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Delivering sustainable fisheries through adoption of a risk-based framework as part of an ecosystem approach to fisheries management

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ABSTRACT

Recently, the role which fisheries play in the provision of marine ecosystem services has been more widely acknowledged, largely as a result in recent years of fisheries management organisations developing and adopting more ecosystem-based approaches to fisheries management (EAFM). Accordingly, several important management and science challenges have been identified. We argue that these challenges represent a number of important steps which underpin effective science based fisheries management, and when taken together and integrated, offer a logical framework by which to best achieve an EAFM. The challenges, or steps of the framework, identified and described are, i. defining appropriate spatial management units based upon significant and coherent ecosystem production processes, ii. assessing multi-species stock dynamics, iii. developing mixed fisheries management approaches, and iv. assessing the impacts of fisheries on non-target species and ecosystem components. The paper considers how the knowledge gained from research on these challenges can be applied to a risk-based management framework as an essential step towards the achievement of the Sustainable Development Goal (SDG) 14 with respect to the conservation and sustainable use of marine resources for sustainable development.

1. Implementing an ecosystem approach to fisheries management

Fisheries, as a provisioning ecosystem service, represent vital components of developed and developing economies, providing income and employment in addition to food and nutrition. The continued benefits derived from sustainable fisheries are dependent upon the achievement of United Nations Sustainability Development Goal (SDG) 14.4 (science-based fisheries management) and SDG 14.2 (productive and resilient ecosystems). The achievement of these sub-targets can also contribute to the achievement of SDG 2 (on ending hunger, achieving food security and improved nutrition), SDG 1 (on ending poverty), and SDG 8 (on sustained, inclusive and sustainable economic growth, full and productive and decent employment). The greater part of world fish supply comes from marine fisheries, currently yielding around 80 million tonnes per annum, with a value of around US$148 billion (FAO, 2016). At the same time, the negative impacts which poorly regulated fishing activities can have on the wider marine ecosystem are increasingly being recognised [72]. While "single-state single-species" fisheries have allowed the implementation of some innovative management systems (e.g. [24]), the interaction between traditional concepts of national sovereignty, marine ecosystems and international relations raises particular problems in managing common fishery resources and the ecosystems of which they are part. Since the early-1980s, various international instruments have been developed with the aim of promoting the sustainable use and rational management of shared marine resources.

Many of the world's most productive fisheries take place on transboundary or high seas stocks, where the "globalised" nature of fisheries has often led to conflict between coastal fishers and those operating in international waters. As a result, formal institutions, typically regional fisheries management organisations (RFMOs), have developed as fora for transparent decision-making and conflict resolution, informed by relevant and responsive scientific advice, supporting the international management and cooperation essential for assessment and regulation of fisheries in areas beyond national jurisdiction (ABNJ), as stipulated by the UN Convention on the Law of the Sea (UNCLOS) and supplemented

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by the Fish Stocks Agreement.[1] Transfer of knowledge and scientific findings within and between these organisations, from areas where fish stocks, the marine environment and associated human factors have been studied, has been facilitated through sharing of practice and experience, for example, via the Food and Agriculture Organization (FAO) of the United Nations.

In line with the understanding of sustainable development as a development "which meets the needs of the present generation without compromising the ability of future generations to meet their needs" [7], managing fisheries sustainably requires protection of ecosystem structure and function while also considering the current and future needs of people as part of marine ecosystems. Sustainable fisheries can also directly contribute to the maintenance or restoration of a wide range of ecosystem services beyond provisioning. For instance, poorly managed by catches of protected, endangered or threatened species can represent an economic cost to fisheries, particularly in developing countries, both through a loss of amenity value of charismatic species, and through the generation of negative perceptions of the products of the fishery. Furthermore, key ecosystem functions and services can be disrupted by the collapse of certain species within their respective functional groups. For instance, top predators have an important regulatory role in the food chain, and large-bodied species play key roles in nutrient cycling and sediment bioturbation [49]. Many other barriers to sustainable fisheries exist, including data deficiencies, particularly with regard to catch data, fleet overcapacity, ecosystem effects of fishing, such as habitat loss, and the frequent disconnect between social and ecological goals [32].

Link and Browman [45] proposed that single species fisheries management (SSFM) and Ecosystem-Based Management (EBM) represent bounding philosophies along a management continuum. At one end, SSFM focuses on a single species or stock. Ecosystem considerations such as habitat, environmental drivers, and predator–prey dynamics can be integrated into the management of a single stock, but management is solely fishery focused. At the other end of the spectrum, EBM represents a holistic approach to management which can go beyond fisheries to include exploration of goals and trade-offs across multiple fleets, sectors, and competing interests (e.g., harvest maximization, economic performance, biological diversity) [22,23]. EBM is expected to lead to more holistic management recommendations by explicitly considering species interactions and environmental processes, quantifying the value of marine ecosystems beyond fishery harvest, and allowing the discussion of trade-offs [16]. Adopting the ecosystem approach provides a means of achieving both fishery and ecosystem-level goals [44].

