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ICES meets marine historical ecology: placing the history of fish and fisheries in current policy context

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As a discipline, marine historical ecology (MHE) has contributed significantly to our understanding of the past state of the marine environment when levels of human impact were often very different from those today. What is less widely known is that insights from MHE have made headway into being applied within the context of present-day and long-term management and policy. This study draws attention to the applied value of MHE. We demonstrate that a broad knowledge base exists with potential for management application and advice, including the development of baselines and reference levels. Using a number of case studies from around the world, we showcase the value of historical ecology in understanding change and emphasize how it either has already informed management or has the potential to do so soon. We discuss these case studies in a context of the science – policy interface around six themes that are frequently targeted by current marine and maritime policies: climate change, biodiversity conservation, ecosystem structure, habitat integrity, food security, and human governance. We encourage science – policy bodies to actively engage with contributions from MHE, as well-informed policy decisions need to be framed within the context of historical reference points and past resource or ecosystem changes.

Keywords: history, management, marine conservation, marine historical ecology, science – policy interface, shifting baseline, sustainable exploitation.

Introduction

The last two decades have seen the emergence of marine historical ecology (MHE), defined as a distinct discipline within the marine sciences that brings a systematic, long-term perspective to the study of interactions between human society and the seas and oceans (Jackson *et al.*, 2001; Holm *et al.*, 2010; McClenachan *et al.*, 2012; Thurstan, 2013; Schwerdtner Máñez *et al.*, 2014). To an extent inspired by Pauly's (1995) seminal study on the "shifting baselines syndrome", and later the Jackson *et al.* (2001) study on historical changes in marine populations and ecosystems, the field has developed through the collaborative efforts of researchers across disciplines (Figure 1). Although MHE could build on a body of earlier work on long-term changes in marine ecosystems, particularly on exploited fish stocks (e.g. Beverton and Holt, 1957; Cushing, 1980; Pope and Macer, 1996), the field has especially developed through the integration of fisheries science, ecology, history, archaeology, sociology, and economics (Lotze and Milewski, 2002; Holm *et al.*, 2010; Lotze and McClenachan, 2013). As a result, knowledge of the past state of marine animal populations and environments has increased substantially (e.g. Lotze *et al.*, 2006; Bolster, 2008; McClenachan, 2009a; Jackson *et al.*, 2011; Cardinale *et al.*, 2015). This information is crucial to providing baselines for defining sustainable levels of exploitation of marine living resources, understanding the functioning and natural variability of marine environments (Jackson *et al.*, 2001), and planning for resilient human communities that depend on these resources (Lotze *et al.*, 2006; Foley, 2011; FAO, 2014).

Our increased knowledge base on the past marine environment and past stock sizes is widely recognized in mainstream scientific journals (e.g. Jackson *et al.*, 2001; Rosenberg *et al.*, 2005; Eero *et al.*, 2011; Cardinale *et al.*, 2015) and popular books (e.g. Kurlansky, 1997; Butcher, 2004; Roberts, 2007; Bolster, 2008). This is also reflected in applied scientific books (Jackson *et al.*, 2011; Kittinger *et al.*, 2015) and university textbooks (Lotze and McClenachan, 2013; Schwerdtner Máñez and Poulsen, 2016). MHE has contributed to marine science through raised awareness of, often, significant resource depletions and habitat degradation related to human pressures. Such results highlight the global nature of the shifting baseline phenomenon (Pinnegar and Engelhard, 2008). Despite this worldwide reach, MHE has often been conducted in relative isolation from contemporary ecological studies. Some authors argue that due to the large scale of changes within marine ecosystems, current conservation objectives should not necessarily be underpinned by historical baselines (e.g. Hobday, 2011), and that we should not necessarily expect recovering populations to achieve historical levels. However, the rapidly growing field of restoration ecology counters this view, as do the growing calls among policy-makers for greater knowledge of past states to set more appropriate baselines for sustainable management (Piha and Zampoukas, 2011; ICES, 2014a). For the future of fishing communities, information of the past is deemed to be of critical importance. Science Europe (2013) singled out MHE as one of "12 compelling cases for policy makers" of the relevance of research.

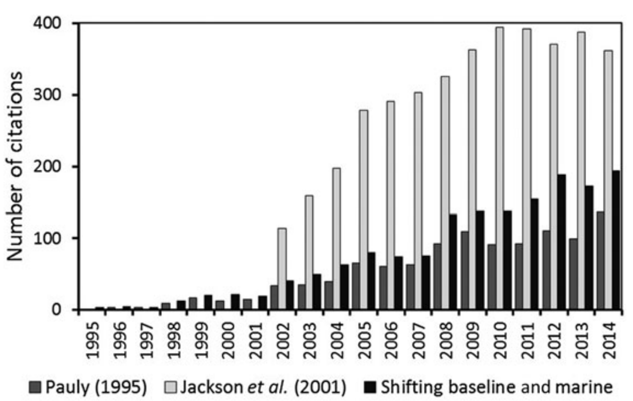

Figure 1. Rise of MHE in the past 20 years, illustrated through citations over time of two key studies: Pauly's (1995) introduction of the "shifting baselines" concept, and Jackson *et al.*'s (2001) synthesis on historical overfishing and the recent collapse of coastal ecosystems, which draws together evidence from a range of disciplines. Also, citations to studies citing both terms "shifting baselines" and "marine". From Google Scholar (extracted 14 May 2015).

In this study, we argue that, in addition to its contribution to scientific knowledge, MHE has the potential to contribute positively to current and future marine policy and management in a tangible, operational way. In several cases, MHE has already made such a difference (Kittinger *et al.*, 2011; Jennings *et al.*, 2014). To demonstrate the value of MHE to marine policy and management, we outline a number of case studies across four continents—North America, Europe, Africa, and Australia—and cover latitudes from the polar oceans to the tropics, including developed countries with highly managed fisheries and countries lacking in fisheries regulation. For each of the case studies, we outline the ecological problem, show how MHE has contributed knowledge or baselines of past change, and illustrate how it has informed management or has the potential to do so in future.

We discuss each case study within a science–policy framework that involves six themes systematically addressed by marine and maritime policies in many countries. They are also closely aligned with the ecosystem-based approach to fisheries management (Pikitch *et al.*, 2004; Laugen *et al.*, 2014). These themes are: (1) climate change and climate-change adaptation; (2) biodiversity and biodiversity loss; (3) ecosystem structure and function; (4) habitat and seabed integrity; (5) food security including human consumption patterns and exploitation; and (6) human dimensions and governance.

Policy context and themes

Globally, marine and maritime policies are being developed in different domains and along different lines of action. In general, these policies aim at managing, planning, and developing multiple uses of the marine environment—e.g. fisheries, shipping, tourism, mining, energy production, and conservation—in ways that address the multiple needs and desires of societies and take into account sustainability for both current and future generations (Jennings *et al.*, 2014).

In Europe, the *Integrated Maritime Policy* (IMP, 2007/575/EU; EC, 2007) is a cornerstone of these policies and is based on the principles of ecosystem-based management (see Box 1 for further details about maritime policies developed by the European Commission). In Australia, the *National Strategy for Ecologically Sustainable Development* (ESD) also follows an ecosystem-based approach to fisheries (Fletcher *et al.*, 2002). *Canada's Oceans Strategy: Our Oceans, Our Future* is a policy framework for *Integrated Management* (IM) of estuarine, coastal, and marine environments (Fisheries and Oceans Canada, 2002). In the United States, the *Interagency Ocean Policy Task Force*, established by President Obama in 2009, named ecosystem-based management a top priority for its *National Ocean Policy Implementation Plan* (Interagency Ocean Policy Task

Force, 2010), and the *Magnuson–Stevens Act* provides authority for its implementation through setting goals in regional and state management (US Department of Commerce, 2007). In South Africa, the *Marine Living Resources Act* (*MLRA*) has governed fisheries since 1998, providing "for the conservation of the marine ecosystem and long-term sustainable utilisation of marine living resources". Recently, however, preparation of an additional act is under way, with the publication of a *White Paper on National Environmental Management of the Oceans* (*NEMO*; DEA, 2014). This white paper includes an ocean governance guiding principle that reads "sustainable use and management of ocean resources and ecosystem services in order to benefit present and future generations" and lists as a strategic priority, the intention to advance sustainable ecosystem-based management in waters under South African jurisdiction. These recent policy developments in countries worldwide require consideration of multiple themes beyond traditional sectoral and single-species management.

Box 1. Description of marine and maritime policies developed by the European Commission (EC). Elsewhere, policies have been or are being developed, often along similar lines.

