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Reference points for predators will progress ecosystem-based management of fisheries

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Abstract

Ecosystem-based management of fisheries aims to allow sustainable use of fished stocks while keeping impacts upon ecosystems within safe ecological limits. Both the FAO Code of Conduct for Responsible Fisheries and the Aichi Biodiversity Targets promote these aims. We evaluate implementation of ecosystem-based management in six case-study fisheries in which potential indirect impacts upon bird or mammal predators of fished stocks are well publicized and well studied. In particular, we consider the components needed to enable management strategies to respond to information from predator monitoring. Although such information is available in all case-studies, only one has a reference point defining safe ecological limits for predators and none has a method to adjust fishing activities in response to estimates of the state of the predator population. Reference points for predators have been developed outside the fisheries management context, but adoption by fisheries managers is hindered a lack of clarity about management objectives and uncertainty about how fishing affects predator dynamics. This also hinders the development of adjustment methods because these generally require information on the state of ecosystem variables relative to reference points. Nonetheless, most of the case-studies include precautionary measures to limit impacts on predators. These measures are not used tactically and therefore risk excessive restrictions on sustainable use. Adoption of predator reference points to inform tactical adjustment of precautionary measures would be an appropriate next step towards ecosystem-based management.

KEYWORDS

adaptive management, Aichi Biodiversity Targets, ecosystem interactions, indirect impacts, management strategy, precautionary approach

1 | INTRODUCTION

The last half-century has witnessed growing scientific and political recognition of the interdependence between exploited natural resources and the ecosystems in which they exist. This has been accompanied by support for ecosystem-based management, which aims to incorporate objectives for other parts of the ecosystem, including predators of fished stocks (Link, 2009; Pitcher, Kalikoski, Short, Varkey, & Pramod, 2009; Smith et al., 2011). There is a significant level of international agreement that implementation of ecosystem-based management is a desirable objective. For example, the 194 member nations of the Food and Agriculture Organisation of the United Nations (FAO) endorse the organisation's voluntary Code of Conduct for Responsible Fisheries (CCRF; http://www.fao.org/3/v9878e/v9878e00.htm, accessed 6th December 2019) which was adopted in 1995 and states that "Management measures should not only ensure the conservation of target species but also of species belonging to the same ecosystem or associated with or dependent upon the target species." Similarly, the 168 signatories to the Convention on Biological Diversity (https://www.cbd.int/convention/text/default.shtml, accessed 6th December 2019) endorse Strategic Plan for Biodiversity 2011–2020 (Aichi) Target 6 (https://www.cbd.int/sp/targets/default.shtml, accessed 6th December 2019), which was adopted in 2010 and calls for implementation of "ecosystem-based approaches" so that "fisheries have no significant adverse impacts on threatened species and vulnerable ecosystems and the impacts of fisheries on stocks, species and ecosystems are within safe ecological limits." The CCRF promotes "the contribution of fisheries to food security and food quality, giving priority to the nutritional needs of local communities," while goal B of the Strategic Plan for Biodiversity 2011–2020 aims to "reduce the direct pressures on biodiversity and promote sustainable use." Thus, ecosystem objectives must be considered alongside maintenance of the socio-economic benefits of exploitation (including food, employment and income). A key difference between the CCRF and Aichi Target 6 is that the latter has a specific target date for implementation, that is 2020. In each case, there is a need to assess progress.

Previous efforts to assess progress towards ecosystem-based management rely on broad indicators, or consideration of specific ecosystem processes (Chown et al., 2017; Pitcher et al., 2009; Secretariat of the Convention on Biological Diversity, 2013; Skern-Mauritzen et al., 2016; Tittensor et al., 2014). It is also important to assess whether fisheries managers have access to the technical resources required to implement ecosystem-based management. Such an assessment is necessary to identify any obstacles to progress or missing resources.

The potential impacts of fisheries include the indirect effects of prey removal upon the predators of fished species, particularly "forage" species such as anchovies (Engraulidae), sardines (Clupeidae) and krill (Euphausiidae) (Hilborn et al., 2017; Pikitch et al., 2014; Sydeman et al., 2017). The majority of predation on forage species is due to other species of fish (Furness, 2002) but public interest tends to be more concerned with seabirds and marine mammals, which have significant value as flagship species (sensu Zacharias & Roff, 2001), as an economic and cultural resource (e.g., as the focus of ecotourism), and as indicators of the state of the wider ecosystem (Croxall et al., 2012; Schipper et al., 2008). These groups are therefore often well monitored and a priority for conservation policy. Consequently, there are clear incentives for implementing management approaches to ensure that fisheries impacts on such predators are within safe ecological limits.