The Ecological Society of America Committee on the Scientific Basis for Ecosystem Management [12] provided one of the first widely used definitions of Ecosystem Management. They defined it as "*management driven by explicit goals, executed by policies, protocols and practices, and made adaptable by monitoring and research based on our best understanding of the ecological interactions and processes necessary to sustain ecosystem structure and function*". In its fifth meeting, the Conference of the Parties to the U.N. Convention on Biological Diversity defined the Ecosystem Approach as "*a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way*" and indicates that is "…*based upon the application of appropriate methodologies focused on levels of biological organization which encompass the essential processes and interactions among organisms including humans and their environment*". Guidance for the implementation of the ecosystem approach was further developed and adopted by CBD COP 7 (CBD Decision VII/11, 2004).

When applied to fisheries, Ecosystem Approaches to Fisheries (EAF) are intended to ensure that the planning, development, and management of fisheries will meet social and economic needs, without jeopardizing the options for future generations to benefit from the full range of goods and services provided by marine ecosystems Garcia et al. [73]. Achieving this purpose requires addressing components of ecosystems within a geographic area in a more holistic manner than is used in classical target resource oriented management approaches. It requires identifying [geographically] exploited ecosystems together with explicit recognition of the many, and often competing, human interests in fisheries and marine ecosystems [73]. Therefore, following Garcia et al. [73] "…*an ecosystem approach to fisheries strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties of biotic, abiotic and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries*".

Similarly, the U.S. Commission on Ocean Policy noted that "U.S. ocean and coastal resources should be managed to reflect the relationships among all ecosystem components, including human and nonhuman species and the environments in which they live. Applying this principle will require defining relevant geographic management areas based on ecosystem, rather than political, boundaries." As the recognition for the need for ecosystem approaches grow (The Future We Want, paragraph 158; SDG 14c; CBD Aichi Biodiversity Target 6), political commitments to ecosystem-based fisheries management are increasing worldwide. Overall, these (and many other) definitions of EAF embody the recurring themes of the need to understand and account for interactions among the parts of the system, the recognition that humans are an integral part of the ecosystem and that potential conflict among human activities can exist (and hence, achieving trade-offs is required), and that EAF is fundamentally a place-based management framework.

There are very few, if any, examples of such EAF frameworks being fully implemented in fisheries at present. However, there are many examples where at least a number of important steps are being addressed. Most of these are in relation to establishing MPAs and undertaking some form of fisheries spatial management, e.g. by way of establishing fishery closures to protect VME and or defining active fishing areas.

The United Nations Conference on Sustainable Development (Rio +20), which took place in 2012, launched a process to develop a suite of Sustainable Development Goals (SDGs). Member states agreed that the SDGs would build upon the Millennium Development Goals (MDGs) and form part of the Post-2015 development agenda. The 2030 Agenda for Sustainable Development, adopted by the UN General Assembly in September 2015, promotes a set of 17 SDGs, encompassing 169 specific targets, covering areas such as poverty, equality, environment and climate, which represent a framework for achieving efficient policies and governance for global sustainable development. Of these, SDG 14 concerns the conservation and sustainable use of oceans, seas and marine resources for sustainable development. Within this goal, target 14.4 aims for states, by 2020, to *effectively regulate harvesting and end overfishing, illegal, unreported and unregulated (IUU) fishing and destructive fishing practices and implement science-based management plans, in order to restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield as determined by their biological characteristics*. The broad scope of this target covers the specific areas of compliance with regulation, protection of vulnerable marine ecosystems, and the assessment of exploited fish stocks. The balance between these objectives will require decision makers to agree trade-offs among alternative management goals.

Seen in the context of wider marine ecosystems and the management of fisheries upon them, there are clear overlaps in scope between this goal, which seeks an end to unsustainable fishing practices, and several others, such as SDG 14.2, which seeks the sustainable management and protection of marine and coastal ecosystems from significant adverse impacts, and 14.5 which mandates the conservation of at least 10 per cent of coastal and marine areas, based on the best available

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[1] However, in practice, many challenges still remain in the implementation of these obligations as observed in the recent UN Fish Stocks Agreement Resumed Review Conference [67].

scientific information. As noted above, clear linkages also exist with respect to the achievement of SDGs 1 (ending poverty), 2 (no hunger) and 8 (employment), among others.

While international agreements have emphasized the link between the precautionary approach and sustainable management of fisheries, little research has addressed the connections and tensions between the ecosystem approach, participatory decision-making, incentives, resource tenure security, and marine ecosystem services. The emphasis in the 2030 Agenda for Sustainable Development and the role of oceans presents an ideal opportunity to re-examine these issues.

This paper addresses the role of the wider ecosystem approach to fisheries management (EAFM) as a tool for the sustainable management of marine resources and alleviation of poverty. The implementation an EAFM, and the relative importance of stock-by-stock management, versus a more holistic assessment of marine ecosystems is a key consideration in the data-limited environments in which developing states typically operate. This speaks directly to the vision contained in SDG 17 on means of implementation of all SDGs, especially with respect to fostering partnerships to achieve these goals. This paper highlights, through case studies and relevant examples, the important steps being developed to implement frameworks for the ecosystem approach for fisheries management globally, and how these have utility in regions with limited resources to support fisheries independent monitoring and assessment. Specifically, the paper considers some of the latest developments in: **i.** place-based management approaches, **ii.** multi-species stock assessments, **iii**. mixed fisheries management, **iv**. identification and mapping of sensitive habitats, and **v.** assessing the significance of habitat impacts.

