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Filling historical data gaps to foster solutions in marine conservation

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ABSTRACT

Ecological data sets rarely extend back more than a few decades, limiting our understanding of environmental change and its drivers. Marine historical ecology has played a critical role in filling these data gaps by illuminating the magnitude and rate of ongoing changes in marine ecosystems. Yet despite a growing body of knowledge, historical insights are rarely explicitly incorporated in mainstream conservation and management efforts. Failing to consider historical change can have major implications for conservation, such as the ratcheting down of expectations of ecosystem quality over time, leading to less ambitious targets for recovery or restoration. We discuss several unconventional sources used by historical ecologists to fill data gaps – including menus, newspaper articles, cookbooks, museum collections, artwork, benthic sediment cores – and novel techniques for their analysis. We specify opportunities for the integration of historical data into conservation and management, and highlight the important role that these data can play in filling conservation data gaps and motivating conservation actions. As historical marine ecology research continues to grow as a multidisciplinary enterprise, great opportunities remain to foster direct linkages to conservation and improve the outlook for marine ecosystems.

1. Introduction

Our oceans have undergone extensive changes as a result of human influence, and consequently we are forced to manage marine ecosystems relative to shifted environmental baselines (Dayton, 1998; Jackson et al., 2001; Pauly, 1995; Roberts, 2012). In many regions human interaction with the marine environment originated hundreds, thousands or even tens of thousands of years before record keeping began (Pandolfi et al., 2003; Rick and Erlandson, 2008; Roberts, 2003). Whilst access to the marine environment and our ability to monitor the oceans has been spurred by technological innovations, such as SCUBA and remotely operated video technology, by the time these advances occurred many ecosystems had already been altered by human activities (Thrush and Dayton, 2002; Thurstan et al., 2014). These temporal gaps in our knowledge are significant and create uncertainties about the extent to which humans have influenced changes in marine ecosystems, particularly as our activities have expanded and intensified.

Where long-term data describing ecological change have been limited or absent, researchers have utilised alternative approaches to fill gaps in our understanding of past change. For example, hindcasting estimates are usually extrapolated from existing time series data, together with contemporary production estimates or life-history parameters, and can provide insights such as the theoretical number of individuals a system can support (Jennings and Blanchard, 2004; Marsh et al., 2005). Patterns of genetic variation

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have been used to infer past effective population sizes for some marine species (e.g., Alter et al., 2007), although these can only provide a single past value, rather than information on population trajectories over time. Space for time approaches have also been used to provide insights into past ecosystems (Hawkins and Roberts, 2004; Pickett, 1989). In these cases remote areas are viewed as a virtual 'time machine' and give us glimpses as to how the seas looked before extensive anthropogenic changes. Useful information on past trophic structuring of communities can be gained from the space for time approach (Barott et al., 2010; Sandin and Sala, 2012). However, the use of reference ecosystems overlooks changes that may have happened in any one place or to wide-ranging species, and even 'so-called' pristine reference marine systems will be impacted by global issues such as climate change and ocean acidification. Furthermore, the only available reference systems (i.e., those least impacted by human activities) are usually remote oceanic systems that are dissimilar to continental coasts and shelf systems, and hence are not suitable controls for the locations that have been the most altered by humans (Sandin et al., 2008). Importantly, few of these approaches are detailed enough to provide an understanding of the trajectories and drivers of past change, and often start with the assumption that contemporary and historical ecosystems are comparable (Lotze and Worm, 2009).

In recent years a multidisciplinary enterprise – marine historical ecology – has developed to produce data to fill gaps in our knowledge of the levels of change and long-term dynamics exhibited by marine ecosystems. It can be described as "the study of past human–environmental interactions in coastal and marine ecosystems and the ecological and social outcomes associated with these interactions" (Kittinger et al., 2015). This field of research spans multiple disciplines, including historical, social, ecological, archaeological and palaeontological disciplines, to unravel temporal changes in marine ecosystems ranging from decades to tens of thousands of years (Coll et al., 2014; Erlandson et al., 2008; Lotze et al., 2006; Pandolfi and Jackson, 2006). Historical data sources have a number of unique features that are of value to contemporary conservation and management. Historical data can improve our understanding of past system dynamics, enabling us to determine whether contemporary systems are acting within the historical range of variability exhibited prior to large-scale human impacts (Morgan et al., 1994). Historical data, if detailed enough, may also provide information on the rate and trajectory (i.e., linear, non-linear) of temporal change. Long-term data can also assist in unravelling the mechanisms driving these changes, and whether the major driving forces have altered over time (Pickett, 1989). Such data may also allow us to identify if contemporary communities are 'novel', that is, they have not previously occurred in the historical record.

