate enough to the change in stock status provoked by the changing pressure (e.g. no correlation between TAC and fishing effort as in Reiss *et al.* 2010). Fishing impacts fish communities and food webs along with other pressure (i.e. bottom-up), making it difficult to disentangle the real effect of fishing alone. In contrast, the fishing effect could be isolated at the community level when looking at the community and biodiversity with the lens of functional groups (Rochet et al. 2010). Predator-prey interactions may result in trophic cascades, but they can be buffered by competitive interactions, that make difficult to predict the fishing pressure effect (Rochet et al. 2013). Fish stock fluctuations are affected by two potentially confounding forces, i.e. the removal of individuals by fisheries and climatic variations affecting the productivity of fish populations. Disentangling the relative importance of these forces has thus been a question of primary

importance for fisheries management and conservation (Rouyer *et al.* 2014). The only way to more broadly differentiate between these effects, is to compare ecosystem structure and function between long-standing non-fished (e.g. MPA or *de facto* MPA) areas and fished adjacent waters but these studies are rare and even less frequently do they incorporate temporal environmental change in the comparisons. Ideally, the studies should consider counterfactuals by applying B(efore) A(fter) C(ontrol) I(mpact) design to provide evidence of the effect of any new implemented management measures on the ecosystem. Most of the studies that compare relationships between different ecosystem components, including the ones we employed to inform our BN rely on experimental designs that confound pre-existing differences with a significant effect (i.e. only applying Control-Impact). A more rigorous approach should account for possible effects of the ecosystem aside from the impacts of implemented management measures. Such evaluation is a hot topic for the policymakers that want to prove the efficacy of their actions (e.g., STECF 2019d).

Effective EAFM requires an understanding of how a fishery that targets one species may indirectly affect other species in the same ecosystem (Smith et al. 2014). Simple knowledge acquisition and further acquiring an end-to-end overview of impacts on EU marine ecosystems should eventually translate into figuring out the direction of causality when looking at time series and correlations. Most studies on fish and fish assemblages are capable of utilizing time series of data. Nevertheless, often, fish stock monitoring surveys can lack power in detecting the change in the fish community structure (Nicholson and Jennings, 2004). Analyzing the long-term changes in ecosystems and disentangling the influence of overfishing and environment require historical data integration. Fisheries-independent data are available only since the mid-1980s, for example, in the Celtic Sea, and thus provide a short-term and truncated vision of fishing impacts (Hernvann and Gascuel 2020). Understanding the ecosystem changes over time is likely to be imperative for a successful ecosystem-based approach to the future management of fisheries at a time of climate change (Lindley et al. 2010). Our findings reinforce the impression that the direction and intensity that these effects propagate in marine ecosystems are uncertain. We also illustrate that while fishing impacts directly upon fish stock levels, the impacts on the broader ecosystem affect future fishing opportunities and delivery of provisioning (landings) and supporting (habitats) ecosystem services. Both environmental and fisheries policy strategies, however, could engage a virtuous circle. By propagating the change induced by the reduction of fishing impacts to other supportive ecosystem components, the CFP management (i.e., among others, to fish at MSY) could contribute to secure future fishing opportunities for the fishing fleets along with fulfilling the market demand, and ensuring coherence in meeting national environmental targets.

By informing policymakers with supporting pieces of evidence accumulated from past studies, our study integrates existing knowledge of fishing impacts in an ecosystem context and further contributes to our understanding of marine ecosystems. The flexibility of such a framework would also allow the uncertainties to reduce along with the addition of new pieces of evidence obtained in future empirical studies. Mathematical models, such as Bayesian networks, can help to take a holistic view and to integrate past and future knowledge in a coherent probabilistic risk assessment framework. Further, the combination of baseline and scenario models we present contributes to our understanding of how to work toward more healthy and resilient ecosystems for viable fisheries while accounting for large-scale environmental changes.

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