2. Place-based management approaches

Ecosystem approaches to management are essentially place-based approaches; they aim to deliver management provisions and advice encompassing multiple stocks which inhabit a common and geographically-defined area. These "ecosystem management" units, and the scale at which they are defined, ideally should capture the core of a functional ecosystem, though other considerations should also be taken into account in defining them (e.g. jurisdictional boundaries and legal issues, main fisheries and fleets, operational issues regarding surveillance and enforcement, etc.). In terms of defining such management units, it is well known that physical oceanographic processes (e.g. ocean fronts and currents) in combination with sea bed characteristics (e.g. sediment type, geology and bathymetry), will largely determine the observed natural boundaries in marine ecosystems, especially when assessed in terms of their productivity and diversity [46,62]. Although, obtaining comprehensive data on the physical properties of the sea can be costly, remote observations by satellite can provide useful data on surface primary production. Indeed, such data has been successfully used to estimate the primary production found at the Flemish Cap off Newfoundland, Canada [47], as well as in large marine ecosystems (LMEs) across the globe [59].

The most effective spatial management units from a fisheries perspective will be those which have a good spatial match between resource exploitation (a fishery) with biological productivity (stock unit), and socioeconomic payoffs [64]. In such cases it should be possible to establish credible Ecosystem Production Units (EPUs) which allow estimates of total fishery production potential to be realistically achieved. However, it should not be assumed that EPUs are fully closed systems; transfer of production across EPU boundaries within a bioregion is to be expected. Establishing EPUs allows a first order consideration for the potential influence of large scale climate/ecological forcing on fishery production, as well as explicitly considering the basic limitation imposed by primary production on fisheries production [11,22,40,62,69,70]. In practical terms, this is aimed at defining a productivity-based Total Catch Ceiling (TCC) at the ecosystem level that should not be exceeded.

3. Multi-species stock assessments

The UN Fish Stocks Agreement (UNFSA) requires states, in their management of straddling and highly-migratory fish stocks, to adopt measures *"based on the best scientific evidence available and* […] *designed to maintain or restore stocks at levels capable of producing maximum sustainable yield (MSY)"*. Inherent in this requirement is the near impossibility of managing a multi-species fishery which maintains all exploited species in at or above levels capable of producing MSY. When interpreting this requirement, it is also important to consider that in implementing it, states shall "tak[e] into account fishing patterns, the interdependence of stocks and any generally recommended international minimum standards, whether sub-regional, regional or global" (UNFSA, Art. 5 (b)). This demonstrates the flexible framework provided by the United Nations Fish Stocks Agreement (NFSA), which can accommodate ecosystem's inability to sustain all stocks at MSY levels at the same time. In this connection, it is also important to highlight that under the precautionary approach guidance provided under the Agreement, "[t]he fishing mortality rate which generates [MSY] should be regarded as a minimum standard for limit reference points. (…). For overfished stocks, the biomass which would produce [MSY] can serve as a rebuilding target" (UNFSA, Annex II, para. 7). This guidance is consistent with the SDG 14.4 political commitment to "(…) restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield as determined by their biological characteristics" (emphasis added).

The FAO (2003), Guidelines for an Ecosystem Based Approach to Fisheries Management, further attempts to account for the interrelationships between and within exploited populations, ecosystems and fisheries. The guidelines state that the understanding and management of fisheries should explicitly take into account interactions between stocks as well as relevant social and economic considerations. The direct and indirect impact of fisheries on the marine ecosystem and vice versa must be assessed to provide management advice in support of an ecosystem approach to fisheries management (EAFM).

Species and fisheries interact in numerous ways in the ecosystem (e.g. trophic changes, habitat disruption). At its most simple level this interaction is represented by predators feeding upon their prey. Numerous frameworks have been developed to model the interactions in marine communities and their response to fishing or other human activities (e.g. Gadget; Ecopath with Ecosim; ARIES). Typically, the data requirements for parameterisation of such models can be onerous, requiring knowledge of population sizes, intrinsic rates of growth and trophic (predator/prey) relationships.

Accordingly, the data requirements and resources needed to develop multispecies indicators of fishing impacts are often lacking and this is particularly true for coral reef fisheries. However, less data-intensive methods have been developed which encompass the wider ecosystem, such as size-spectra analysis. Size-based analyses require fairly simple data collection techniques and may provide useful metrics of community responses to exploitation by fisheries [54,57]. The size composition of communities can usefully be described using size spectra, relationships between abundance (by body size class) and body size of aggregated assemblages regardless of taxonomy [39]. The resulting slopes and mid-point heights of the size-spectra respond to changes in mortality rates and the indirect effects of mortality. Steepening of the slope can represent a decrease in the number of large fish, an increase in the number of small fish, or both. For example, Graham et al. [29] found size-spectra of the fish communities on Fijian coral reefs became steeper and declined in height with increasing fishing intensity. The response to exploitation was greatest for larger fish. Steepening of the slope with increasing fishing intensity in this case largely resulted from reductions in the relative abundance of large fish and not from the ecological release from predation of small fish following depletion of their predators.

In addition, harvesting targets based on size-spectra analyses can vary widely depending on the assumptions of predation and body growth. The information needed to implement such harvest control rules may differ little from existing fisheries data collection programmes [66]. The larger differences would be in how the information would be used at the aggregated ecosystem scale – whether size-based management rules are capable of preserving ecosystem functions to avoid the extirpation of species, or if more complex models are necessary, has yet to be evaluated.