Under the framework of marine historical ecology, researchers from across the world have amalgamated data on different geographical and oceanic regions, from temperate to tropical climates (Pandolfi et al., 2003; Reise et al., 1989), and benthic to pelagic systems (Baum and Worm, 2009; Edgar and Samson, 2004). Over the last 15 years, several synthetic papers (e.g., Jackson et al., 2001; Pandolfi et al., 2003), popular and academic books (e.g., Jackson et al., 2011; Kittinger et al., 2015; Roberts, 2007) and a global research initiative, the History of Marine Animal Populations (Holm et al., 2010; Schwerdtner Máñez et al., 2014), have initiated a surge of interest in the collation and analysis of historical data on marine ecosystems, aiding our understanding of long-term changes in the oceans and the roles that humans have played in driving these changes. In many cases researchers have found that degradation, or even fundamental alterations of marine ecosystems, have occurred as a result of human activities such as fishing, pollution or the introduction of non-native species (Bax et al., 2003; Bowen and Valiela, 2001; Roberts, 2007). Historical ecology has also been an important component in shaping debate about the changing role of conservation in an increasingly human-dominated world (Kueffer and Kaiser-Bunbury, 2014; The Breakthrough Institute, 2012).

Although there is much potential for historical data to contribute to conservation data gaps, these data are not without their challenges. These include disparate sources or incomplete data, historical data collection methodologies that may be of questionable reliability or where analytical robustness is uncertain, or where data reporting is subject to unknown biases (issues that are not just confined to historical data sets). Yet if these challenges are addressed, the insights afforded by a greater understanding of historical conditions can alter how scientists and the public perceive the condition of our natural environment today, with implications for how conservation goals are set and prioritised (Caro et al., 2012; Kueffer and Kaiser-Bunbury, 2014).

In this paper we discuss the implications of historical data gaps for conservation and management. We demonstrate that even in situations where historical data are limited, information on past trends can be uncovered when alternative, perhaps unconventional, data sources are considered. We highlight innovative approaches or techniques that have provided novel insights into past ecosystem dynamics. We then provide examples of how historical data can be used to help address a range of conservation challenges.

2. Implications of historical data gaps for conservation

Historical data gaps contribute to shifting environmental baselines or cultural amnesia, described as social or institutional losses in memory (Papworth et al., 2009). These shifted baselines can ultimately lower ambitions for conservation if degraded states are accepted as natural (Pauly, 1995). Targets to rebuild or restore ecosystems or communities can only reflect what is known about previous ecosystems and/or species abundance. Thus, a lack of appreciation for how an ecosystem has changed can have major implications for conservation and management.

Historical data have been used to illustrate changes in species abundance, and commonly show that the magnitude of change over long time scales is greater than contemporary data sets suggest. One of the better-known examples of how historical data can readjust our perspective of the productivity of past environments is in the comparison of historical and contemporary cod (*Gadus morhua*) biomass on Canada's Scotian Shelf (Rosenberg et al., 2005). Contemporary analyses of cod biomass showed an increase from 1970 – the beginning of recent records – then a decrease from 1980 onwards. Alone, these data would suggest that targets for the rebuilding of cod stocks be set to the 1980s level, for which indeed, people have argued (Rosenberg et al., 2005). However, historical data on individual vessel catch and effort during the mid-19th century, when combined with population modelling, suggest that total cod biomass during the 1980s – its contemporary peak – was just 4% of the historical levels of cod on the Scotian Shelf alone (Rosenberg et al., 2005). Similar examples where historical data have uncovered past productivity that was much higher than contemporary systems include the Adriatic Sea, where multidisciplinary investigations suggested that 98% of traditional marine resources had been depleted to under half their previous abundance (Lotze et al., 2011). In the Wadden Sea, historical sources showed that many targeted species were severely reduced by the early 20th century (Lotze, 2005), when fishery records began to be kept.