The EC's cornerstone marine strategy is the *Integrated Maritime Policy* [IMP, COM (2007) 575: EC, 2007], as it integrates a number of transversal policy instruments: in the fields of Blue Growth [COM (2012) 494: EC, 2012] and Blue Innovation [COM (2014) 254: EC, 2014], Marine Knowledge [COM (2010) 461: EC, 2010a], Marine and Maritime Research [COM (2008) 534: EC, 2008b], Maritime Spatial Planning [COM (2013) 133: EC, 2013a], Integrated Maritime Surveillance [COM (2009) 538: EC, 2009a], and Sea Region Strategies in EU waters (Baltic Sea: Helsinki Convention; Mediterranean Sea: Barcelona Convention; Black Sea: Bucharest Convention; Northeast Atlantic: OSPAR Convention). The EU *Marine Strategy Framework Directive* [MSFD, COM (2008) 56: EC, 2008a] addresses the environmental aspects of the IMP, and provides a common framework and goals for EU member states to achieve GES (also abbreviated as GEnS) in national marine waters by 2020. In this framework, GES represents the status where human pressures are considered sustainable since they do not irreversibly hamper biodiversity and the recoverability potential for ecosystem components (Borja *et al*., 2012). GES needs to be assessed according to a set of indicators and criteria established under the Commission Decision [COM (2010) 477: EC, 2010b] for a range of descriptors including, among others, "Commercial fish and shellfish" (Descriptor 3), "Biodiversity" (Descriptor 1), and "Seabed integrity" (Descriptor 6).

Marine Knowledge 2020 [COM (2010) 461: EC, 2010a] is an essential component within the IMP as it focuses on centralizing marine data from different sources with the aim to reduce operational costs, provide wider access to quality-checked data, and reduce uncertainty in knowledge of the oceans and the seas as a sound basis for managing future changes. A number of policy instruments also require indicators, targets, time-series, and historical trends to underpin implementation, e.g. the *Common Fisheries Policy* [CFP, *Regulation* COM (2013) 1380: EC, 2013b], the *Water Framework Directive* [WFD, COM (2000) 60: EC, 2000], the *Habitats Directive* [COM (1992) 43: EEC, 1992], and the *Birds Directive* [COM (2009) 147: EC, 2009b] in marine areas and coastal zones.

The section below provides brief descriptions of the six policy themes we use here to describe the application of our marine historical case studies in supporting and informing management. Note that each of these themes has worldwide relevance, although some may feature more prominently in some parts of the world than in others. Because fisheries management is a relevant topic common to all cases, it is not explicitly included as a policy theme. However, aspects of fisheries resource management that explicitly address one or more of the topics below are highlighted.

(1) *Climate change*. Global temperatures are rising, glaciers are melting, rainfall patterns are shifting, extreme weather events are becoming more common, and there is concern that ocean acidification will increasingly affect marine life. These trends are likely to continue and potentially worsen (IPCC, 2014). Marine research needs to focus beyond the impacts of climate change on commercially valuable stocks to include the broader consequences for marine ecosystem structure and functioning. Policies are also increasingly addressing climate-change adaptation and planning for resilient human communities.

(2) *Biodiversity conservation*. Worldwide, biodiversity loss is happening at an unprecedented rate, on land as well as in the marine environment (Dirzo and Raven, 2003; McCauley *et al*., 2015). In the past 10 years, both policies addressing biodiversity loss and indicators assessing progress towards sustaining diversity have been developed. In 1992, the United Nation's Convention on Biological Diversity (CBD) marked the international community's commitment to addressing biodiversity loss. In response, regional-scale and national policies have been put in place in line with the CBD Strategic Action Plan 2011–2020 and the Aichi Biodiversity Targets (CBD, 2011).

(3) *Ecosystem structure and function*. Researchers and decision-makers are progressively recognizing the need to consider ecosystem structure and functioning, beyond the focus on targeted species, to achieve sustainability of marine resource use. Marine foodwebs play a key role in regulating ecosystem services beyond fisheries, as trophic interactions control energy flow between ecosystem components and contribute to the diversity and structure of marine ecosystems and their responses to change (Worm *et al*., 2006). Knowledge and effective governance of ecosystem structure and functioning are essential to maintain societal services for future generations (Pikitch *et al*., 2004; EC, 2008a).

(4) *Habitat and seabed integrity*. Marine habitats are affected by many anthropogenic pressures. A range of human activities including seabed mining, trawl fisheries, offshore energy platforms, moorings, and dredging for shipping has caused damage to the seabed over large areas (Benn *et al*., 2010). Nearshore habitats, as nursery and spawning areas often critical for the self-renewal of marine populations, are impacted by land-based sediments and pollutants flowing from rivers and by coastal development. Knowledge of the levels and effects of these impacts is needed to preserve critical seabed structures and healthy habitats for many forms of marine life at multiple life history stages.

(5) *Food security including human consumption patterns and exploitation*. With a global population projected to reach 9

billion by 2050, consequent human needs will necessitate a doubling of food production and drastic reductions in losses of food and waste, in addition to sustainable management of our natural resources (Foley, 2011; FAO, 2014). These food security demands are a strong incentive for effective policies aimed at sustainable aquaculture and fisheries, while maintaining biodiversity and the provision of other ecosystem services.

(6) *Human dimensions and governance*. For a substantial part of the global population, livelihoods are partly or wholly dependent on the marine environment, and fish and shellfish are a crucial source of protein (FAO, 2014). In turn, human impacts are likely some of the most important acting on marine ecosystems. Consequently, inclusion of human dimensions and governance is an essential "pillar" within ecosystem-based marine management. The importance of "bottom–up" governance to complement the traditional "top–down" policies is being increasingly recognized (Levin *et al*., 2009). Along with the reliance of people on marine ecosystems, this means that effective governance involves the "empowerment" of people through knowledge exchange, i.e. effective ways of sharing knowledge to enhance environmental awareness and sustainable policies (Fazey *et al*., 2012, 2014; e.g. *Marine Knowledge 2020* in EU context, see Box 1), and increased awareness, known as "ocean literacy".

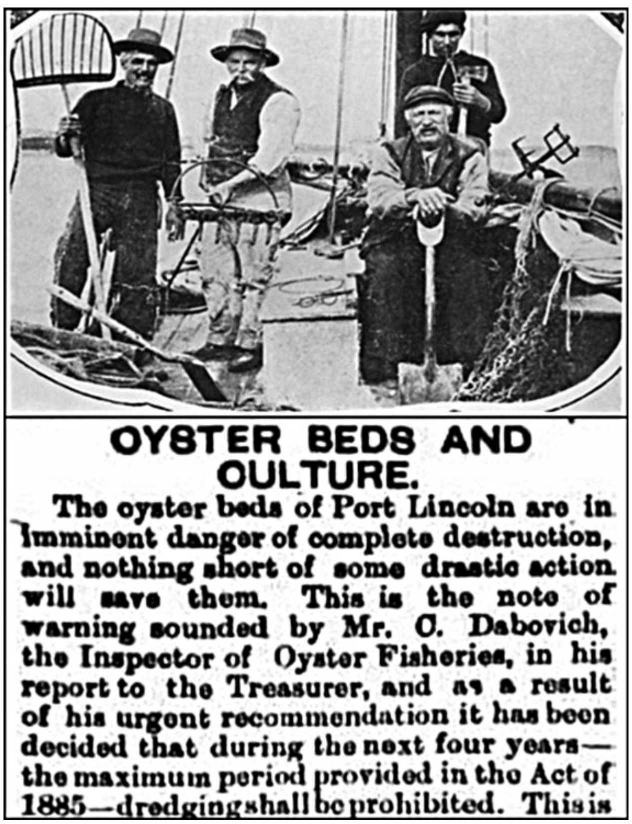
OYSTER BEDS AND CULTURE.
The oyster beds of Port Lincoln are in imminent danger of complete destruction, and nothing short of some drastic action will save them. This is the note of warning sounded by Mr. C. Dabovich, the Inspector of Oyster Fisheries, in his report to the Treasurer, and as a result of his urgent recommendation it has been decided that during the next four years—the maximum period provided in the Act of 1885—dredging shall be prohibited. This is

Figure 2. South Australian oyster fishers with their gear (top; State Library of SA, B54098) and a snippet from a late 19th century newspaper article airing concerns about the overexploitation of oyster reefs (*Adelaide Observer,* 14 January 1899).

MHE case studies demonstrating applied value in policy context

To illustrate the applied value of MHE, we have made use of a selection of case studies in the context of the ICES Working Group on the History of Fish and Fisheries [ICES WGHIST: see, for example, ICES (2011, 2013)]. The cases are representative of the global approach taken in WGHIST, although the preponderance of examples from the Northeast Atlantic reflects ICES' strong tradition of work here. In total, 13 case studies were examined, and these are outlined in Table 1; six of these are described below, and the remaining seven are described in Supplementary Material. For each case study, we highlight the ecological problem, show how MHE contributed, and the policy relevance. Where applicable, we point to references to similar case studies elsewhere (Table 1).

Case 1: Australia—Recovering *Ostrea angasi* oyster reefs lost from coastal ecosystems and society's memory

The problem

Oyster reefs sustain important marine ecosystems and economies, but widespread overexploitation has occurred worldwide contributing to changes in ecosystem function, including the loss of water filtering capacity, complex hard substratum, and reef-associated species. In southern Australia, native *O. angasi* reefs have become functionally extinct (Beck *et al*., 2011), but little attention has been given to this loss in relation to declines in water quality and productivity. Considerable investment is now made in the treatment of poor quality coastal water along these same coastlines, a problem which may have been compounded by the decline of oyster reefs.