Increasing information needs will be particularly difficult for developing countries which already face problems in implementing conventional fisheries management and where small-scale multispecies fisheries dominate. In contrast to issues such as mixed catches in fisheries which can potentially be lessened through changes in fishing practices, the interaction between predators and prey can only be affected through changing the numbers of prey and/or predators. These interactions result in trade-offs between yield and abundance of different species, and robust scientific advice must therefore be accompanied by increased communication between science and policy-makers when undertaking multi-species assessments to ensure the complexities and uncertainties in the stock interactions are fully understood.

4. Mixed fisheries management approaches

Fisheries in developed countries are typically regulated through restrictions on entry (e.g. licencing), coupled with a mixture of input (e.g. vessel capacity limits, gear requirements, days-at-sea restrictions) and output (e.g. total allowable catches, bycatch thresholds, discard bans) controls; the combination of which defines the regulatory landscape in which a given fishery operates. In recent years, much effort has been put towards reducing unintended mortality in mixed fisheries, through the avoidance and mitigation of discards - the throwing back of unwanted catches, often dead or dying. Discarding is an inevitable consequence of any unselective fishing practice, and this seemingly wasteful practice is common among commercial fisheries with restrictive output controls.

With the agreement on the reform of the European Union's Common Fisheries Policy (CFP) in 2013, the issue of discards in European fisheries became central to the debate. This policy, adopted subsequently to the publication of the FAO International Guidelines on Bycatch Management and Reduction of Discards [21], introduced the staged implementation of an obligation for fishers to land all regulated species. Landing of undersized, unmarketable or beyond-quota species imposes a cost on fishers by taking up space in the hold which could be filled by more valuable target species. Therefore, discard reduction strategies have followed two paths; elimination of catch through technical measures, and avoidance of areas where fish likely to be discarded are abundant through spatial management.

Technical measures which avoid the capture of non-target species are considered ideal as they avoid issues associated with catch-related morbidity. Sorting, or the use of Nørdmore grids have become a requirement in small-mesh shrimp trawl fisheries in many parts of the world. These grids deflect larger bycatch species, such as, for example, rays or turtles out of the net while allowing smaller species such as shrimps to pass into the cod-end unimpeded (e.g. [63,28,65]). Furthermore, studies of fish behaviour in response to towed gear can be used to design gears which favour the escape of non-target species once in the net, such as the use of “square-mesh panels”, which retain their shape under load, in the upper sections of trawl gears. This has been shown to facilitate the escape of small haddock, which rise as they move towards the back of the net.

Another useful approach is the spatial management of discards, especially to protect juveniles and species under moratoria, which can also serve as a buffer against management errors and recruitment failure [52]. Predictive maps of the abundance of discards using Bayesian spatial models have been developed for the North Sea, which show hot spots of high discard concentration for each metier. Seasonal and spatial effects, and the knowledge of the factors influential to discarding behaviour, could be used in mitigation measures for future fisheries management strategies [50]. However, misidentification of hotspots and uncertain predictions, can culminate in inappropriate mitigation practices which can sometimes be irreversible.

Balanced harvesting has been proposed in recent years as a means to implement an ecosystem approach and mitigate the ecological effects of mixed fisheries on marine ecosystems with limited data. The theoretic rationale behind balanced harvesting is inspired by classic ‘surplus production’ theory, which predicts that the fishing mortality leading to MSY is proportional to natural mortality. In an unexploited situation, natural mortality is equal to production per unit of biomass, and it is therefore expected to scale to body mass raised to the power of -0.25 [5]. The emergent conclusion is that the largest yield from an ecosystem is achieved when all species are fished proportional to their theoretical productivity, therefore small species should be fished more intensely than large species. Most fish have large size differences between offspring and adults, and it is therefore relevant to consider whether productivity is best measured at the stock level (as in classic surplus production theory) or at the level of individuals. The prevailing axiom of single-species MSY-based management strives to enforce fishing mortality and size selectivity to maximize production in a manner that juvenile fish are protected from fishing. An exploitation pattern where each individual is exploited in proportion to its productivity challenges the predominant belief that MSY is achievable only when juveniles are protected.

Studies of the impact of balanced harvesting have mainly been explored through a number of modelling frameworks. Simulations in Ecosim have shown that increasing the exploitation rate of small species generates less change in biomass distribution across trophic levels than increasing exploitation rate equally across species [8]. Garcia et al. [25] compiled results from a series of Ecosim and ATLANTIS models, and concluded that unselective harvesting was superior to selectively fishing fewer ecosystem components. The unselective pattern was better in terms of total yield and biomass, and produced fewer local population extinctions. A central piece of empirical evidence making the case for balanced harvesting comes from studies of African freshwater fisheries, which demonstrated that non-regulated fisheries predominantly targeting smaller individuals had little impact on the overall size structure of the local fish communities [74].