Historical data have also been used to illustrate local extirpation of a species or habitat. An example of how having a complete historical record could lead to different conservation regimes can be found when profound changes to the faunal composition of an area occurred before formal scientific data were collected. The giant clam *Hippopus hippopus* occurs in Kiribati and other islands in the South Pacific region but not in Fiji, and no written records exist to provide evidence of its past presence there. However, the discovery of new archeological evidence suggests that this species once occurred on Fijian reefs, before becoming extinct in Fiji around 750 B.C., in part due to anthropogenic exploitation (Seeto et al., 2012). Knowing that this clam was once part of the fauna of shallow inshore Fijian reefs may help conservation biologists and government officials reassess options for the suitability and development of giant clam farms and clam restoration projects in this region (Sulu et al., 2012).

Long-term studies also indicate that in some locations, high abundances of low trophic level fishery species, such as shrimps, prawns or shellfish, are a historical anomaly, facilitated by the removal of their predators by earlier fisheries and habitat modification by trawls and dredges (Brown and Trebilco, 2014; Parsons et al., 2013). In the Gulf of Maine historical fisheries for finfish such as cod and haddock (*Melanogrammus aeglefinus*) declined as a result of fishing pressure, whilst lobster (*Homarus americanus*) flourished in the absence of predators (Jackson et al., 2001; Steneck et al., 2011). A similar story has occurred in the Firth of Clyde, where historical data show that a variety of finfish species once dominated Clyde fisheries, but that since the 1980s a single species of lobster, *Nephrops norvegicus* has been the mainstay of Clyde fishing communities (Thurstan and Roberts, 2010).

This last example, whilst highlighting the important role that historical data has to play in uncovering past ecosystem change, demonstrates that the setting of contemporary conservation or management targets are as much a social as an ecological decision. Sustaining modern fisheries in the Gulf of Maine and the Firth of Clyde rely on maintaining the present, altered state, while goals that are based on historical knowledge of ecosystem structure and function may call for more active restoration. Thus, even in cases where these simplified ecosystems are less resilient to environmental perturbations than historical communities (Howarth et al., 2014; Schindler et al., 2010; Steneck et al., 2011), rebuilding systems towards an earlier state can be ecologically, socially and economically difficult as stakeholders may prefer the societal and economic benefits brought about by the modern ecosystem. However, in these situations, a historical perspective may still be of use in informing stakeholders and managers of the ecological *potential* for rebuilding depleted fish stocks, thus enabling more informed decisions to be made about the future of these ecosystems. In the case of the Clyde, knowledge of changes in the composition of marine communities as a result of fishing (Heath and Speirs, 2012) has formed the basis of proposals that call for changes in the way in which Clyde fisheries are managed, in particular, to restore past diversity and resilience to inshore fisheries (SIFT, 2015).

3. Using novel data sources to foster solutions to historical data gaps

Monitoring data and government records are not always available to fill gaps in our understanding of past ecosystem change. In these cases researchers have turned to unconventional sources of data to foster solutions to historical data gaps. In Hawaii, for example, evidence suggests that Native Hawaiians fished coral reefs intensively for centuries prior to European contact (Friedlander et al., 2013; Kittinger et al., 2011), but over the last century fundamental changes in fishery composition occurred, including a switch from a reliance on reef fish to reliance on pelagic species (McClenachan and Kittinger, 2012). However, formal quantitative annual commercial fisheries data for Hawaii only exist from the 1940s onwards, creating a large data gap that requires innovative approaches to untangle long-term fisheries trends (Friedlander et al., 2015; Shackeroff et al., 2011). Decorative seafood menus gathered by collectors were used to fill this particular data gap, pinpointing the timing of change in exploitation targets from reef fish to pelagic fish and confirming high reef fish consumption in the early 20th century (Van Houten et al., 2013). Over longer time scales, archaeological findings, fisheries landings data, and per capita consumption estimates were used to reconstruct historical fisheries yield for Hawaii across seven centuries. This reconstruction demonstrates that overall yield was likely maintained over the four centuries prior to the arrival of Europeans, despite high pre-European human population densities (Longenecker et al., 2014; McClenachan and Kittinger, 2012). That fishing levels were maintained under these conditions has been linked to the effective enforcement of a range of management measures, including restricted harvesting of reef species and reef areas and regulation of fishing gear, with implications for management of heavily targeted reef fisheries today (Kittinger et al., 2011).

Likewise in Australia, state landings data for finfish began to be collated after the Second World War, but references prior to this period suggest that substantial levels of fishing occurred many decades prior to the start of official documentation, including the capture of large numbers of fish by recreational fishers (Thurstan et al., in press). Government reports from this period do not provide catch and effort data, but alternative sources of archival data, such as newspapers and popular articles, have been found in some cases to contain detailed information on these developing fisheries. In Queensland, recreational fishing trips for snapper (*Pagrus auratus*) – today an iconic recreational fishery – began being undertaken during the late 19th century, with the catch commonly recorded in local newspapers. Application of statistical approaches to the quantitative data and qualitative narratives from these sources provided insights into catch rates during the early development of the fishery (Thurstan et al., in press).