Contribution of MHE

Historical records were used to evaluate the past presence, distribution, and abundance of oyster reefs formed by *O. angasi* in South Australia and their loss due to overexploitation (Alleway and Connell, 2015). Using diaries and correspondence of fisheries inspectors, government reports, legislation, photographs, and maps, a profile of their status during the 1800s and 1900s was created, and a "collective amnesia" regarding their past ecological and economic value identified. Commercial oyster fishing began in the early days of the colony (ca. 1836), and continued for more than a century (Figure 2). Since this time, the interim 180 years and a previous lack of data have contributed to the loss of an important ecological baseline. This resulted in a disparity between the amount of attention historically paid to this habitat and what it is afforded today. Research regained this baseline and clarified the current lack of awareness.

Policy relevance

Recovering the historical ecological baseline provided the impetus to begin affecting the actual recovery of oyster reefs (*Theme 2 Biodiversity*; *Theme 4 Habitat and seabed integrity*). Stakeholders, led by the University of Adelaide and South Australian Government, are collaboratively implementing a holistic restoration programme from policy changes through physical restoration (*Theme 6 Human dimensions and governance*). This "living reefs programme" works to improve the lost ecological values of water filtration and habitat complexity by rebuilding oyster reefs as a habitat significantly impacted by human activity.

Table 1. Overview of 13 MHE case studies from across the globe, with a brief description of the ecological problem, the contribution of MHE, and the policy relevance. For each case study, we indicate to which policy theme(s) it contributes, and references are provided to similar case studies elsewhere. Notation of policy themes: 1—climate change; 2—biodiversity conservation; 3—ecosystem structure and function; 4—habitat and seabed integrity; 5—food security; 6—human dimensions and governance. See text for further detail on case studies 1–6, and see Supplementary Material for detail on case studies S1–S7.

Case study	Problem	Contribution of historical data	Policy relevance	Policy themes	Similar case studies elsewhere
1. South Australia oysters (*Ostrea angasi*)	Loss of oyster reefs from coastal system	Evaluated distribution and abundance of oyster reefs in the past (Alleway *et al.*, 2014)	Data incorporated into restoration effort *Living Reefs Programme*	2, 4, 6	Zu Ermgassen *et al.* (2012) and Grabowski *et al.* (2012): evaluation of importance lost oyster beds, Chesapeake Bay, United States
2. South Africa linefish	Long-term population declines	Illustrated substantial changes in catch composition and declines in catch rates over time (Penney *et al.*, 1999; Griffiths, 2000)	Historical evidence revealed the magnitude of catch rate declines and supported strong policy intervention	2, 4, 5, 6	Worm *et al.* (2006): haddock collapse, and recovery through marine reserve and fishery closure, Georges Bank
3. North Sea herring (*Clupea harengus*)	Loss of spatial diversity and stock resilience	Extended time-series on key stock parameters to inform changes in spawning components and spatial diversity (Lescrauwaet, 2013)	Data used to set local management targets, enhancing the potential for recovery of spatial resilience	4, 5, 6	Harma *et al.* (2012): changes in herring population structure, Celtic Sea; Hutchinson *et al.* (2003): loss of cod substock, western North Sea
4. North Sea cod (*Gadus morhua*)	Slow recovery from overfishing, and unknown drivers of change	Extended fishing and environmental time-series to provide evidence for drivers of cod biomass dynamics (Engelhard *et al.*, 2014a; ICES, 2014b)	Provides evidence for main drivers of change and information to support management decisions	1, 3, 5	Frank *et al.* (2005, 2011): similar patterns in climate, plankton, herring, and cod dynamics, Scotian Shelf
5. Baltic Sea fisheries	Unknown drivers of change	Extended biomass time-series demonstrating differing drivers of change over time (Eero *et al.*, 2007; Eero, 2012)	Contributes to defining ecological and stock reference points, supported *Baltic Sea Action Plan*	1, 3, 6	Pope and Macer (1996): extended biomass time-series, North Sea gadoids; Toresen and Østvedt (2000): herring, Norwegian Sea
6. Adriatic Sea elasmobranchs	Unknown baseline abundance	Evidenced declines in elasmobranch abundance and diversity (Ferretti *et al.*, 2013; Raicevich and Fortibuoni, 2013; Barausse *et al.*, 2014)	Data supported the setting of management and conservation measures	2, 6	Ellis *et al.* (2005): elasmobranchs, UK waters; Ward-Paige *et al.* (2010): loss of sharks, Caribbean
S1. Queensland snapper (*Pagrus auratus*)	Unknown baseline abundance	Provided catch and effort data (popular media) before official landings records; showed early impact recreational fisheries (Thurstan *et al.*, 2016)	Potential for data to validate and be included in stock assessment models	3, 6	McClenachan (2009a, b): declines in large trophy fish including groupers, Florida
S2. South Australia fisheries	Use of mean trophic level (MTL) index	Linked declines in MTL to establishment of fisheries for low TL species, not overfishing (Alleway *et al.*, 2014)	Reconsideration of MTL from fisheries catches as an indicator of marine ecosystem health	3, 5	Pinnegar *et al.* (2002): Celtic Sea fisheries; Essington *et al.* (2006): showing "fishing through the foodweb" for global fisheries
S3. Bay of Fundy ecosystem	Loss of resilience and ecosystem structure	Revealed system resilience was driven by local dynamics and highlighted importance of forage fish, notably anadromous species (Klein, 2013)	Provides information to support and prioritize management decisions, including conservation anadromous forage fish	3, 5	Wolff (2000): loss of forage fish, southern North Sea; Lotze and Milewski (2002): declines, Bay of Fundy; Ames and Lichter (2013): cod and alewife, Gulf of Maine
S4. Scotland oysters (*Ostrea edulis*)	Loss of oysters from coastal system	Demonstrated fundamental changes in the Firth of Forth benthic ecosystem over the last 200 years (Thurstan *et al.*, 2013)	Potential to inform EU Habitats Directive and Marine Strategy on GES baselines	3, 4, 6	Riesen and Reise (1982), Lotze (2005): benthos, Wadden Sea; Edgar and Samson (2004): shellfish, Tasmania; Lotze (2010): loss of oysters, Chesapeake Bay
S5. Ireland herring (*C. harengus*)	Uncertainty in rebuilding targets	Demonstrated long-term dynamics of the stock and reasons for previous stock collapse (Clarke *et al.*, 2011)	Demonstrated that rebuilding targets and other reference points are appropriate	1, 5	Toresen and Jakobsson (2002): collapse, management response, and rebuilding in herring, Norwegian Sea

Continued

Table 1. *Continued*

Case study	Problem	Contribution of historical data	Policy relevance	Policy themes	Similar case studies elsewhere
S6. Kattegat–Skagerrak fisheries	Unknown stock structure	Showed past stock structure and subpopulation richness, revealed different dynamics local substocks (Cardinale *et al.*, 2009, 2011, 2012)	Results applied to redefinition of management units for plaice, turbot, and pollack by ICES	3, 5	Rosenberg *et al.* (2005): reconstruction of cod stocks on Scotian Shelf; Payne (2010): different dynamics herring substocks
S7. Northeast Atlantic	Evidence of genetic impacts of fishing	Historical data and archived otoliths support evidence of links between fishing and genetic change (fisheries-induced evolution; Diopere, 2014; Laugen *et al.*, 2014; Pinsky and Palumbi, 2014)	Improves understanding and evidence base for management decisions	2, 5, 6	Olsen *et al.* (2004): fisheries-induced evolution in Newfoundland cod; Engelhard and Heino (2004): herring, Norway; Mollet *et al.* (2007): North Sea sole

Case 2: South Africa—Linefish depletion: historical evidence contributes towards drastic management interventions ("state of emergency")

The problem

A comprehensive management framework was introduced in South Africa in 1985 in an attempt to regulate commercial and recreational hook and line fishers (Penney *et al.*, 1989), collectively referred to as the "linefishery". These measures followed the conviction among fishers and fishery scientists that many line-caught fish were overexploited. However, it is likely that the management of linefish at the time suffered from a shifting baseline bias (Griffiths, 2000), and convincing scientific evidence required to drive strong policy interventions was lacking. The regulations introduced did not effectively curb rising effort in both recreational and commercial sectors, and catch rates remained low, decreased further, or collapsed (Winker *et al.*, 2012).

Contribution of MHE

Van der Elst (1989) and Penney *et al.* (1989) were among initial efforts to investigate historical (early 1900s) catch records from South Africa's first research vessel, SS "Pieter Faure" (Figure 3). These records, compared with contemporary data, revealed substantial changes in catch composition and showed how some previously dominant species had almost disappeared from catches during the 20th century. Penney *et al.* (1999) and Griffiths (2000) expanded this work by collating available historical catch and effort records for the KwaZulu-Natal and Cape Provinces, respectively. Set against modern data, these historical records provided quantitative evidence of the drastic extent to which line-caught species (several of them endemic) were depleted.