Implementing balanced harvesting in traditional fisheries would require increased targeting of smaller-sized ecosystem components, for example through the elimination of minimum mesh size regulations. The resulting fisheries could, however, turn out to be less profitable in markets where large fish often return a higher price per kilogram than small fish. In many developed (richer) countries, the demand for small fish for human consumption is low. In these countries, balanced harvesting may result in a change towards industrial fisheries for production of fish meal and oil or for providing feed to the aquaculture industry, concomitant with a reduced yield of wild-caught, high value fish for human consumption. In developing countries dominated by artisanal, data-limited fisheries, and where consumers are willing to buy and use small fish for human consumption, balanced harvesting may be easier to implement. Although balanced harvesting is an interesting concept, its practical implementation and the ecological and socio-economic consequences need further study before it can be wholeheartedly recommended as a general principle to guide the sustainable exploitation of fish communities in the context of ecosystem-based management.

In data-rich environments, the utility of satellite tracking or vessel monitoring systems (VMS) and electronic logbooks have been used. For example, VMS data has been used to establish real-time management systems which dis-incentivised the targeting and capture of cod in a mixed whitefish fishery [33], to derive maps of fishing activity for the understanding and mitigation of impacts of mobile fishing gears on vulnerable benthos [27], and to parameterise models of fleet behaviour for use in management simulations [48]. Licence conditions can be used to require foreign vessels fishing in a state's waters to carry VMS, but rolling the system out to coastal fishers at a cost level that is acceptable in the developing world may be challenging. Fisheries management authorities in developed countries have implemented increasingly high performance VMS systems, incorporating algorithms capable of automatically determining which vessels under monitoring are most likely operating illegally. While this shows how seriously those countries take the potential of VMS in managing their fisheries, it does not mean that VMS requires this level of sophistication to be a valuable fisheries management tool. Simple GPS data recorders, or suitably equipped smart-phones, uploading spatial information to a central database following a fishing trip, offers a low-cost solution to recording spatial data from small-scale fisheries. The lack of “real-time access” to this data may represent a drawback to managers, however the precision of the data in determining where and how fishing is taking place, and the many ancillary uses to which this information can be put, offers fisheries managers and scientists in developing countries a tool of considerable value. In fostering the means of implementation of the SDGs, through different resource mobilisation initiatives and partnerships (SDG 17) as well as technology transfer (SDG 14.a), special attention to these types of solutions to poor data collection could be further explored.

5. The application of habitat identification and mapping methods in support of sustainable fisheries management

The physical nature of the seabed environment plays a vital role in determining the structure and function of seabed communities. The importance of such abiotic factors in determining the status of benthic communities is well known, to the extent that the physical characteristics of the seabed environment can often be used to provide a good estimate of the types of benthic community likely to be found inhabiting the seabed [38]. From a fisheries management perspective this is important, especially in respect of demersal fisheries, as the seabed environment often provides an important habitat resource, such as providing a source of food for fish at different life stages, opportunities for fish to avoid predation and areas for fish to spawn. In recognition of these potential functional associations between fish and seabed habitats the term Essential Fish Habitat (EFH) has often been used [58], especially where such associations are known to play a significant role in maintaining populations of commercial fish and shellfish species [4].

Significant areas of EFH are often important areas for marine biodiversity. For example, the Pink shrimp (*Pandalus montagui*) is typically associated with biogenic reef building polychaete worm *Sabellaria spinulosa,* inhabiting gravelly sandy sediments at depths less than 50 m, to the extent that fishermen pursuing *Pandalus* have been reported to use small trawls to search for lumps of *S. spinulosa* which they regard as an indication of good fishing grounds [71]. Such relatively shallow water biogenic reef habitat has been shown [26] to support a more diverse fauna than nearby areas.

The same increase in species richness has been observed for reefs of sponges and corals in the deep sea when compared to their nearby surroundings. Such areas of sponge aggregations and cold-water coral reefs are usually found along continental margins at depths > 200 m and in Areas Beyond National Jurisdiction (ABNJ). For these types of habitat, the FAO International Guidelines for the Management of Deep-sea Fisheries in the High Seas [20], provides a sound basis for protecting their associated vulnerable and sensitive communities (termed Vulnerable Marine Ecosystems, VMEs) from the potential deleterious effects of bottom trawling activities.

The concept of deep sea VME was first introduced following discussions at the United Nations General Assembly (UNGA) and the drafting of UNGA Resolution 61/105 which was adopted in 2006. Criteria which define the characteristics of VME indicator taxa are given in the FAO guidance [20], but typically these relate to both structural and functional attributes of an organism e.g. *inter alia*, its ability to modify the habitat through creating biogenic structures or reefs, uniqueness or rarity, functional significance, fragility, increased longevity, slow growth and/or slow maturation. Such organisms include deep sea sponges and corals, but the guidance clearly states that merely detecting the presence of an indicator species itself is not sufficient to identify a VME. This has two related and important implications; firstly, the full spatial distribution of a species that meet the VME criteria does not necessarily constitute a VME, and secondly, the presence of actual VME must possess a level of organization larger than the scale of a singular/individual presence. Another important consideration is that areas where VMEs are *likely* to occur should also be identified and protected (UNGA resolution 61/105, para. 83 (c)). These VME elements are typically topographical, hydrophysical or geological features, including fragile geological structures, that potentially support species groups or communities that qualify as VMEs.