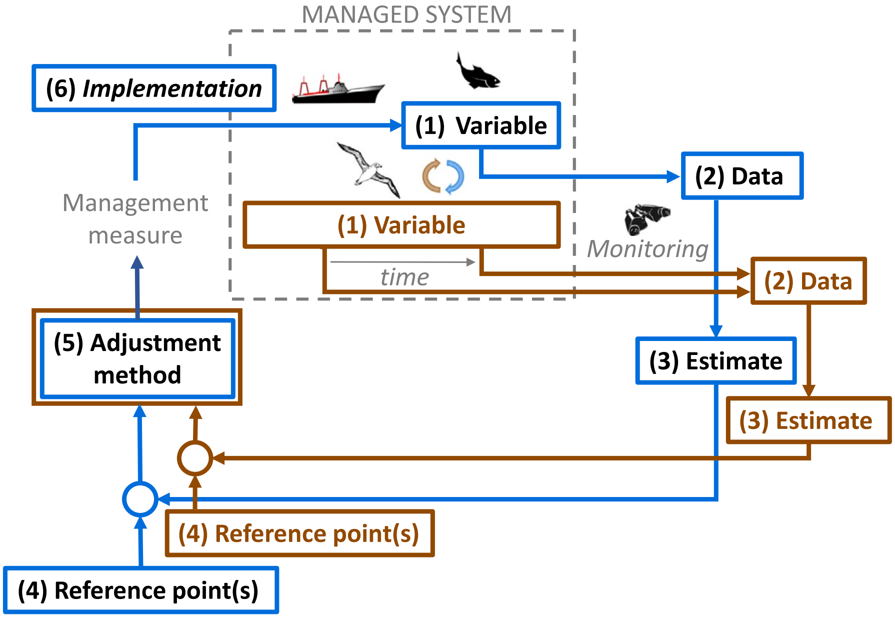

FIGURE 1 The components of the target species feedback loop (blue) which is often used in management strategies with objectives for the fished stock and the fishery (usually maintaining biomass and productivity above a defined threshold and minimizing disruption to the fishery). Also shown are the extra or enhanced components of a predator feedback loop (brown) which has additional objectives (e.g., to maintain predators of the fished stock within defined safe ecological limits). Predator data may be collected at different times relative to data on the fished stock. See text for further explanation of the numbered components

TABLE 1 Summary of case-study locations, target species, recent catches and representative seabird or mammal predators of concern, ordered by ascending total catch

Location	Fished species	Catch (*t*) ·(C/B)	Predators
Burry Inlet, Wales, UK (Northeast Atlantic)	Common cockle (*Cerastoderma edule* Cardiidae)	1,191 (10)	Eurasian oystercatcher (*Haematopus ostralegus*, Haematopodidae)
Western Cape (Southeast Atlantic)	S. African sardine (*Sardinops sagax ocellatus*, Clupeidae)	45,560 (13.6)	African penguin (*Spheniscus demersus*, Spheniscidae)
Scotia Sea & West Antarctic Peninsula (Southern Ocean)-INTERNATIONAL	Antarctic krill (*Euphausia superba*, Euphausiidae)	236,939 (0.4)	Adélie penguin (*Pygoscelis adeliae*, Spheniscidae) macaroni penguin (*Eudyptes chrysolophus*, Spheniscidae) Antarctic fur seal (*Arctocephalus gazella*, Otariidae)
North Sea (Northeast Atlantic)-INTERNATIONAL	Lesser sandeel (*Ammodytes marinus*, Ammodytidae)	518,277 (16.7)	Black-legged kittiwake (*Rissa tridactyla*, Laridae)
US Northeast Pacific	Walleye pollock (*Gadus chalcogrammus*, Gadidae) Pacific cod (*G. microcephalus*, Gadidae) Atka mackerel (*Pleurogrammus monopterygius*, Hexagrammidae)	1,881,000 (10.7)	Steller sea lion (*Eumetopias jubatus*, Otariidae)
North-central Humboldt Current (Southeast Pacific)	Peruvian anchovy (*Engraulis ringens*, Engraulidae)	2,983,944 (38.4)	Peruvian booby (*Sula variegata*, Sulidae) Guanay cormorant (*Leucocarbo bougainvillii*, Phalacrocoracidae) Peruvian pelican (*Pelecanus thagus*, Pelecanidae) South American fur seal (*Arctocephalus australis*, Otariidae) South American sea lion (*Otaria flavescens*, Otariidae)

Note: INTERNATIONAL indicates fisheries management by international agreements. Catch and catch/biomass (C/B) estimates are for 2017. Further details are provided in the even-numbered tables in Appendix S1.