Policy relevance

Both Penney *et al.* (1999) and Griffiths (2000) emphasized the inadequacy of linefish regulations in slowing or reversing the overexploitation of nearshore, line-caught fish which was threatening biodiversity and eroding valuable fishery resources (*Theme 2 Biodiversity*; *Theme 5 Food security and exploitation*). Both studies advocated a reduction in fishing effort and recommended the use of well-placed protected areas to safeguard healthy populations of resident fish (*Theme 4 Habitat and seabed integrity*). Based on this and other evidence, the Minister of Fisheries declared a state of emergency in the fishery in 2000, leading to a drastic curtailment of commercial linefishing effort (*Theme 6 Human dimensions and governance*). Following this drastic reduction resulting from the inclusion of historical data, recent analyses of catch rates have shown evidence of recovery in many linefish stocks (Winker *et al.*, 2012).

Case 3: Western Europe—North Sea herring: a key area for post-spawning aggregations revealed

The problem

The North Sea herring (*Clupea harengus*) stock consists of four "spawning components", which differ in life history traits and migrate to separate spawning areas at different times of year (Payne, 2010). Of these, Belgian fisheries traditionally targeted the "Downs component" after spawning on the Flemish Banks in the southern North Sea between November and March (Gilson, 1931; Gilis, 1962; Figure 4). These "autumn herring" fisheries disappeared when Downs herring collapsed in the 1950s, preceding the North Sea-wide collapse of the 1970s (Cushing, 1992). Later, North Sea herring recovered, but the Downs component recovered far slower than the rest of the stock, by some two decades (Payne, 2010). However, management objectives for conserving Downs herring were based on recent data only and may have missed information on spatial diversity crucial to stock resilience.

Contribution of MHE

Time-series on abundance, age distribution, and mortality of Downs herring post-spawning aggregations were reconstructed along with environmental data from hitherto overlooked sources in national archives (scientific surveys, fisheries statistics, and biological studies; Lescrauwaet, 2013). This extended available time-series on key stock parameters back to the 1930s, including World War II (a period for which few fisheries data exist). The data also demonstrate the historical importance of the Flemish Banks (Sandettie sandbank area) for autumn herring fisheries in a socio-economic context.

Policy relevance

This newly obtained historical information is now actively being used as additional evidence to set local management targets and programmes of measures, such as criteria for establishing marine protected areas and marine spatial planning (Special Area of Conservation "The Flemish Banks"; *Theme 4 Habitat and seabed integrity*). These measures enhance the protection of the Downs herring component and therefore preservation of North Sea

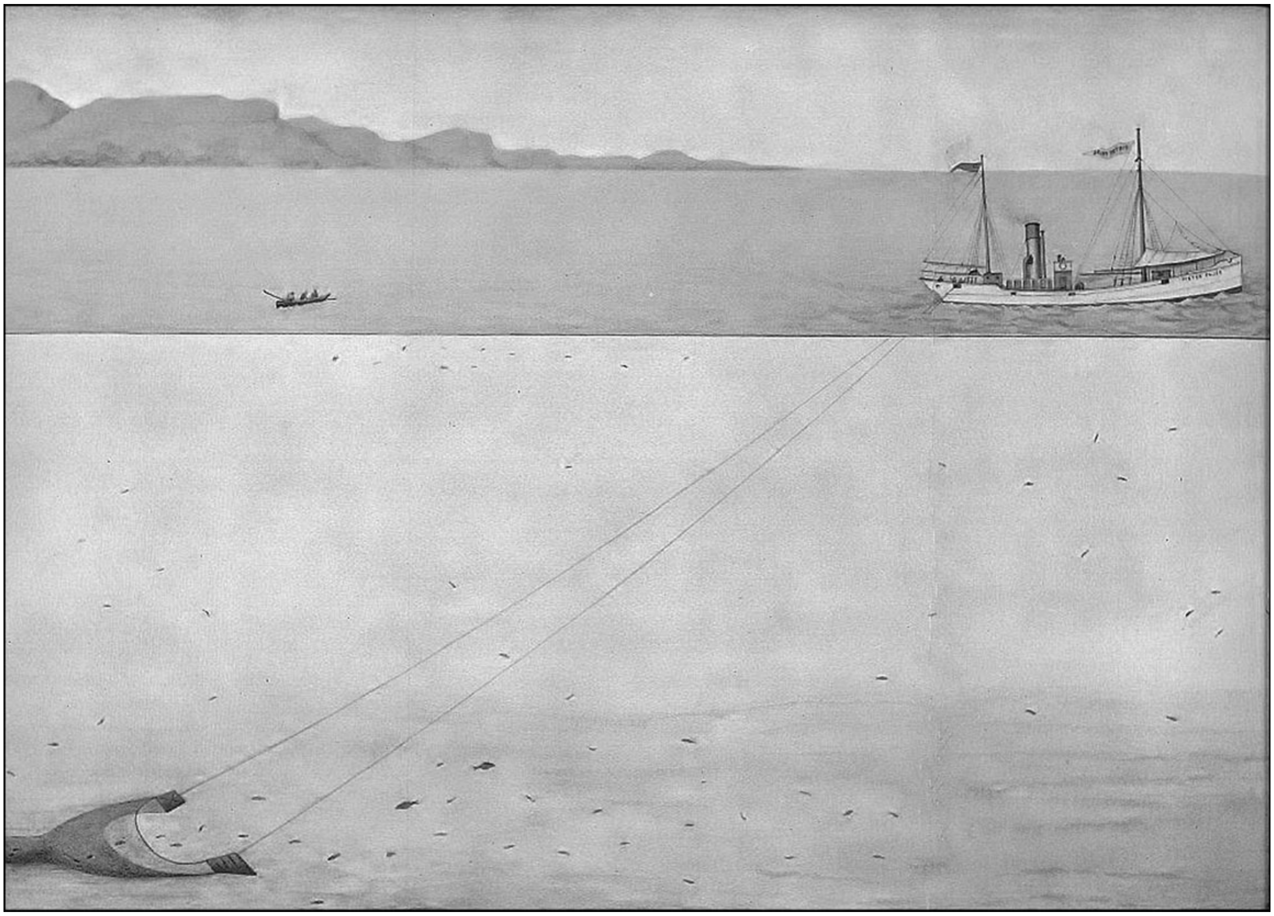

Figure 3. Drawing of SS "Pieter Faure" trawling in Cape waters in 1898. She was the first research vessel (and steam trawler) in the region and conducted trawl surveys in South African waters between 1898 and 1906. Source: Department of Agriculture, Cape of Good Hope Parliament.

herring overall (*Theme 5 Food security and exploitation*). The recovery of the spatial components of North Sea herring requires local measures in key reproductive habitat, which complement management at the stock level (*Theme 6 Human dimensions and governance*).

Case 4: Western Europe—North Sea cod: interactions between fishing, fisheries management, and ecosystem change

The problem

Since 1960, North Sea cod (*Gadus morhua*) has experienced phases of expansion, overfishing, and recovery. Assessments (e.g. ICES, 2014b) show that cod recruitment was prolific during 1963–1986 ("gadoid outburst"), when spawning-stock biomass (SSB), fishing mortality (F), and landings reached a peak. After 1987, recruitment halved, but F remained high, so SSB and landings were depleted. Following warnings about stock collapse (Cook *et al.*, 1997), recovery measures through strict fishery regulations started in 2001, despite socio-political difficulties (Bannister, 2004). F has now reduced to the 1963 level, and SSB is increasing gradually, but since 1998, recruitment has halved again to a historical minimum, resulting in concern whether North Sea cod can recover (Horwood *et al.*, 2006) to former levels of biomass (Figure 5).

Figure 4. Large catch of herring landed at the quayside of Ostend, Belgium during the 1930s (source: Gilson, 1931). In these years, very large quantities of post-spawning herring were taken from the Flemish Banks, just off the Belgian coast; knowledge of the former importance of these grounds was highlighted by Lescrauwaet (2013).

Contribution of MHE

Cod data from 1920 (Pope and Macer, 1996) show that the high level of recruitment in the gadoid outburst was unprecedented (Figure 5).