Such considerations raise the possibility of utilising species and habitat distribution modelling techniques to predict the extent and location of sensitive and vulnerable habitats (consistent with UNGA resolution 66/68, paragraphs 131 and 132) which may serve as EFH. Indeed, the mapping of VME and EFH areas, combined with management which recognizes the importance of such areas for sustainable fisheries whilst protecting biodiversity, represents a first step towards facilitating the implementation of EAFM concepts. It is therefore not surprising to observe that fisheries management organisations (especially RFMOs) have started to adopt such measures as part of their overall fisheries conservation and enforcement measures [47]. A response which has been assisted by the advent of predictive habitat mapping and assessment tools.

Predictive modelling of the distribution of VME or essential fish ‘habitat’ may be achieved in a variety of ways. Where the habitat is formed by a single dominant species (as in the case of deep sea sponge grounds), two different approaches have commonly been used. The first models the distribution of the species [31,37]; the second models the distribution of the habitat [41,60,61]. Where both approaches have been used it is often observed that the habitat distribution has a more restricted extent compared to the predicted species distribution [34,47,53]. However, it has also been observed that techniques which model the distribution of habitat are sensitive to the spatial resolution of the environmental data (e.g. bathymetry) used to parameterise the model [1]. In such cases where low spatial resolution bathymetric data has been used to predict broad scale VME distribution there tends to be significant overestimation of suitable habitat [1]. Nevertheless, where a ‘habitat’ is composed of a distinct assemblage of species (as typified by e.g. biogenic reef), then the distribution of that assemblage may be modelled with relatively low error [14,18,51], and when overlaid with the modelled distribution of key indicator species accurate habitat distribution maps can be generated at a range of spatial scales [19,47,56].

It has been noted that for certain exploited stocks, which are closely coupled to the status and functioning of habitat sensitive processes, that establishing spatial management measures which protect EFH may be more effective in achieving sustainable fisheries, than regulating fishing effort and landings alone [30,68]. It is also apparent, that the regions of the world which depend most heavily on marine fisheries for alleviating food poverty, are also in areas where marine biodiversity tends to be high. It therefore, stands-to-reason, that approaches which map and protect EFH will have the potential (perhaps more than anywhere else) to contribute to the sustainability of marine ecosystems and their living marine resources in such regions as well as delivering the socio-economic benefits within a healthy and sustainable fishery. In this connection, the UN Convention on Biodiversity (CBD) initiative to describe ecologically or Biologically Significant Marine Areas (EBSAs) can play a relevant role in the identification of EFH including in developing states where budget limitations constrain marine scientific research. The EBSA process – a science-driven process – initiated in 2010 (CBD Decision X/29) through regional workshops to describe areas that meet the EBSA criteria adopted by the CBD in 2008 (CBD Decision IX/20), has described 204 EBSAs globally to date. A number of these areas (in their entirety or partially) match the VME and EFH criteria [15].

6. Assessing the significance of habitat impacts

Fishing operations that contact the seabed can have unwanted, and often severe, environmental effects. Impacts most commonly documented include the scraping and ploughing of the seabed, resuspension of sediments smothering the fauna, killing of non-target benthic animals, and the dumping of processing wastes [10,36]. There is also growing evidence that environmental changes attributable to fisheries practices can have negative impacts on habitat quality, biodiversity, and the structural and functional integrity of ecological assemblages [13,2,3,35,43].

Whilst the direct impacts of different types of fishing gears on the marine environment have, in general, been well studied, there is much less known about the long-term effects of fishing on the health and functions of marine ecosystems. Indeed, the long-term sustainability of a fishery may not only depend on achieving MSY within overall TCC limits, but also on the ability or resilience of the ecosystem to sustain fishing impacts on a time-scale commensurate with fishing effort at MSY [55].

The capacity/ability of an ecosystem to 'recover', as well as withstand, pressures and impacts, depends on its resilience. This does not imply a static, ideal state, since change is normal in many marine habitats. There is a growing literature on what determines resilience and what happens when it is weakened (see, for example, the Resilience Alliance – www.resalliance.org). Resilience depends on the ecology of its component species and habitats and the interactions between them operating at different scales. In a more biodiverse habitat there is potentially more 'functional redundancy' whereby one species can take up the ecological role of a lost species. In some cases, comparison of more and less biodiverse systems does indicate a degree of 'ecological insurance' in the former. However, this is not always the case, for example, if all species performing the same function respond to a pressure in the same way. Also, in low diversity ecosystems, abundance may be as important as diversity for maintaining ecological roles of species.

Such considerations imply that not all fishing impacts on habitats and species (beyond the targeted species) will be significant, it will depend very much upon a combination of the resilience of the ecosystem (e.g. its sensitivity) and the amount of fishing effort the ecosystem receives (e.g. the exposure to the fishing impact). In terms of fisheries management this has potentially two important consequences, namely; i. limiting the amount of unit area fishing effort to a level that will ensure that any part of the ecosystem can be sustainably fished at that level, or ii. managing the spatial footprint of fishing such that only a proportion of the ecosystem is exposed to fishing at an unsuitable level any one time. However, the practical utility of limiting wide-scale unit area fishing effort at a level commensurate with the recovery times of the most sensitive species in the system is in many cases too restrictive. Therefore, approaches implementing EAFM tend to adopt some form of spatial management of the fishing footprint by way of designating fishery closure areas [47]. This not only ensures a proportion of the most sensitive habitat in the ecosystem is protected, but it also ensures that areas once fished have an opportunity to recover, thus providing new fishing opportunities in the future. Again, the time-scale and extent of such closures will depend upon a combination of on the resilience of the ecosystem and the level of exposure to fishing pressure.