Fishery management usually aims to maintain socioeconomic benefits by keeping fished stocks within safe ecological limits while minimising disruption to the fishery. The process for achieving this is generally known as a management strategy or management procedure (Kvamsdal et al., 2016; Punt et al., 2016; Rademeyer, Plagányi, & Butterworth, 2007). Typically, such management strategies are based on feedback loops (Figure 1) containing adjustment methods, which vary measures such as catch limits or spatial closures in response to information about the state of the fished stock. Such methods could be adapted to respond to information from other ecosystem variables (Rice, 2009), and it is therefore conceptually appealing to develop ecosystem-based management by extending these target species feedback loops to explicitly include objectives for predators and estimates of their status (Hill & Cannon, 2013; Matsuda & Abrams, 2013). This is the stated aspiration for the management of the Antarctic krill (*Euphausia superba*, Euphausiidae) fishery in the Southern Ocean (Constable, Mare, Agnew, Everson, & Miller, 2000; Croxall, Everson, & Miller, 1992).

A predator feedback loop intended to ensure that impacts on predators of the fished stock are within safe ecological limits contains six essential components (Figure 1). These are (1) state variables for the fished stock and the predators which are the focus of management objectives and which are (2) regularly monitored to provide (3) state estimates; (4) reference points representing management objectives for the state variables; (5) a method for adjusting fishing activities in response to the differences between the state estimates and the reference points; and (6) an effective means of implementing these adjustments. Reference points can include both targets (desirable states to achieve) and limits (the boundaries of undesirable states to avoid) (Hall & Mainprize, 2004). Adjustments to fishing activities could include changes to catch limits, fishing effort or fishing locations. Adjustment methods could be algorithmic harvest control rules (Hill & Cannon, 2013; Matsuda & Abrams, 2013; Punt et al., 2016; Rice, 2009), or could be based on consultation, discussion, legal or legislative process (Kvamsdal et al., 2016).

Predator feedback loops would, in principle, meet one of the key requirements of ecosystem-based management: to consistently make appropriate adjustments in a timely manner when necessary (Link, 2010; Pitcher et al., 2009) (but see Matsuda & Abrams, 2013). The individual feedback loop components also provide the building blocks for alternative ecosystem-based management approaches (Hall & Mainprize, 2004; Pitcher et al., 2009; Punt, 2010). The presence of these components is therefore an indicator of progress towards ecosystem-based management.

We assessed the presence or absence of target species and predator feedback loop components in the management systems of six fisheries (Table 1) which are located in four oceans, target either fish, crustacea or molluscs and range in scale from a single estuary to a whole ocean basin (Figure 2). Together these represent about 6% of reported global catch (FAO, 2018). In each fishery, the potential indirect impacts upon bird or mammal predators of the fished stock are well publicized and well studied. These fisheries should therefore be amongst the most likely to have appropriately advanced management systems.

2 | METHODS

Our aim was to provide an objective assessment of the presence or absence of each feedback loop component (Figure 1), as an indicator of progress towards ecosystem-based management, in the six case-study fisheries. The case-studies cover a representative range of spatial scales, catch volumes and governance systems (Table 1, Figure 2). They were selected because concerns about potential indirect fishery impacts upon at least one species of seabird or marine mammal are well documented in the scientific literature. The Convention on Biological Diversity does not apply to two of these fisheries (i.e. the North Pacific groundfish and Antarctic krill fisheries which are, respectively, governed by a non-signatory state and the separate international Convention on the Conservation of Antarctic Marine Living Resources, CCAMLR). Nonetheless, the objective of implementing ecosystem-based management is clearly stated in these cases (https://www.fisheries.noaa.gov/insight/understanding-ecosystem-based-fisheries-management, https://www.ccamlr.org/en/organisation/camlr-convention-text, both accessed 6th December 2019). Thus, our approach provides an indication of progress at the leading edge.

We assembled a team to write a case-study for each fishery (Appendix S1). The team included at least one predator specialist and at least one fishery or fish biology specialist to ensure a balance of viewpoints. The teams wrote the case-studies in conjunction with the lead author to ensure that they include clear statements about the details or absence of each of the feedback loop components. The case-studies also include further information about the fished stock, its predators and management system, knowledge of predator dynamics, developments in the management approach, and reference points for the predators where they have been formally adopted by government agencies.

Three authors (SLH, JH and NR) then worked together to assess the presence or absence of the six feedback loop components based on evidence presented in the case-studies. A predator feedback loop is an extension of a target species feedback loop (blue components in Figure 1) with extra components which provide information about predators and an enhanced adjustment method which responds to this information as well as the estimated state of the fished stock (brown components in Figure 1). Our assessment of target species feedback loops evaluated the presence or absence of the blue components and our assessment of predator feedback loops evaluated the presence or absence of the extra (brown) components.