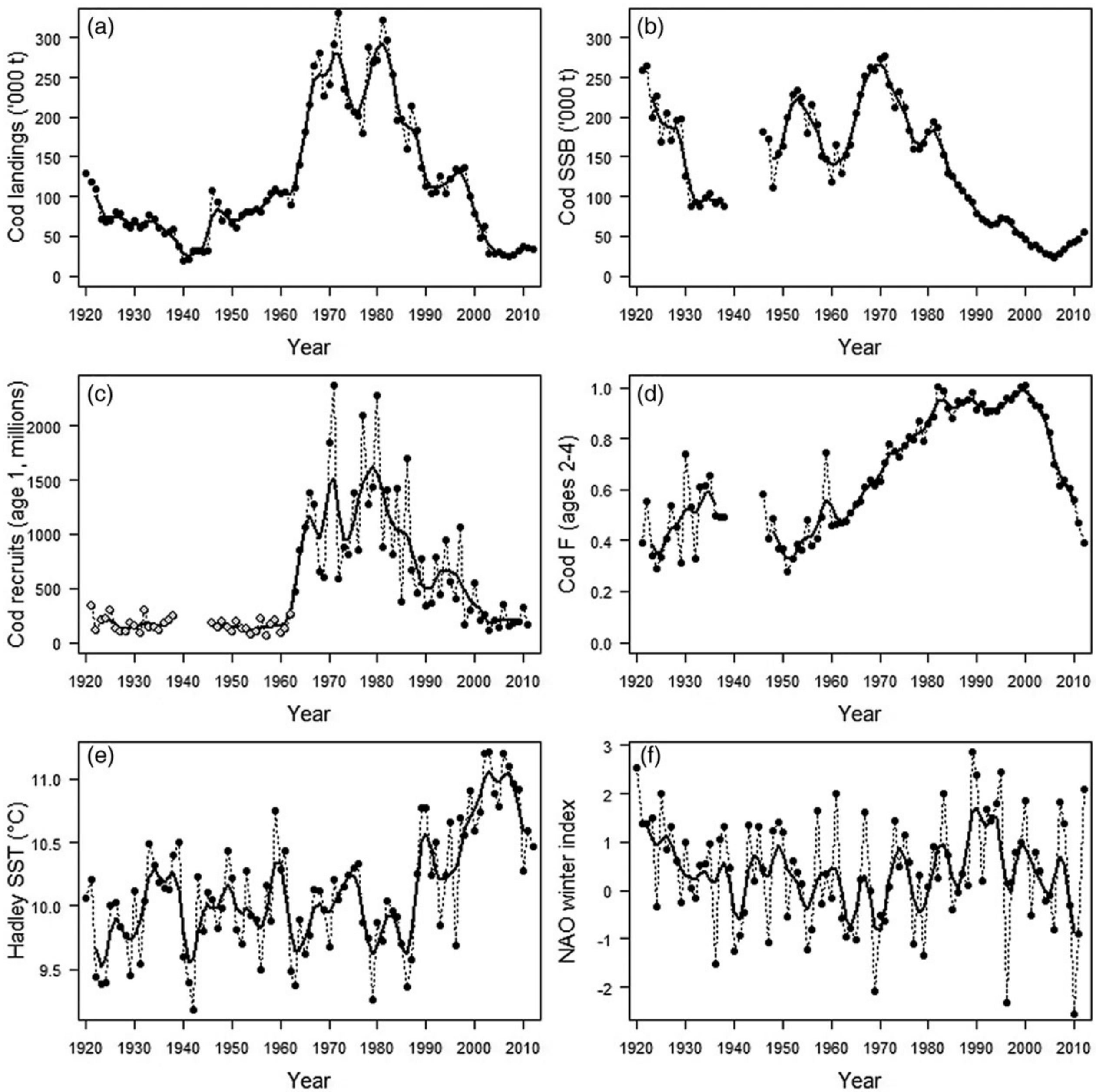

Figure 5. North Sea cod: long-term changes in (a) landings; (b) spawning-stock biomass (SSB, shown at the same scale; (c) recruitment at age 1; and (d) fishing mortality (F; averaged over ages 2–4; no estimates for WWII), compared against (e) the annual mean sea surface temperature (SST) in the North Sea, and (f) the NAO winter index. Redrawn from Engelhard *et al.* (2014a). Stock estimates for 1920–1962 from Pope and Macer (1996); data after 1963, and all landings data from ICES (2014b). Due to technical differences between these studies, recruitment estimates pre- and post-1963 not directly comparable (hence different symbols used); it is, however, well established that recruitment levels during the "gadoid outburst" (1960s to early 1980s) were unprecedentedly high.

It coincided with cold sea temperatures and a negative phase of the North Atlantic Oscillation (NAO; ICES, 2014b), and with a herring collapse (1965–1976). The latter is important because herring prey on gadoid eggs and juveniles, while cod larval diet overlaps that of adult herring (Cushing, 1980). After 1987, reduced cod recruitment coincided with changes in abundance, size, and species composition of calanoid copepods (Beaugrand *et al.*, 2003), as well as with warmer seas (O'Brien *et al.*, 2000) and changes in ecological stability, all linked to positive phases of the NAO (Beaugrand *et al.*, 2008) and the Arctic Oscillation (NOAA, 2015). Recovering herring biomass since 1980 (Payne, 2010) could be an additional factor explaining why cod recruitment is not recovering.

Policy relevance

MHE shows that the expansion, overfishing, and recovery of North Sea cod are influenced by climate-related changes in water temperature and plankton (*Theme 1 Climate change*), and possibly by the collapse and recovery of North Sea herring (*Theme 3 Ecosystem function and structure*). Continuing minimal cod recruitment means that despite the marked fall in harvest rate, cod recovery is likely to be constrained; to ensure sustainable exploitation of this resource, it remains imperative to keep fishing mortality low (*Theme 5 Food security and exploitation*).

Case 5: Northern Europe—The *Baltic Sea Action Plan* supported by extended cod and sprat time-series

The problem

The Baltic Sea ecosystem changed drastically during the 20th century, owing to increased exploitation, eutrophication, reduction of marine mammal abundance (especially seals), and, more recently, climate change (MacKenzie *et al.*, 2002; HELCOM, 2007; Eero *et al.*, 2011). Many of these changes occurred before systematic biomass time-series for key fish species were recorded, notably cod and sprat (*Sprattus sprattus*). Longer time-series on key fish species are needed to resolve impacts of various drivers for fishery and ecosystem management.

Contribution of MHE

Cod and sprat biomass time-series were too short (starting in 1966 and 1974, respectively) to cover the period when the Baltic Sea was less eutrophic, colder, contained higher biomasses of seals (documented predators of cod and sprat; MacKenzie *et al.*, 2011), and experienced more frequent inflows of saline, oxygen-rich water from the North Sea (needed for successful cod reproduction). New, longer stock biomass time-series for both species were constructed from historical fishery reports (Eero *et al.*, 2007; Eero, 2012). Analyses of stock development showed that different forcings (exploitation, seal predation, eutrophication, and climate variability/change) were important during different periods, influencing how multiple foodweb and ecosystem processes affect stock development (Eero *et al.*, 2011; MacKenzie *et al.*, 2011, 2012).

Policy relevance

The studies by Eero *et al.* (2011) and MacKenzie *et al.* (2011, 2012) identified major historical drivers of cod and sprat biomass and carrying capacity in the Baltic Sea (*Theme 1 Climate change; Theme 3 Ecosystem structure and function*). These indicators can contribute directly to providing new estimates of stock reference points such as B_{MSY} (biomass at which maximum sustainable yield is theoretically achieved; Köster *et al.*, 2009). The findings provided ecological background for the development of the *Baltic Sea Action Plan* (HELCOM, 2007) adopted in 2007 as an ambitious multinational programme to restore the good ecological status of the Baltic marine environment by 2021, and regularly updated in ministerial meetings (*Theme 6 Human dimensions and governance*).

Case 6: Southern Europe—New historical baselines on sharks and rays in the Adriatic Sea influence the *Marine Strategy Framework Directive*

The problem

In the Adriatic Sea, fish have been exploited for thousands of years (Lotze *et al.*, 2011). Over the past century, marked changes in marine communities have been documented, with a dramatic decline in large predators (Fortibuoni *et al.*, 2010). Among exploited fish, elasmobranchs (sharks and rays) showed the strongest decline, owing to direct fishing and bycatch (Ferretti *et al.*, 2008, 2013; Fortibuoni *et al.*, 2010; Barausse *et al.*, 2014). This has resulted in biodiversity loss, potentially influencing the entire community and consequently ecosystem functioning (Ferretti *et al.*, 2013).

Contribution of MHE

The combination of multiple historical data sources (naturalists' accounts, documents from archives, libraries, natural history museums, and fish markets; Figure 6) allowed the establishment of more accurate baselines for elasmobranch diversity and abundance in the Adriatic Sea. This is particularly relevant since systematic monitoring surveys only began in the 1980s. According to historical documents, 43 elasmobranch species were previously present in the area (Raicevich and Fortibuoni, 2013). Most of these were common until the 1950s, but declined in the following decades (Figure 6; Ferretti *et al.*, 2013; Barausse *et al.*, 2014) and are currently threatened or even locally extinct (Dulvy *et al.*, 2003). This is the case for common skate (*Dipturus batis*), white skate (*Rostroraja alba*), sandy ray (*Leucoraja circularis*), tope shark (*Galeorhinus galeus*), and angel shark (*Squatina squatina*; Ferretti *et al.*, 2013; Raicevich and Fortibuoni, 2013).

Policy relevance

The reconstruction of historical levels of elasmobranch diversity, as well as improved understanding of the population trends (*Theme 2 Biodiversity loss*), supported the setting of management measures set for their conservation in the Adriatic. Importantly, this included the regulation of minimum landing sizes for all commercial elasmobranch species as an environmental target to be met by 2020 within Italy's implementation of the EU *Marine Strategy Framework Directive* (*Theme 6 Human dimensions and governance*).