These concepts are, in part, reflected in the guidance regulating the conduct and assessment of deep sea fisheries typically associated with RFMOs. For example, as noted above, the UNGA resolution 61/105 (2006) requests RFMOs to, in accordance with the precautionary approach and ecosystem approaches, assess whether bottom fishing activities have significant adverse impacts (SAIs) on vulnerable marine ecosystems (VMEs) and to ensure that proper conservation and management measures are in place to prevent such impacts. The guidance also requests that RFMOs close areas to bottom fishing where VMEs (including seamounts and cold water corals) are known to occur or are likely to occur (based on the best available scientific information) and to ensure that such activities do not proceed unless conservation and management measures have been established to prevent SAIs on VMEs. Furthermore, following a review of the implementation of UNGA Resolution 61/105, the UNGA Resolution 64/72 (2009) emphasized that impact assessments are to be conducted in accordance with the FAO Deep-Sea Fisheries Guidelines [20] criteria. Besides providing guidance on the management of deep-sea stocks and describing what constitutes a VME, the FAO Guidelines define SAI and provide the criteria for assessing such impacts. SAI are defined as those impacts that compromise ecosystem integrity (i.e. ecosystem structure or function) in a manner that: i. impairs the ability of affected populations to replace themselves; ii. degrades the long-term natural productivity of habitats; or iii. causes, on more than a temporary basis, significant loss of species richness, habitat or community types. In addition, the following six factors or criteria should be considered when determining the scale and significance of an impact.

i. the intensity or severity of the impact at the specific site being affected;
ii. the spatial extent of the impact relative to the availability of the habitat type affected;
iii. the sensitivity/vulnerability of the ecosystem to the impact;
iv. the ability of an ecosystem to recover from harm, and the rate of such recovery;
v. the extent to which ecosystem functions may be altered by the impact; and
vi. the timing and duration of the impact relative to the period in which a species needs the habitat during one or more of its life history stages.

Temporary impacts are defined as those that are limited in duration and that allow the particular ecosystem to recover over an acceptable time frame. The FAO Guidelines recommend that such timeframes are to be decided on a case-by-case basis and should typically be in the order of 5–20 years, taking into account the specific features of the populations and ecosystems. However, in determining whether an impact is temporary, both the duration and the frequency at which an impact is repeated should be considered. If the interval between the expected disturbance of a habitat is shorter than the recovery time, the impact should be considered more than temporary. In circumstances of limited information, the precautionary approach should be applied with respect to the nature and duration of impacts.

The FAO Guidelines also determine that the results of the impact assessments will contribute to the determination of proper conservation and management measures to ensure long-term conservation and sustainable utilization of low-productivity fishery resources in addition to measures that confer adequate protection and prevent SAIs on VMEs.

There are very few examples of where the FAO SAI assessment criteria have been applied in practice, but one such case is in NAFO which recently completed a re-assessment of its bottom fisheries [47]. Through access to fishing vessel VMS data [9] and fishery independent survey trawl data on VME indicator species biomass (mainly sponge, gorgonians and sea pens), NAFO have been able to conduct a quantitative analysis which directly addresses FAO SAI criteria (i–iii) and indirectly allows an estimate of criterion (iv) to be made [47]. The advantage of undertaking such an assessment is that the proportion of VME impacted, against VME protected and VME at risk of impact can be made and used to determine the likelihood of SAI having occurred in the past or is likely to occur in the future. However, a major limitation and issue in determining SAI is not in determining the extent of impact, but in not knowing what proportion of the available habitat can be impacted. There is some evidence to suggest that for habitat features designated under the EU Habitat Directive in the Baltic Sea that unfavorable condition is reached when 25% or more of the habitat feature has been impacted [42]. However, such figures appear to be arbitrarily set with little justification provided in terms of their functional relevance.

Nevertheless, a clear benefit of using the impact approaches defined by the FAO and the SAI methods developed by NAFO [47], is that once the sustainable limits of fishing effort and impact have been determined for a specific habitat type, the fishing effort limit can be applied to habitat of the same or similar type in areas where impact studies are lacking. This then introduces the advantage of establishing habitat sustainability fishing limits in regions which are most able to afford the necessary studies to inform such limits, after which they can be applied in data poor situations through simply monitoring fishing vessel effort (via VMS and other remote tracking technologies) in combination with predictive maps of habitat type. This approach could also contribute to the achievement of the Aichi Biodiversity Target 6 (on sustainable fisheries) adopted by CBD parties in 2010 (CBD Decision X/2). Among other things, it aims to apply ecosystem approaches to fisheries to ensure sustainability and commits contracting parties to avoid SAIs on threatened species and vulnerable ecosystems (not restricted to VMEs, but VME-inclusive). The target *al*so limits fisheries impacts on stocks, species and ecosystems to those “within safe ecological limits”. While such limits will differ from ecosystem to ecosystem, as noted above, the approach suggested here might assist with the implementation of this target.