The presence or absence of each component was assessed against the following criteria:

Variable - Management formally recognizes a defined variable for the fished stock (in target species feedback loops) or predator (in predator feedback loops), either as an explicit objective, or as a routine consideration in decision-making.

Data—Regular (e.g., annual) data are available which describe some aspect of the state of the fished stock or predator population.

Estimate—Management decisions are sometimes or always informed by estimates derived from the data.

Reference point—Management has an explicit objective for a defined state variable.

Adjustment method—Management adjusts fishing activities in response to changes in estimates derived from the data.

Implementation—There is an effective process to ensure that management decisions are implemented in practice.

Where a criterion was met, the component was assigned a score of one, otherwise it was assigned a score of zero. A predator feedback loop does not necessarily need a separate implementation process to achieve objectives for predators, as the relevant measures

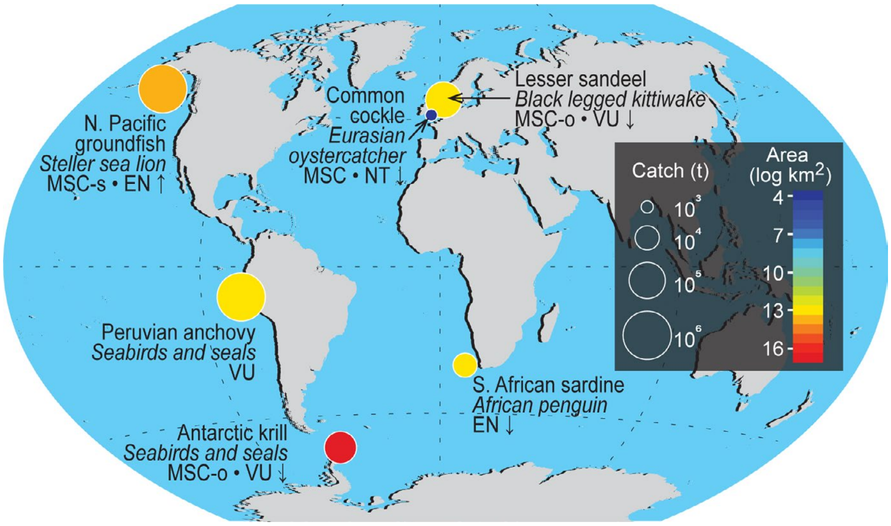

FIGURE 2 Location (circles), catch level (circle size) and spatial area of management (circle colour) for each case-study. Also listed are the main fishery target species, representative predators (italicized), Marine Stewardship Council certification status (MSC – certified fishery, MSC-o – certified operators, MSC-s – certified stocks), IUCN Red List status of the most threatened predator (NT - near threatened, VU - vulnerable, EN – endangered), including direction, if known, of population trend (arrows)

may be similar to those used to achieve objectives for the fished stock. Consequently, we did not assess implementation as an extra component in the predator feedback loop.

The principles of the predator feedback loop could be adapted to include objectives for any species or other parts of the ecosystem that may be impacted by fisheries. Progress, or otherwise, in achieving objectives for fished stocks and their predators therefore indicates the potential for controlling impacts on the wider suite of "stocks, species and ecosystems" mentioned in Aichi Target 6. Our criteria focus on the implementation of individual components and therefore relax some of the dependencies between components which exist in functional feedback loops. Notably, our criteria allow the "data" or "estimate" components to score one even when "variable" scores zero. This highlights the caveat that our assessment does not consider whether individual components of the predator feedback loop identified in each case-study are fit for purpose. Such an assessment might only be possible when the whole feedback loop has been implemented and it is possible to evaluate whether the components function as a coherent whole. Nor does our approach assess the state of development of components which have not been implemented.

The specific phrases from the case-studies which provide evidence of presence or absence are compiled in even-numbered tables in Appendix S1. These scores and their supporting evidence were shared with the entire group of co-authors who were asked to scrutinise and, if necessary, challenge any of the scores. This process led to some clarification of the language used to describe the components and resulted in agreement amongst the co-authors about the final set of scores.

We used the Marine Stewardship Council (MSC) website (https://fisheries.msc.org/en/fisheries/, accessed 8th March 2019) to identify the MSC status of case-study fisheries, and we used the International Union for Conservation of Nature (IUCN) Red List website (https://www.iucnredlist.org/, accessed 8th March 2019) to identify the Red List status of predators of the fished species.