Cases S1 – S7: supplementary case studies

Seven additional examples where MHE research contributes to policy are provided by Cases S1–S7 (see Table 1 for an overview, and Supplementary Material for full detail). Taken from Australia, North America, and Europe, these are moreover illustrative of the

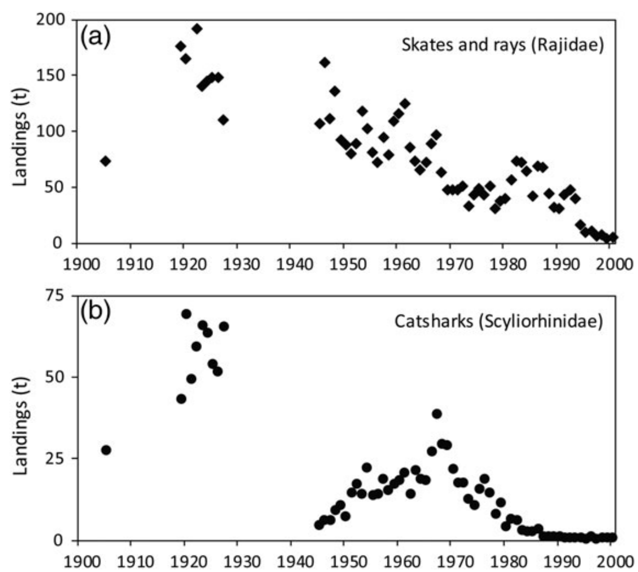

Figure 6. Long-term declines in landings of (a) skates and rays (Rajidae) and (b) catsharks (Scyliorhinidae) at the fish markets of Venice and nearby Chioggia, Italy, between 1900 and 2000 [redrawn from Raicevich and Fortibuoni (2013)]. The declining trends are illustrative of significant population declines of these and several other vulnerable elasmobranch species in the northern Adriatic Sea (Fortibuoni *et al.*, 2010).

Figure 7. Historical sketch, "A Kettle of Fish", by A. Collingridge illustrating Queensland's recreational snapper fishery already popular during the 1880s. Data extracted from short, popular newspaper articles describing this fishery formed an important source of information in the Thurstan *et al.* (2016) study on long-term trends in snapper fisheries. See case study S1 (Supplementary Material). Source: Trove, National Library of Australia.

richness of data sources that MHE has drawn upon, in addition to conventional biological and fisheries datasets. In Australia, for example, 19th century narratives from newspapers and popular magazine articles (Figure 7) were used to provide catch and effort data on Queensland snapper (*Pagrus aurata*), pre-dating official catch statistics by some 70 years (Case S1). In Scotland, maritime charts from the 1850s were used to map historical oyster beds that are long gone, but of relevance in the context of marine spatial planning (Figure 8, Case S4). Other case studies have informed about multidecadal change in the mean trophic level of fisheries catches (Case S2, Australia) and about ecosystem resilience (Case S3, Bay of Fundy, North America), or have pushed stock assessments back in time (Case S5, herring off Ireland; and Case S6, gadoid stocks off Sweden and Denmark). Historical datasets, combined with genetic information taken from decades-old otoliths stored in archives, have supported the evidence base on fisheries-induced evolution, i.e. the selective effects of fishing impacting the genetic composition of fish stocks (Case S7; see Supplementary Material).

Discussion

The case studies presented illustrate the diversity of ways in which MHE can contribute to topics currently high on the global marine policy agenda. Although far from exhaustive, our examples—stemming from four different continents—bring demonstrable evidence of value to specific marine management and policy instruments in the regional or national context. The six themes used for classification represent broad policy areas relevant to science–policy assessment. They were pragmatically chosen as they broadly correspond to clusters of policy domains (environmental, economic, and social) or to key concepts embedded in more recent policy action (ecosystem-based approach, ocean, and/or resource governance). Arguably, there may be a considerable degree of overlap between the themes as applied to the specific cases, and fisheries policies are a common theme throughout all case studies.

Policy themes revisited

Theme 1 Climate change is a priority for at least three case studies (4, 5, and S5; Table 2). Aspects in which MHE contributes to this policy theme include better characterization of species population parameters (recruitment, biomass, and growth) and their ecology (feeding and distribution patterns) under different climate conditions (Table 2). MHE helps to identify past and current cause–effect relationships and to fine-tune predictive modelling power for assessing potential climate-change impact. The long-term time-series of MHE are particularly relevant considering the temporal scale on which climate change operates and was a major feature in the IPCC Fifth Assessment Report [IPCC, 2014; see also Fromentin and Powers (2005); Rijnsdorp *et al.* (2010); Engelhard *et al.* (2011, 2014a); Brander (2015) and Fortibuoni *et al.* (2015)].

At least four case studies (1, 2, 6, and S7) address past conditions in marine biodiversity or even documented cases of extirpation, relevant to *Theme 2 Biodiversity* (Table 2). When these reference conditions are described in relation to varying levels of exploitation in the past, they may contain key information for current management as they help inform levels of sustainable use of resources. As an example, the "Large Fish Indicator", which was developed for the North Sea within the OSPAR Convention and used in several ICES Working Groups, was also adopted as an indicator for the EU MSFD (EC, 2008a; Greenstreet *et al.*, 2010; Engelhard *et al.*, 2015). Its target value of 0.3 at the scale of the North Sea was based on the use of historical trawl survey data, carried out between 1920 and 1982 (Greenstreet *et al.*, 2010).

Often, changes in biological diversity are also relevant to *Theme 3 Ecosystem structure and function* (case studies 4, 5, S1, S2, S3, S4, and S6; Table 2), especially where changes in community composition were documented (Essington *et al.*, 2006; Raicevich and Fortibuoni, 2013). *Theme 4 Habitat and seabed integrity* receives support from MHE studies on oyster beds or reefs or other biogenic habitat (case studies 1 and S4), and their preservation or restoration, or from studies highlighting key habitat for specific life stages of fish (case studies 2 and 3; Table 2). Combined, the three policy themes on biodiversity, ecosystem structure and function, and seabed integrity are instrumental to marine conservation and sustainable management throughout the world today, and explicit support MHE can provide for the ecosystem-based approach in marine policies is evidenced from the case studies presented here [see also Lotze *et al.* (2006), Kittinger *et al.* (2011), and Ferretti *et al.* (2013)]. In the EU MSFD, these policy themes, together with the concept of *maximum sustainable yield* in fisheries, are considered an integral part of achieving good environmental status (GES, GEnS) in EU marine waters by 2020 (EC, 2008a).

Similarly, the adoption of the ecosystem-based approach in fisheries management requires taking these concepts on board and taking a broader historical perspective to patterns of human exploitation of marine living resources in support of *Theme 5 Food security and exploitation* (case studies 2, 3, 4, S2, S3, S5, S6, and S7; Table 2). MHE can help highlighting past stock abundance, placing current management targets in context (e.g. Rosenberg *et al.*, 2005; Clarke *et al.*, 2011). Importantly, analyses of long-term datasets can lead to better understanding of the relative effects of different drivers on stock dynamics, including fishing pressure, climate change, eutrophication, habitat degradation, and predator–prey interactions; time-series of short duration often do not allow disentangling these factors (Rijnsdorp and van Leeuwen, 1996; Beaugrand *et al.*, 2008; Eero *et al.*, 2011; Engelhard *et al.*, 2014a, b; Brander, 2015).

Table 2. Overview of policy themes, ways through which MHE case studies can contribute to each of these, and their potential relevance for policy instruments.

Policy theme	Focus on case studies	MHE contributions	Examples of policy with targets/indicators
Climate change	4 North Sea cod 5 Baltic fisheries S5 Ireland herring	Long time-series, variability in population parameters, and environmental parameters	UN: IPCC EU: MSFD, UK Climate Change Act 2008 United States: National Ocean Policy Implementation Plan
Biodiversity convention	1 Australian oysters 2 South Africa linefish 6 Adriatic elasmobranchs S7 Genetic impacts fishing	Reference conditions, species conservation status	UN: Aichi Biodiversity Targets (CBD) Australia: Marine Biodiversity (Fisheries Management Act) EU: MSFD, Natura 2000 South Africa: NEMO United States: Marine Mammal Act, Endangered Species Act
Ecosystem structure and function	4 North Sea cod 5 Baltic Sea fisheries S1 Queensland snapper S2 South Australia fisheries S3 Bay of Fundy ecosystem S4 Scotland oysters S6 Kattegat–Skagerrak fish	Reference conditions, cause–effect relationships between pressures and ecosystem components	Australia: Fisheries ESD EU: MSFD, Natura 2000 South Africa: NEMO United States: Magnuson–Stevens Act
Habitat and seabed integrity	1 Australian oysters 2 South Africa linefish 3 North Sea herring S4 Scotland oysters	Reference conditions (including spatial extent) under specified pressure levels in the past	EU: MSFD, Natura 2000, Landscape Convention, Underwater Heritage, Trilateral Wadden Sea Government Policy South Africa: NEMO United States: Magnuson–Stevens Act
Food security and exploitation	2 South Africa linefish 3 North Sea herring 4 North Sea cod S2 South Australia fisheries S3 Bay of Fundy ecosystem S5 Ireland herring S6 Kattegat–Skagerrak fish S7 Genetic impacts fishing	Reference conditions, cause–effect relationships between pressures and ecosystem components, patterns of resource use	Australia: Fisheries ESD EU: CFP South Africa: MLRA, NEMO United States: Magnuson–Stevens Act
Human dimensions and governance	1 Australia oysters 2 South Africa linefish 3 North Sea herring 5 Baltic Sea fisheries 6 Adriatic elasmobranchs S1 Queensland snapper S4 Scotland oysters S7 Genetic impacts fishing	Management plans, management structures, best practices for sustainable and resilient communities	EU: Aarhus Convention, Europe 2020 Strategy, Marine Knowledge, Land and Waterscape Conventions South Africa: MLRA, NEMO United States: Magnuson–Stevens Act