In the United States, historical menus and cookbooks have been used to demonstrate changes in consumer preferences over time, providing insights into how societal preferences or consumer demand can shape exploitation patterns (Hall and Camhi, 2012; Levin and Dufault, 2010). Art and photographs have also successfully provided insights into historical fish availability, changes in relative abundance or size, as well as changes in cultural phenomena such as trophy fishing (Guidetti and Micheli, 2011; McClenachan, 2009), whilst historical admiralty charts and surveys have been used to estimate changes in the extent and biomass of oyster reefs in estuaries throughout the United States, from ca. 1880 to the present day (Zu Ermgassen et al., 2012). Museum collections are also useful repositories of information on past biodiversity. Ancient shark toothed weapons from Kiribati were analysed to identify the species of sharks used in the production of these weapons. Comparison with contemporary species lists led to the discovery that two species of sharks had been extirpated from these waters before the first formal scientific surveys took place (Drew et al., 2013).

Whilst historical data gaps exist for fisheries and fish assemblages, our lack of knowledge of long-term change in marine habitats is even more acute. Regular monitoring of marine ecosystems, even shallow water systems such as coral reefs, rarely commenced prior to the 1980s. Without such data, it is often difficult to unravel the impact of cumulative stressors from the natural dynamics exhibited by such systems, or to know whether the system we observe today is fundamentally different from its historical counterpart. The application of high-precision dating tools such as Uranium-series thermal ionisation mass spectrometry and multi-collector inductively coupled plasma mass spectrometry to coral reef matrix cores have provided an accurate chronology on the timing of historical mortality events in coral communities of the

Great Barrier Reef, Australia, prior to monitoring activities. The development of these innovative technologies has been critical to driving new discoveries of historical dynamics within the Great Barrier Reef ecosystem, for assessing the impact of industrial development on its inshore reef systems and for informing discussion on recovery goals (Clark et al., 2014; Lybolt et al., 2011). For example, Roff et al. (2013) used these techniques to identify a collapse in *Acropora* assemblages in the central Great Barrier Reef during the middle 20th century. Whilst more recent declines in coral cover have been ascribed to acute disturbance events such as bleaching episodes, cyclones and crown-of-thorns starfish (De'ath et al., 2012), the long-term stability exhibited by these assemblages over centennial time scales and the timing of their decline suggested that the ultimate cause of the collapse was due to prolonged increases in sedimentation and nutrient loading caused by land-use changes after European settlement (Roff et al., 2013).

Whilst our understanding of long-term change is still limited, these examples – while not exhaustive – demonstrate that sources exist to close these data gaps and that unconventional data sources can be used to demonstrate changes in marine ecosystems over time (Fig. 1).

4. Integrating historical data into contemporary conservation and management

The emergence of marine historical ecology as an interdisciplinary field of research and the continuing discovery and engagement of historical data reveals the value of these approaches to meet current conservation challenges (Kittinger et al., 2015). In this section, we provide specific examples to show that integration of historical data to address real-world management issues can be achieved.

4.1. Setting baselines for restoration

The first, and most obvious example of the use of historical data is in the setting of restoration goals. In the Chesapeake Bay, data on the location and extent of historical oyster (*Crassostrea virginica*) beds, sourced from late 19th and early 20th century surveys have been used to inform restoration targets (U.S. Army Corps of Engineers, 2012). Whilst it is acknowledged that the historical baseline upon which restoration goals are based does not constitute pristine conditions, they have provided a benchmark against which restoration progress can be assessed (U.S. Army Corps of Engineers, 2012). Oysters were once a valuable species in the Chesapeake, but centuries of habitat degradation and overharvesting resulted in their reduction to <1% of former abundance (Wilberg et al., 2011). Despite the decline their cultural value remained, which has been important in mobilising community support for large-scale restoration efforts (U.S. Army Corps of Engineers, 2012). Similarly, in Maine, restoration of habitat connectivity for anadromous fish has resulted in the resurrection of historical alewife (*Alosa pseudoharengus*) fisheries, which have been inactive for 200 years in some locations. These fisheries provide economic and social benefit to communities, motivating community interest in restoration and creating positive feedbacks between ecological restoration, community engagement and local pride (McClenachan et al., in review). The maintenance of cultural value is important, as in other countries not only have once-extensive oyster beds been lost, but the cultural and ecosystem values associated with these have also disappeared from collective memory (Alleway and Connell, 2015; Thurstan et al., 2013). This loss of awareness of the past presence of these species, together with fundamental changes in the benthos, make future restoration efforts less likely.