3 | RESULTS

Appendix S1 presents the six detailed case-studies. Five case-studies include all of the target species feedback loop components whereas one (the Antarctic krill fishery) lacks regular estimates of the state

TABLE 2 Summary of case-study scores

	Common cockle		South African sardine		Antarctic krill		Lesser sandeel		North Pacific groundfish		Peruvian anchovy	
	S	P	S	P	S	P	S	P	S	P	S	P
Variable	1	1	1	1	1	1	1	0	1	1	1	0
Data	1	1	1	1	1	1	1	1	1	1	1	1
Estimate	1	1	1	1	0	0	1	1	1	1	1	0
Reference point	1	1	1	0	1	0	1	0	1	0	1	0
Adjustment method	1	0	1	0	1	0	1	0	1	0	1	0
Implementation[a]	1	NA	1	NA	1	NA	1	NA	1	NA	1	NA
Total	6	4	6	3	5	2	6	2	6	3	6	1

Notes: A score of 1 indicates the presence of the relevant component of a target species feedback loop (Figure 1) with objectives for the fished stock and fishery (S) or the extra and enhanced components of a predator feedback loop with additional objectives for predators of the fished stock (P).
[a]A predator feedback loop does not necessarily need a separate implementation to achieve objectives for predators, as the relevant measures (e.g., catch limits, catch distributions, closures) may be similar to those used to achieve objectives for the fished stock.

of the fished stock (Hill et al., 2016; Table 2). Although estimates of krill density in some areas are available for most years, there is no agreed method for using these estimates to assess overall stock biomass and long-term catch limits are evaluated through simulation (Constable et al., 2000).

All of the case-studies had at least one of the extra components required in a predator feedback loop, that is regular predator monitoring data. With one exception (North Pacific groundfish), this monitoring is not conducted by the agency responsible for fishery management and, in the Burry Inlet example, it is conducted by a non-governmental organization. Despite the availability of these data, only four of the management systems explicitly recognize a predator state variable. First, African penguin population size is included in the simulation models used to select the rules for adjusting South African sardine catch limits in response to the state of the fished stock (de Moor & Butterworth, 2014). Second, management of the North Pacific groundfish fishery includes a consultation process to ensure that the fishery avoids jeopardising Steller sea lion recovery, defined in terms of population trends, in locations where the Steller sea lion population is listed under the US Endangered Species Act (National Marine Fisheries Service, 2008). Third, the Burry Inlet cockle fishery has a legally designated target for the number of Eurasian oystercatchers that the site should support (Stillman et al., 2010). Finally, CCAMLR, the Convention on which management of the Antarctic krill fishery is based, is explicit about the need to restore depleted predator populations.

The Burry Inlet cockle fishery has the most complete set of extra components for a predator feedback loop and is the only case-study with an explicit reference point for predators. Nonetheless, this case-study, like the others, lacks an adjustment method which responds to information about predators. Instead, the catch limit for cockles is based on estimated cockle biomass minus a fixed allocation for the target predator population (Stillman et al., 2010). The fishery is required to reserve this allocation regardless of current oystercatcher population size.

In the cases of the South African sardine and North Sea sandeel fisheries, reference points for predators (Department for Environment, Food & Rural Affairs, 2014; Department of Environmental Affairs, 2013) have been formally defined by government agencies which do not have direct responsibility for setting fishery quotas (Table 3). In the case of the North Pacific groundfish fishery, reference points for Steller sea lions are defined by a separate branch of the agency with management responsibility (NMFS, 2008). Although considered through a consultation process, these reference points are not used directly in setting quotas. All of these examples are target reference points.

Four of the fisheries in the case-studies are wholly or partly certified by the MSC (Figure 2). This reflects the advanced state of the target species feedback loop in all cases, although it is noteworthy that the least advanced case-study in this respect (Antarctic krill) includes certified operators. There is no relationship between certification and the scores for the predator feedback loop.

TABLE 3 Reference points which have been defined for seabird and seal predators in the case-studies

Case-study	Predator	Variable	Reference point	Reference point type	Reference point status	Use in fishery management
Common cockle	Eurasian oystercatcher	Breeding population size	13,590	Target	Legal requirement	Yes
South African sardine	African penguin	Population growth rate (breeding pairs)	1% p.a.	Target	Objective of Biodiversity Management Plan	No
Lesser sandeel	Black-legged kittiwake	Breeding success	Should not be significantly different from levels expected under prevailing sea surface temperature	Target	Objective of UK Marine Strategy	No
North Pacific groundfish	Steller sea lion (Western stock)	Population growth rate (juveniles and adults)	3% p.a. over 30 years	Target	Objective of Recovery Plan	Indirectly, through consultation

Aichi Target 6 states that "fisheries [should] have no significant adverse impacts on threatened species." Thus, red-listed species should be protected from such impacts. Five of the case-studies have at least one predator species which is categorized as vulnerable or endangered in the IUCN Red List. The highest scoring case-study in terms of the predator feedback loop (common cockle) has the least threatened predator population, while those with the joint second-highest score (South African sardine and North Pacific Groundfish) had the most threatened predators.