Contributing to *Theme 6 Human dimensions and governance*, eight MHE cases reported here (1, 2, 3, 5, 6, S1, S4, and S7; Table 2) reveal the past importance of resources, techniques, exploitation patterns, and food sources that otherwise are threatened to be lost to humanity, or—if well managed—may open new opportunities for coastal communities in the future. A practical field of application includes the Heritage conventions or policies in coastal and waterscape management (e.g. the Trilateral Wadden Sea Government policy: TWSC, 2010). Examples of best practice in MHE case studies include the sharing of data and information in open environments and outreach in formats that are relevant to different branches of the community (Clodia database, Adriatic Sea: Mazzoldi *et al*., 2014; HiFiData, North Sea: Lescrauwaet *et al*., 2010).

Although EU policies and case studies from European waters are well represented here, they are demonstrative of similar policy evolutions in other regions around the world (see the section "Policy context and themes"). Most policy targets aim for a state where human pressures can be considered sustainable if they do not irreversibly damage biodiversity and the potential for recovery of ecosystem components (Borja *et al*., 2012). The process of reconstructing historical baselines and trends in support of ecosystem-based management therefore refers to ecosystem components as well as to pressures, requiring a multidisciplinary approach (Bolster, 2008). In the EU MSFD, three approaches were suggested for setting baselines in relation to GES: (i) baseline as a state at which the anthropogenic effects are considered to be negligible (i.e. pristine state); (ii) baseline set in the past; and (iii) current baseline (WGGES, 2011). MHE contributes mainly towards informing the first two of these approaches. When contrasted with the current status of environmental parameters, historical data inform the setting of reference points, directions, and targets for management (Borja *et al*., 2012). The contribution of MHE has proved to be particularly influential and enlightening when reconstructed baselines are able to characterize pristine states or states where anthropogenic

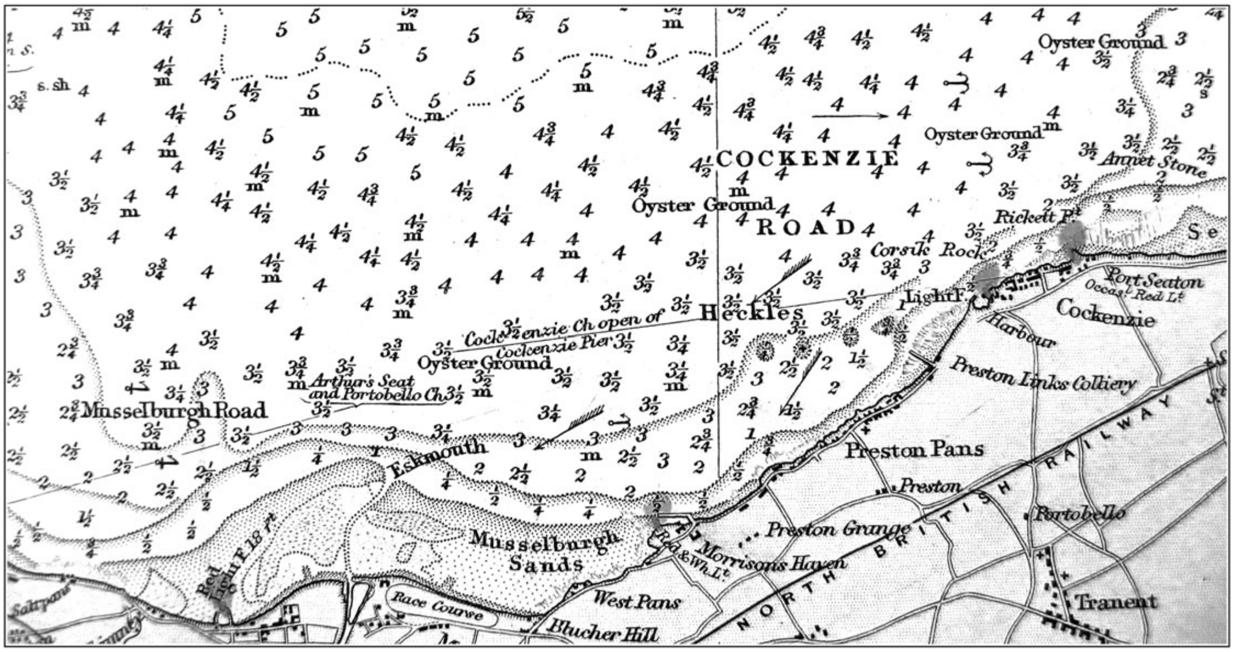

Figure 8. Detail of 19th century map of the Firth of Forth just east of Edinburgh, Scotland. Note at least four references to oyster grounds, all gone now, in this small part of the map. Source: UK Hydrographic Office. See case study S4 (Supplementary Material).

pressures were negligible (Lotze *et al*., 2006; Greenstreet *et al*., 2010; McClenachan *et al*., 2012; Alleway and Connell, 2015). Such studies are critical to avoid the gradual erosion of shifting baselines.

Studies encompassing a long temporal scale and integrating different data sources have frequently revealed the magnitude of resource depletion and overexploitation (Rosenberg *et al*., 2005; MacKenzie *et al*., 2011, 2012; Raicevich and Fortibuoni, 2013). Such findings provide ethical and ecological underpinning to promote further enforcement of conservation measures in, for example, the Adriatic (11) and the North Sea (6, 8).

Another direct contribution of MHE towards conservation relates to the assessments for the IUCN Red List of threatened species (McClenachan *et al*., 2012). Classification schemes of species (near-threatened, vulnerable, critically endangered) follow quantitative criteria that include, for example, declines in abundance over a time-span of up to three generations for species with long life cycles (IUCN Standards and Petitions Subcommittee, 2014). A contribution of MHE to species conservation includes the use of historical data to establish traits of vulnerability of exploited species, allowing policy-makers to prioritize conservation measures in data-poor situations (Dulvy *et al*., 2003; Harnik *et al*., 2012).

Ocean policies need to strike the balance between societal needs and the continued health and productivity of marine ecosystems. MHE can be instrumental in this respect as historical information may help to engage communities and add validity to policy decisions. In at least 10 out of 13 case studies presented here, a clear *governance* aspect was taken into consideration. We see this as indicative of the demand for MHE products as ocean policies increasingly focus on the generation of instruments (such as indicators, targets, monitoring schemes, management plans, etc.) and mechanisms (management committees, steering and advisory groups, and others) by which knowledge and information products can translate into good *governance* (Fazey *et al*., 2012, 2014).

In summary, the MHE case studies presented here provide evidence of the value of a range of data in describing historical baselines and assessing past change. They may have different levels of robustness, depending on the quality and quantity of the available data, the expert judgement used in the interpretation of those data, and the transparency of the approach. Moreover, in practice, historical baselines may be difficult to apply to the determination of targets for sustainable management in the absence of a clear correlation with human impact or initial state (WGGES, 2011). The use of historical data can also be challenging in reconciling issues of scale. Our scientific understanding of marine ecosystems may have very different time-scales compared with those of specific policy or management decision requirements (Perry and Ommer, 2003). An additional obstacle to the application of MHE in decision-making is that gathering historical information can be time-consuming and its interpretation challenging. In some cases, managers may omit historical perspectives or data due to time-constraints.

The ongoing efforts of international bodies (e.g. ICES, EMODNET, and PICES) to develop accessible, quality-controlled, long-term time-series and historical datasets are instrumental in facilitating the uptake of historical baselines and reference conditions. The ICES WGHIST has identified close to 100 datasets with key metadata that have been made available to the wider science and policy community through the ICES dataportal catalogue. Similar initiatives have long been in place with regard to climate datasets (e.g. ICOADS, HADISST, and CLIWOC).