Fig. 1. Examples of unconventional data sources and techniques used in historical ecology research. (a) Percussion core sampling of an inshore coral reef in the Great Barrier Reef (courtesy of The National Environmental Research Program Project 1.3), (b) core section resulting from percussion core sampling (courtesy of M. Lepore), (c) multi-collector inductively coupled plasma mass spectrometer to conduct U-series dating of coral fragments sourced from cores (courtesy of J. Zhao), (d) catch from a 1947 Queensland fishing trip (courtesy of Heritage Library, Sunshine Coast Council), (e) early 20th century recreational fishing publication (Welsby, 1905) and (f) close up of a shark-toothed knife from the Gilbert Islands (courtesy of J. Drew).

4.2. Developing long-term metrics for monitoring and evaluation

If we are to accurately monitor long-term change, appropriate metrics are required. The degree to which metrics can be standardized across time periods and data types is essential to consider when attempting the integration of contemporary and historical data sets. A lack of resolution in many historical data sets often means that comparisons with more detailed contemporary data are difficult to achieve (McClenachan et al., 2012a). However, the adoption of indicators that require either broad-scale data or a simple index of change is often a viable solution to standardising data sources across long time periods. Such indicators are beginning to be adopted by marine policies such as the European Marine Strategy Framework Directive (MSFD) and the European Habitats Directive, which require the setting of reference conditions against which current ecological status can be compared (Borja et al., 2012; Raicevich, 2013). For example, the Large Fish Indicator is an index, applied to demersal fish communities in the North Sea, that describes the proportion of fish by weight in the sample >40 cm in length (Greenstreet et al., 2011). Such size-based indices reflect the effects of fishing pressure upon fish populations, and can indicate the sustainability of fishing effort. A comparison of survey data undertaken between the 1920s and 1980s showed no significant variation in the proportion of large fish in the catch over time (Greenstreet et al., 2012). After this period the proportion of large fish declined, leading managers to ascribe the 1980s as a suitable reference period upon which recovery targets should be based. It is important to note that in this context, historical reference conditions are not intended to reflect a pristine ecosystem. Indeed, by the 1920s major ecosystem change had already occurred in benthic marine ecosystems, including declines of large elasmobranchs (Dulvy and Reynolds, 2002) and losses in productivity (Thurstan et al., 2010, 2014). Instead, historical data were used in this context towards identifying sustainable levels of exploitation (Rice et al., 2012; Zampoukas et al., 2014).

A second issue to consider when developing long-term metrics is the modern decision-making framework. Even where historical information is readily available, contemporary assessment criteria or decision-making frameworks may not be set up to maximise the use of historical data. For example, IUCN decline criteria are limited to 10 years or three generations, whichever is longer. This short time-scale led to a down listing of two species of sawfish from critically endangered to endangered because the greatest declines occurred before the period to which IUCN criteria are applied, not because the conservation status of the two species had improved (Dulvy et al., in press). Similarly, data requirements for formal fisheries assessment methods commonly preclude disparate or incomplete historical data from being incorporated (Alexander et al., 2011; McClenachan et al., 2012a). Despite these issues, some types of historical data may be more readily incorporated than others, particularly if spatial expansion or changes in fishing effort can be estimated. Indices of relative change are an important component of fisheries assessments, and historical data that provide information on relative trends over time could be used to extend existing time series or be incorporated as separate model inputs. Such data include time series of catch rates, total landings and biomass estimates (MacKenzie et al., 2011; Poulsen et al., 2007; Rosenberg et al., 2005). Alexander et al. (2011) suggested 'catch density' – catch per area fished – as a potential metric for overcoming the problem of integrating historical data into stock assessments. Using three examples across different spatial and temporal scales, they showed that catch density could be calculated from a range of disparate data sources, including anecdotal archival data, and successfully compared with contemporary data. In all cases, the use of this index provided quite different perspectives than catch data alone.