4 | DISCUSSION

Although most of the case-studies have established single-species management, none have fully implemented ecosystem-based management. This suggests that the 2020 deadline for Aichi Target 6 will not be met, joining other missed deadlines for widespread implementation of ecosystem-based management, such as the 2010 deadline stated in the 2002 Plan of Implementation of the World Summit on Sustainable Development (https://www.un.org/ga/search/view_doc.asp?symbol=A/CONF.199/L.7&Lang=E, accessed 6th December 2019).

Fishery managers in each case-study have access to predator monitoring data, but none of them has implemented a method for adjusting fishing activity in response to these data. This lack of progress with adjustment methods is related to the lack of key input information, particularly about which predator state variables are important and what the objectives for them are (Hall & Mainprize, 2004; Punt et al., 2016). Reference points, which encapsulate these two pieces of information (Hall & Mainprize, 2004; Hill, 2013), are missing in most case-studies.

MSC certification is not a reliable indicator of ecosystem-based management. Such certification requires that fisheries "must be managed so that other species and habitats within the ecosystem remain healthy" (https://www.msc.org/en-us/standards-and-certification/fisheries-standard, accessed 6th December 2019) and has been used as to measure progress towards Aichi Target 6 (Tittensor et al., 2014). However, there was no relationship between MSC certification and predator feedback loop scores in our case-studies.

4.1 | Contributory factors

The Antarctic krill and Peruvian anchovy fisheries shared the joint lowest aggregate score. The former operates over the largest spatial scale of the case-studies and is managed by consensus amongst 25 members, representing almost 4 billion people. The highest scoring fishery is a small-scale artisanal fishery for common cockles managed on behalf of the Welsh Government, which represents just over 3 million people. The contrast between these two case-studies (Table 2) suggests that barriers to progress increase with scale and complexity (see also Hill et al., 2015).

The status of the Antarctic krill fishery contrasts with the stated intention to implement "feedback management" (Constable et al., 2000) and the significant multinational effort that has been devoted to progressing the elements of a predator feedback loop (Constable, 2011). Feedback management is seen as a logical development of an ecosystem monitoring programme recording predator performance variables, such as offspring production, at various sites throughout the Southern Ocean since 1985 (Agnew, 1997). The purpose of this programme is to detect ecosystem changes and determine which changes are attributable to fishing (Agnew, 1997). However, the specifics of how it will be used in management, including the relevant state variables, reference points and decision rules, remain to be agreed upon (Constable et al., 2000; Hill & Cannon, 2013). Potential obstacles to progress include the need for consensus, the voluntary basis of participation in the development of management, differences amongst scientists on how to provide advice and a lack of perceived urgency (Constable, 2011; Constable et al., 2000; Hill, 2013).

Delays in the implementation of ecosystem-based management are also linked to uncertainty about how fisheries impacts propagate through food webs (Hilborn et al., 2017; Matsuda & Abrams, 2013; Punt, 2010). Other factors, including environmental conditions, can affect predator populations directly (Ropert-Coudert et al., 2015) or via prey availability (Sydeman, Poloczanska, Reed, & Thompson, 2015). However, coupling between predator and prey dynamics is often non-linear and noisy and can be very weak (Hilborn et al., 2017). Furthermore, populations of relatively long-lived predators consisting of multiple generations are often buffered against short-term fluctuations in prey species, such that there may be substantial time delays in population responses to food shortages (Forcada, Trathan, & Murphy, 2008; Sydeman et al., 2015). Seabirds and marine mammals often do not recruit to the breeding population until they are five or more years old, so breeding population size might not reveal the effects of successive breeding failures until it is too late to take remedial action (Parsons et al., 2008). Competition from other predators feeding on the same prey might also be important. For example, the effect on forage fish stocks of changes in predatory fish populations can be greater than the effect of fishing (Engelhard et al., 2008; Furness, 2002).

The uncertainty surrounding fishery-predator interactions and the adversarial nature of much debate about fishery impacts on predators leads to a situation in which any evidence that predators are not within safe ecological limits can be seen as a failure of fishery management. This might have contributed to the reluctance of fishery managers to adopt predator reference points.