7. Discussion and conclusions

The science challenges outlined above (which will underpin effective science based fisheries management) represent a number of important steps which when taken together and integrated, form a logical framework by which to deliver EAFM (Fig. 1). With respect to achieving United Nations Sustainability Goal 14.4 (interpreted in light of SDG 14.2 and 14.5) it is clear that the extent to which each step in the framework is implemented (with associated enforcement and monitoring protocols) will be resource-dependent, but there are options and methods which can be applied at each step appropriate to data limited or data poor situations [17]. For regions with limited resources and lack of monitoring and enforcement infrastructures, it may be tempting to focus on a single step, e.g. fulfilling the data needs for single species stock assessments and enforcing minimum catch and landing sizes through net mesh size enforcement and market sampling *etc*. However, whilst this may help to ensure the survivability in the short term of individual fish within a population, the long-term sustainability of fish populations, as a source of food in many of these regions, will also depend on the quality and health of the habitat and not just on the number of surviving individuals of fish. Reef-based fisheries are particularly sensitive in this respect as they are typically composed of a diverse range of large numbers of small individuals which tend to be closely associated with their habitat. In such circumstances setting minimum catch sizes through modifications to net mesh sizes will do little to mitigate the long-term impacts of fishing gears on essential fish habitat. Therefore, fisheries managed under these circumstances are likely to have little chance of achieving long-term sustainability, unless other considerations of the EAFM can be implemented, such as protecting habitat and managing the spatial footprint so as allow areas of ecosystem to recover from the effects of fishing. Capacity development and technology transfer focusing on the relevant components of the EAFM roadmap described here (e.g. identification of ecosystem production units, multi-species modelling, habitat suitability models/mapping) would contribute to the implementation of relevant SDGs such as 1, 2, 8, 14 and 17 as well as Aichi Biodiversity Target 6. Existing information on areas important for biological and ecological processes such as EBSAs and VMEs, and EFHs should be used in EAFM and EBM more broadly. Data collection, more specifically, should also receive proper attention, especially in light of non-costly technologies such as simple GPS data recorders, or equipped smart-phones, uploading spatial information to a central database following a fishing trip. Technology transfer partnerships could also incorporate these types of technologies in implementing SDG 14 (and other related SDGs, as

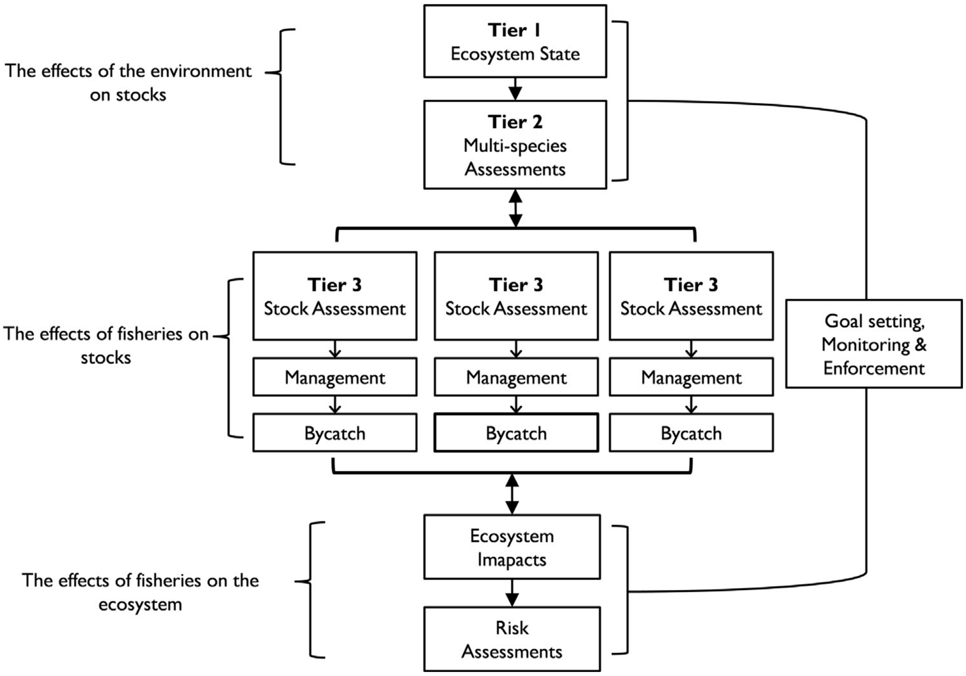

Fig. 1. Key steps for implementing the ecosystem approach to fisheries management. Tier 1 corresponds to the place-based management step – the effective integration of Tiers 1 and 2, with Tier 3 (single species stock assessments) remains a challenge for most fisheries management organisations.

discussed above) since it offers a low-cost solution to recording spatial data from small-scale fisheries. The lack of “real-time access” to this data may represent a drawback to managers; however, the precision of the data in determining where and how fishing is taking place, and the many ancillary uses to which this information can be put, offers fisheries managers and scientists in developing countries a tool of considerable value.

EAFM, as described here, is therefore likely to be of greater importance in achieving sustainable fisheries and derived ecosystem services in regions which depend more heavily on wild capture fisheries as a source of income and nutrition, and thereby contributing to (at least partially) relevant SDGs on the end of poverty and hunger, improving food security, nutrition and well-being. In this respect, the EAFM steps suggested in this paper can contribute to the maintenance or restoration of other regulatory and supporting ecosystem services, such as nutrient cycling, biotubation of sediments, and CO_2 sequestration, disaster risk reduction in addition to cultural services that contribute to human well-being.

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