The previous examples show that there are a number of different metrics that could be used to compare contemporary and historical data. However, even data that are not of sufficient resolution to be directly incorporated into quantitative models may still be of importance to the stock assessment process, for example, by endorsing or disputing model assumptions, such as the point in time where virgin biomass is assumed (Thurstan et al., in press). Furthermore, whilst formal assessments are the norm for industrialised fisheries, this does not extend to the majority of fisheries worldwide, which include many multi-species and small-scale fisheries that cannot be assessed using conventional methods (Friedlander et al., 2015). In the absence of formal survey and population data, historical information such as abundance indices and landings/catch history may be the only sources available to inform managers of broad-scale trends (Friedlander et al., 2015).

4.3. Challenging ingrained paradigms

A common problem that arises from an absence of historical data is the assumption that marine ecosystems (and their components) are not being substantially altered or degraded by human impacts (Bolster, 2006). Often, the burden of proof is upon scientists to demonstrate that human activities cause damage, such that a lack of data suggests a lack of impact (Royal Commission, 2005; Zeller et al., 2011). In the marine environment, this assumption has led to continued degradation in the form of pollution, habitat loss and overexploitation.

For example, fisheries were historically perceived as abundant and largely resilient to human pressure (Garstang, 1900; Huxley, 1883), the ocean was open access, and fishing was seen as a right (McClenachan, 2013; Russ and Zeller, 2003). These factors have set a precedent where in the absence of data, damaging activities are allowed to occur unobstructed (Brooks et al., 2014; Dayton, 1998). A lack of data, especially on the initial impacts of fishing, which generally have a more pronounced effect than impacts on already heavily altered systems (Jackson et al., 2001; Thurstan et al., 2014), supports this paradigm. Ecological risk assessments consider the potential risks of human activities to the functioning of marine ecosystems, and are often reliant upon information sourced from published material or expert knowledge (Pears et al., 2012). However, the information base for many marine species remains limited, preventing such studies from adequately assessing lesser-known or more cryptic species. McClenachan et al. (2012b) documented a link between data and conservation action for marine species; less charismatic groups of species have greater data deficiencies, which may be perceived as a lack of risk and can translate to a lack of conservation action.

Furthermore, when stakeholders are unable to perceive the extent of past change, they may be less likely to support actions to improve ecosystem status (Scyphers et al., 2014). Often, individuals perceive their own fishing activities as low impact, but fail to appreciate the influence of increasing numbers of fishers (McClenachan, 2013). For example, Coleman et al. (2004) showed that recreational fishers accounted for up to 64% of the take for species of concern in the Gulf of Mexico, while Shiffman et al. (2014) showed that trophy fishing removes the largest, most fecund individuals, with 85 species listed in the International Game Fishing Association world record guide classed as threatened by the IUCN Red List of Species (Shiffman et al., 2014). Stakeholders may also be unaware of ecological degradation across long periods of time, particularly where change has occurred across generations, the expansion of fisheries to greater depths and further offshore, or technological development have masked declines (Swartz et al., 2010). In cases where entrenched paradigms or shifted baselines exist, a historical perspective can provide important data to inform local communities and decision-makers of the magnitude of changes that have occurred. Communicating the experience of older fishers can also play an important role in combating such paradigms, as older fishers are likely to have experienced more striking declines than younger fishers (Beaudreau and Levin, 2014; Sáenz-Arroyo et al., 2005).

4.4. Recognising and responding to cumulative stressors

The impacts of cumulative stressors over time also commonly remain unaccounted for, either because the potential synergies acting among multiple stressors are not recognised, or because they are challenging to assess and manage using existing protocols. For example, despite major water regime changes occurring over a 150 year period as land was cleared for crops and pasture, the chronic effects of this pollution on the inshore reefs of the Great Barrier Reef went undocumented until the 1980s, with the resultant belief that declines in inshore reefs were largely due to acute disturbances such as cyclones or coral bleaching events (Brodie et al., 2001; Roff et al., 2013). Historical perspectives have aided our understanding of the mechanisms driving these changes, and emphasise that impacts should not be managed in isolation. Species with broad geographical distributions may also be inadequately protected by piecemeal conservation efforts that fail to recognise how cumulative stressors have impacted historical and contemporary populations. For example, sawfish were once widespread but are possibly the most endangered group of marine fishes in the world today as a result of their association with threatened coastal habitats, low intrinsic rates of population increase, the high value of their fins, and ease of catchability (Dulvy et al., in press). However, these declines are difficult to assess because of the species' large range sizes and long history of human interaction. Only when a global assessment incorporating historical information was undertaken was the scale of change to sawfish populations able to be fully comprehended. Comparisons of historical and contemporary data gathered for this assessment suggested that sawfishes have been extirpated from 80% of their historical range (Dulvy et al., in press).