Ultimately, the lack of predator reference points indicates uncertainty about the specific objectives for predators. This uncertainty can exacerbate uncertainty about the nature of impacts and stall the development of appropriate management approaches (Hill, 2013; Regan, Colyvan, & Burgman, 2002).

4.2 | Precautionary measures

Most of the case-studies use precautionary measures. These include the low catch limit for Antarctic krill, which is intended to limit competition between krill predators and the fishery (Hill et al., 2016); the partial closure of the North Sea sandeel fishery, which was prompted by low black-legged kittiwake breeding success and potential overfishing of the adjacent sandeel subpopulation (International Council for the Exploration of the Sea, 1999); fishing restrictions near Steller sea lion rookeries and African penguin colonies (Jemison, Pendleton, Hastings, Maniscalco, & Fritz, 2018; Pichegru, Grémillet, Crawford, & Ryan, 2010); and reservation of a fixed allocation of cockles in the Burry Inlet (Stillman et al., 2010). These examples are all fixed rather than tactical measures. Some case-studies identify tactical measures that are not informed by predator status but might benefit predators by protecting the fished stock. These measures include closures in the North Pacific groundfish fishery when fished populations fall to low levels (Kvamsdal et al., 2016) and localized spatial closures in Peruvian anchovy fisheries when catches containing >10% juveniles are reported in a fishing zone (PRODUCE, 2016).

Precautionary measures are used when risks are difficult to assess (Garcia, 1996). Such measures have their own associated risks, including reductions in catch which might not be necessary if more information were available and, in the case of spatial closures, the risk of simply displacing the problem (Greenstreet, Fraser, & Piet, 2009). Protecting predators from the potential effects of fishing reduces sensitivity to fishing and might therefore increase the difficulty in resolving uncertainties about fishery impacts.

Disagreements about the necessary magnitude, location and timing of precautionary measures are common, especially when there are no agreed reference points to inform their use or evaluate success. In the case of the Antarctic krill fishery, for example, the question of how to spatially distribute catch limits has not been resolved after a quarter-century of debate (Hill et al., 2016). In the case of the Peruvian anchovy fishery, the idea of precautionary spatial closures is at least 80 years old but has not yet translated into practical management measures (Bertrand et al., 2012).

4.3 | Reference points

Reference points are critical components of ecosystem-based management (Hall & Mainprize, 2004; Link, 2010; Rice, 2009). Defining predator reference points is feasible as evidenced by their existence outside the fisheries management context. The reference points in Table 3 are examples of stakeholder objectives for predators, which could be adopted or adapted for the specific purpose of fishery management. Each describes a target reference point, identifying a desirable predator state or range of states. The only example of a predator reference point in the case-studies (for oystercatchers in the common cockle fishery) is also a target reference point. Limit reference points, which identify the boundaries of undesirable states (Hall & Mainprize, 2004), are rare for predators.

Environmental variability and change affect predators through a variety of direct and indirect pathways, not least through effects on the productivity of forage stocks (Sydeman et al., 2015). Environmental change can mean that goals, which are achievable under current conditions, are not achievable under future conditions. This has led to the development of relative reference points (Hill, 2013), which change over time to track environmental conditions. An example is the black-legged kittiwake reference point (Table 3) in which breeding success is assessed relative to that expected under current environmental conditions (Cook, Dadam, Mitchell, Ross-Smith, & Robinson, 2014). Such reference points generally require a model to determine the expected state.

Environmental variability can mean that the vulnerability of predators to the indirect effects of fishing varies over time. In particular, stress can accumulate over multiple years of poor environmental conditions, resulting in amplified impacts (Parsons et al., 2008). Conservation objectives are generally framed in terms of population size (Croxall et al., 2012; Schipper et al., 2008), which is unlikely to be a particularly sensitive or timely indicator of stress. Some variables, such as reproductive success or offspring growth, provide an early indication of stress that could eventually translate into population changes (Cook et al., 2014). Thus, reference points based on these so-called "leading" or "threshold" indicators are likely to be more useful for timely adjustment of fishing activities than reference points based on population size alone (Cook et al., 2014; Hall & Mainprize, 2004).

4.4 | Recommendations

Precautionary measures offer a middle ground between protecting predators by preventing fishing (which is not compatible with "sustainable use") and implementing fully developed predator feedback loops. As the case-studies show, precautionary measures to protect predators are often used without a specific definition of objectives in the form of reference points. Many of the risks, especially those to sustainable use, could be reduced by using precautionary measures tactically, that is when proximity of a state estimate to an appropriate reference point indicates a need.