Nevertheless, the adoption of such baselines to set management targets is controversial as it is not always fully understood to what extent a decrease or release of pressure may lead to the full recovery of the targeted ecosystem to previous levels of abundance or ecosystem components and functions (Duarte *et al*., 2015). While several recent studies have shown that there is a high potential for the recovery of some taxa and functions (e.g. Lotze *et al*., 2011), the expectation that recovery is simply the inverse process of deterioration through reversible trajectories proved naïve (Duarte *et al*., 2015). In this context, managers are reluctant to set targets based on past baselines on the assumption of the so-called legacy effects (O'Higgins *et al*., 2014); known effects of human activities in the past are not necessarily instrumental for predicting the impact of future activities. Still, even in the latter context, MHE can give guidance in defining thresholds of pressure that may trigger structural and functional degradation in ecosystems and in setting reference levels, especially in data-poor situations.

Notwithstanding the challenges presented by historical data and baselines, they are essential to understand past changes and the impacts that human activities have had on the marine environment. Many countries have absorbed marine historical research outputs in their environmental policies. This uptake has been particularly effective when the research has been supported by published output and reference conditions were clearly linked to pressures exerted on the variables under investigation.

Implications for management

There is an increasing demand for policies to be more evidence-based. This is particularly true for ocean policies, as awareness regarding the role of oceans in global climate regulation and productivity patterns is growing, and many emerging economic opportunities are ocean-based (European Marine Board, 2013).

This is an opportunity and good timing for the recognition of the added value of MHE. The case studies included here were selected to illustrate the diversity of scale, geographical range, and data products that are relevant to policy development and implementation. We have been far from exhaustive, and there are considerable efforts in many other marine and terrestrial systems globally.

However, the cases demonstrate that MHE has developed beyond proof of concept and regularly provides applied value to science and policy in a variety of ways:

(i) provides data on historical baselines and historical range of variability of biological and environmental parameters (including previous species distributions), broadening the knowledge base on which to build sustainable policies;

(ii) enhances our understanding of the effects of anthropogenic disturbances on marine ecosystems, their structure and functioning, facilitating the development of appropriate policy instruments, targets, and indicators;

(iii) provides excellent case studies that can be used to increase public awareness on the role played by humans in shaping the current status of the seas contributing to the growing of ocean literacy and the direct involvement of citizens in their protection;

(iv) enhances insights into the long-term responses of marine biota to climate change, helping society to assess its impacts and moreover to adapt to future climate change;

(v) supports the development of fisheries based on historical conditions of the marine environment and the recovery of sustainable practices from the past; and

(vi) new algorithms and models are being developed by the MHE community to deal with integrating qualitative and quantitative data, and lessons can be drawn from the innovative approaches used to integrate biological data, environmental data, and data on human uses in support of policy development and assessment.

Recently, MHE has become established as a discipline, with scores of new case studies being published each year. A few are chosen immediately for their explicit policy relevance, but also for their ability to capture the public imagination. Far too often, however, studies stay within the academic domain even if potentially relevant to policy and fail to reach out more widely in the absence of a dedicated translational research practice (Holm *et al.*, 2010; Fazey *et al.*, 2012). The MHE community should be further encouraged to improve knowledge exchange by highlighting their research in view of current policies; essentially, findings will have to be presented clearly, concisely, and in a defendable way (Raymond *et al.*, 2010). For MHE to achieve its full potential, a number of challenges situated in different domains of science, policy, and governance must also be overcome. While researchers should continue to further the accessibility of their work and facilitate communication and integration as much as possible (Bainbridge, 2014), there is an equally important role for fisheries advisers and marine managers worldwide. In balancing the multiple uses of the marine environment and trading off the current use of marine resources with that of future generations, decision-makers must be made aware of the holistic and long-term view that MHE has to offer as crucial support for informed decisions. It is mostly at the *science–policy interface* that targeted efforts will generate the strong and urgent catalyst effect that is required for this transformation. Considerable progress in this respect has been achieved through strategic action (Fazey *et al.*, 2012).

We, therefore, call upon science–policy bodies to actively engage with the contribution of MHE in policy and management from an early phase. In practice, this could be achieved by making explicit reference to and prioritize the uptake of MHE in strategic marine science policy documents as well as in data and information management plans. Furthermore, it could become an integrated component in capacity-building and in education and training programmes for early-career scientists. Continued and increased efforts for further integration of the MHE science community and policy support will benefit sustainable management and conservation of marine resources as well as the communities that depend on these.

Looking forward and recommendations

With the advent of the internet and increases in computing power, it has never been easier to locate and explore scores of historical information and make this available for the benefit of the wider community. Previously invisible and thought lost, datasets are being rediscovered in archives and basements around the world, digitized and analysed using modern computational methods, and deployed for applied and important purposes. Building on these developments and as an increasingly recognized discipline, MHE can make a difference to long-term marine management. Often, there is the clear *potential* for outputs to be included in policy; in a subset of cases, outputs have *already* been incorporated into policy; and in a further subset, MHE has already had a (demonstrable) *impact* on marine conservation or resource recovery (illustrated in Figure 9 for our case studies). We suggest the following:

- In cases where MHE has clear potential to contribute towards improved policy, historical ecologists are encouraged to (i) engage with policy- and decision-makers about the management implications of the historical evidence; (ii) inform the public of their research; and (iii) consider packaging and promoting their key findings to achieve real impact and uptake.

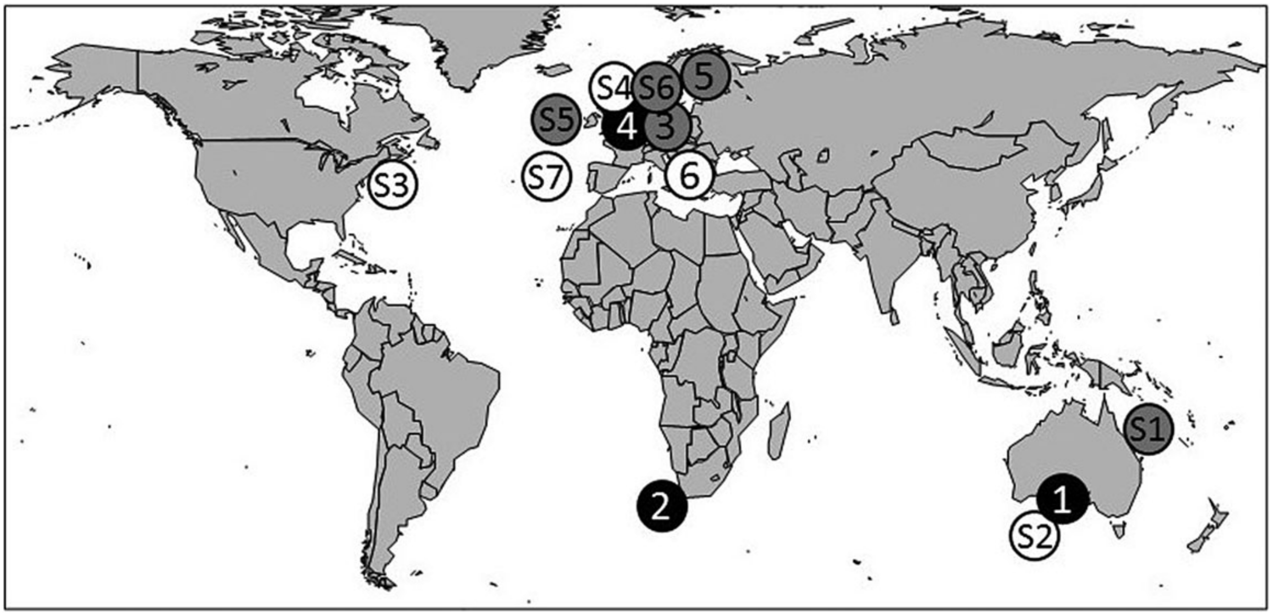

Figure 9. Policy influence of the documented MHE case studies (numbering follows text), distinguishing cases that have potential to be included in policy (*white*), cases that have already been taken on-board policy (grey), and cases that have already had a (demonstrable) impact on marine conservation and/or sustainable exploitation (black). Notice, however, that the distinction between these categories is somewhat arbitrary and scale-dependent. For example, in the Bay of Fundy (Case S3, see Supplementary Material), MHE has demonstrated fundamental importance of anadromous forage fish impacted by hundreds of dams, but no policy change has yet occurred; however, recent removal of two dams has already resulted in localized recovery of anadromous fish (Klein, 2013).

- In cases where MHE outputs have already been incorporated in policy, historical ecologists are encouraged to (i) follow up to assess whether the policy change indeed has desired effects; (ii) use the uptake to guide their future research efforts; and (iii) highlight successful application as evidence of the value of their work.
- In cases where MHE has already had a (demonstrable) impact, historical ecologists are encouraged to (i) highlight this as a demonstration of the value of MHE; (ii) continue monitoring the situation to assess whether desired effects are reached and/or maintained; and (iii) use the lessons learned to guide their research efforts towards similar cases where an effective difference to improved governance of marine resources could be made, while at the same time feeling empowered to maintain some "blue skies" research.

We envisage a future where MHE scientists will increasingly "think policy", so that their work might more readily make a difference, and where policy-makers will increasingly "think MHE" in support of long-term marine conservation and sustainable resource use.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Acknowledgements

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