As described previously, some high value, low trophic level fisheries today are historical anomalies. Similarly, in some ecosystems transitions to species compositions, interactions and functions unprecedented in the historical record have been observed (Graham et al., 2014; Hobbs et al., 2009). However, whilst these transitions often appear to occur over short time scales or as the result of an acute disturbance event, they can be the result of many years of cumulative stressors. For example, coral reef ecosystems in the Caribbean shifted quite suddenly from being dominated in the 1980s by coral (*Acropora cervicornis* and *Acropora palmata*) to macroalgae (Hughes et al., 2013). Whilst a mass mortality of the algal grazing urchins (*Diadema antillarum*) provided a proximate cause of this switch, and recent events including bleaching episodes helped to maintain coral reefs in algal dominated states, longer-term trends suggested it was the slow degradation resulting from centuries of fishing pressure that set the stage for the regime change witnessed (Hughes et al., 2013; Jackson et al., 2001). Interactions between fishing and climate effects have also been proposed as the cause of the dramatic shifts witnessed in demersal fish species composition in the northwest Atlantic, where large benthic predators such as cod (*G. morhua*) collapsed and forage fish and macro invertebrates considerably increased (Benoît and Swain, 2008; Choi et al., 2004). However, recent research suggests that these systems may be slowly returning to a community structure once more dominated by cod and other large benthic fish (Frank et al., 2011). These examples suggest that, if we are able to recognise when cumulative impacts may be leading an ecosystem towards regime change, a window of opportunity potentially exists within which progress towards reversing these shifts could be made (Hughes et al., 2013). In these cases, a historical perspective is a valuable tool to help recognise a) when ecosystem components or dynamics are acting outside of their historical range of variability, and b) the cumulative stressors and their social drivers that act together to create regime shifts, but which, on their own, may not signal a transitional change.

5. Acknowledging the role of qualitative sources in filling data gaps

Historical ecology research – including many of the examples we have highlighted – often focus upon quantitative findings, such as changes in catch per unit of fishing effort, changes in biomass or areal extent of a habitat, or differences in the average size or abundance of fish over time. However, in many cases precise information is not always required to address a particular knowledge gap and to assess whether fundamental changes have occurred that should trigger conservation action (Hall-Arber et al., 2009; Hicks et al., 2014). The loss of phenomena such as spawning aggregations (Aguilar-Perera, 2006) or the timing of fundamental alterations to benthic communities (Ames, 2004; Thurstan et al., 2013) can be addressed qualitatively, providing enough information for management action to be taken. Likewise, narratives can provide qualitative indications of past abundance, which, for species that are particularly vulnerable to human activities, may be sufficient evidence to show that major declines have occurred (Sáenz-Arroyo et al., 2006; Williams et al., 2010). For example, Sáenz-Arroyo et al. (2006) synthesised descriptions of the Gulf of California and its marine wildlife by 16th–19th century travellers. In contrast to present-day populations, these historical sources consistently described high abundances of large, vulnerable marine species including whales, turtles, oysters and large fish. Significantly, examination of historical sources raised the possibility that the highly endangered vaquita (*Phocoena sinus*) was once widely distributed throughout the Gulf of California, a proposition that had not previously been considered by scientists (Sáenz-Arroyo et al., 2006).

Often qualitative historical data comes in the form of local or traditional ecological knowledge (Berkes et al., 2000; Drew, 2005). This kind of knowledge can be critical for data-poor areas (Johannes, 1998), where formal quantitative surveys are not present. For example, Aguilar-Perera (2006) described the loss of a spawning aggregation for Nassau Grouper (*Epinephelus striatus*) off the southern Mexican Caribbean coast, which had been part of the local knowledge of fishers for at least the past 50 years. Similarly, Ames (2004) used historical testimony and fisher knowledge to identify long-lost cod spawning grounds in the Gulf of Maine, highlighting the necessity of minimising further losses of locally adapted sub-populations. Traditional and local ecological knowledge of Alaska Native subsistence and commercial fishers was also used to explore observations of ecological changes in Cook Inlet over time (Carter and Nielson, 2011). Interviews illustrated additional potential environmental and human activity-related threats to the Cook Inlet beluga whale population that had not been identified in formal management plans (Carter and Nielson, 2011). In these examples, qualitative historical data provided valuable information to plug existing data gaps, and identified additional conservation priorities that were not recognised using contemporary data alone.