It is likely that fishery impacts on predators will be most severe when predator populations are already experiencing stress due to naturally induced food shortages (Pardo et al., 2017; Parsons et al., 2008). It is therefore appropriate to apply precautionary measures during periods of stress to minimize any additive impacts that could damage predator and prey populations. This requirement to minimize impacts rather than steer the predator populations towards a goal suggests that limit reference points are more suitable than target reference points.

Stress in predator populations, and therefore the potential for fishery impacts, can accumulate over multiple years, even in populations that are well buffered against short-term environmental fluctuations. Therefore, reference points based on time-integrated representations of leading indicator variables (e.g., the number of recent years of low reproductive success, Hill, Forcada, Trathan, & Waluda, 2010) may be appropriate.

Relative reference points may help to avoid penalising fishers when climate change negatively impacts predator populations. These reference points can downgrade objectives over time. Thus, rather than identifying safe ecological limits per se, they identify conditions that are deemed tolerable given the prevailing environmental conditions.

The decision to take action to protect predators involves various risks including the risk of triggering unnecessary action, the risk of failing to trigger necessary action and the risk that necessary action is too late to be effective (Hill et al., 2010). The process of identifying indicators and defining reference points should include an evaluation of these risks (Hill et al., 2010; Legg & Nagy, 2006; Reid, Croxall, & Murphy, 2007). The appropriate management response will depend on the balance of stakeholder objectives. For example, prioritising food security might mean accepting a greater risk of impact.

Although predator data are available in each of our case-studies, such data are not necessarily available for all fisheries, and the quality of ecological monitoring programmes is notoriously variable (Legg & Nagy, 2006). Qualitative indicators have been used to identify environmental conditions that are likely to be stressful for marine species (Peterson et al., 2014) and to summarize the overall state of marine ecosystems (Zador, Holsman, Aydin, & Gaichas, 2017). These have influenced fisheries management decisions but have not been used tactically due to a lack of reference points (Zador et al., 2017). The development of reference points for suites of qualitative indicators would allow tactical decision-making where appropriate predator monitoring data are not available.

Many things can change over time, including environmental conditions, the amount of information available to evaluate the management approach, and the balance of stakeholder objectives. For example, reducing fishing pressure is one of the few options available to mitigate climate change impacts on predators (Klein, Hill, Hinke, Phillips, & Watters, 2018), which could lead to favouring of conservation objectives over use. Thus, periodic evaluation and possible revision of reference points is essential.

Our recommendations are that fisheries managers should adopt predator reference points based on time-integrated representations of leading indicators where possible. They should use these reference points to trigger precautionary action to avoid compounding stress on predator populations. Precautionary action cannot guarantee that predator variables will remain within the bounds defined by predator reference points because fishing might not be the main or only cause of stress. Consequently, there is a mutual benefit to conservation-focused stakeholders and fisheries managers in recognising that breaches of reference points do not automatically represent failures in fishery management. Public discourse between conservation-focused and use-focused stakeholders can progress from adversarial to cooperative (Dunn, 2005). Using such discourse to identify shared objectives, indicated by reference points, provides a tangible basis for both directing and evaluating future management.

The adoption of predator reference points in fisheries management will not resolve the uncertainties highlighted above, but it will remove an important barrier to progress in ecosystem-based management. This will start a process that should lead to better understanding and management of these uncertainties, especially if the process includes a decision-making framework specifically designed to reduce uncertainty as ecosystem monitoring information accrues over time. Adaptive management provides this framework (Walters, 1986) and is a preferred strategy for achieving ecosystem-based management, especially when information is scarce (Hall & Mainprize, 2004; Pitcher et al., 2009).

5 | CONCLUSIONS

Active management of fishery impacts, which nonetheless allows sustainable use, requires the resources to gather and respond to information from those parts of the ecosystem which may be affected, including birds and mammals. Our study highlights important gaps in these resources and supports previous concerns about inadequate progress towards Aichi Target 6 (Hill et al., 2015; Skern-Mauritzen et al., 2016; Tittensor et al., 2014). The critical gap, a lack of predator reference points, is surmountable, and national responses to Aichi Target 6 and the CCRF are an opportunity to establish these reference points and to ensure that they are recognized as fishery management objectives. Clarity about objectives will make it feasible to adjust precautionary measures in response to information about predators. This tactical approach would allow precaution while reducing the risks to sustainable use. It will also pave the way towards truly adaptive management strategies which reduce uncertainty about how ecosystems respond to fishing and provide a better balance between conservation and use.

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DATA AVAILABILITY STATEMENT

The data analysed in this study consists of the text provided in the Appendix S1 and data on MSC and IUCN Red List status from the referenced websites. Appendix S1 is referenced to the relevant literature. All of this information is freely available.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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