Management decisions are often made within a contested policy environment where science is but one facet of decision-making. In these cases, qualitative historical data have an important role to play in focussing management priorities. For example, historical narratives may have the power to engage stakeholders – an increasingly integral component of the decision-making process – to a greater degree than quantitative research with complex model outputs or highly specialized scientific methodologies (Golden et al., 2014; Lotze and McClenachan, 2013). Alternatively, stakeholders may bring their own experiences and narratives to the process, thereby effecting change. Bringing in data collected by citizen scientists, oral narratives or originating in traditional ecological knowledge may also allow for participation by groups marginalized by more formal science methodologies.

Narrative descriptions of change may also be particularly effective when dealing with problems that are politicised, at which point, science is rarely the strongest influence on decisions (Gelcich et al., 2009; O'Leary et al., 2011). Moreover, whilst stakeholders may be aware of changes in their local environment, these perceptions are usually intertwined with multiple other factors such as societal values, resource dependency or poverty (Scyphers et al., 2014), all of which contribute to a perception of their environment that is difficult to represent using quantitative data alone. In these cases, ecological knowledge is not only useful to understand the past and present ecology of ecosystems, but is also an important source to help us understand coupled cultural and biodiversity losses (e.g., Drew, in press). Historical research has also demonstrated that there are many diverse ways of perceiving the environment (Shackeroff et al., 2011). Often, causal mechanisms of change may be disputed among stakeholders, but all will agree that change has occurred (Scyphers et al., 2014; Shackeroff et al., 2011). In these cases, historical narratives can work towards unifying policies by highlighting the similarities in stakeholders' experiences rather than emphasising differences of opinion.

6. Discussion

Historical ecology and related studies have demonstrated that human-induced ecological change has occurred over long periods of time (hundreds to thousands of years). In many cases, these changes have been far more dramatic than suggested by contemporary data alone (Pandolfi et al., 2003; Roberts, 2007; Rosenberg et al., 2005). In this article we describe the implications of historical data gaps for conservation and management, how unconventional sources continue to improve our understanding of data gaps, and the value and ongoing challenges of integrating historical data into contemporary conservation practise. By improving our understanding of past ecosystems, historical data can be used to set more ambitious conservation targets and highlight where conservation action is required. Novel historical research has successfully highlighted the myriad data sources and techniques that exist to inform our understanding of past change. Even though pristine conditions are rarely feasible or aspired to, a historical perspective can still be of value in deciding appropriate benchmarks for conservation or recovery objectives, and in measuring the success of conservation actions.

In particular, it is important to identify and reduce historical data gaps in order to calibrate ambitions for conservation, and the opportunities historical perspectives offer for more effective management. While lack of knowledge often hampers action, practitioners in this field must rise to the challenge of better integrating insights from historical ecology into management. The shift to alternative marine management paradigms, such as the movement from single species to ecosystem-based management (EBM), provides additional avenues for the incorporation of historical perspectives. Moreover, the requirement for EBM to account for impacts to the wider ecosystem (Pikitch et al., 2004) requires frameworks and methodologies that are able to integrate information sourced from varying temporal and spatial scales. Bayesian networks, for example, seem particularly well suited for integrating disparate data sources, such as those typically supplied by historical ecology studies, and are being increasingly applied in ecological studies and environmental decision-making (Aderhold et al., 2012; Ellison, 1996). Public engagement with historical ecology research and results may also help to empower local communities to set and achieve conservation goals. This can be particularly effective when the species or environment under scrutiny is high on the political agenda (e.g., the potential listing of the Great Barrier Reef World Heritage Area as 'In Danger'). Finally, *moving beyond numbers* is necessary to fully realise the value of historic data. Qualitative data sourced from narratives, pictures or photographs can present strong messages to stakeholders and the general public, and potentially have greater leverage in politicised contexts than quantitative outputs from shorter time periods.

The emergence of marine historical ecology occurred only recently, and several decades after its terrestrial equivalent (Meyer and Crumley, 2011), but its subsequent growth has been characterised by a highly creative multidisciplinary fusion of perspectives that continue to broaden and deepen our understanding of both past and present. As additional data sources are found and techniques for analysis developed, and as this field of research continues to grow in impact and acceptance among both scientific and practitioner communities, it will continue to transform our perceptions of marine ecosystems. Working to apply these findings to conservation and management frameworks is the next critical step towards improving the outlook for marine ecosystems and the benefits they provide to people worldwide.

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