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Fishes in a changing world: learning from the past to promote sustainability of fish populations

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Populations of fishes provide valuable services for billions of people, but face diverse and interacting threats that jeopardize their sustainability. Human population growth and intensifying resource use for food, water, energy and goods are compromising fish populations through a variety of mechanisms, including overfishing, habitat degradation and declines in water quality. The important challenges raised by these issues have been recognized and have led to considerable advances over past decades in managing and mitigating threats to fishes worldwide. In this review, we identify the major threats faced by fish populations alongside recent advances that are helping to address these issues. There are very significant efforts worldwide directed towards ensuring a sustainable future for the world's fishes and fisheries and those who rely on them. Although considerable challenges remain, by drawing attention to successful mitigation of threats to fish and fisheries we hope to provide the encouragement and direction that will allow these challenges to be overcome in the future.

Key words: challenges; fish; fisheries; future; global change; sustainability.

INTRODUCTION

Fish populations are of immense global value, shaping ecosystem services for billions of people worldwide (Holmlund & Hammer, 1999; Worm *et al.,* 2006; Cooke *et al.,* 2016). However, our planet is currently facing unprecedented environmental and societal changes that are having dramatic effects on fish and fisheries (Arthington *et al.,* 2016; Waters *et al.,* 2016). Understanding the probable scope of these changes is crucial in allowing us to develop mitigation strategies, manage fish populations, and minimize negative effects for those who rely on them. Moreover, the pivotal position of fishes in aquatic ecosystems renders them important indicators of environmental health (Graham *et al.,* 2015; Lynch *et al.,* 2016). Effective assessment and proactive management at the ecosystem level has the potential to considerably improve the resilience of aquatic ecosystems to global change, preventing potentially disastrous declines in fish populations (McCauley *et al.,* 2015; Scheffer *et al.,* 2015). The success of such management relies on the ability to identify current and future threats to fishes and using past successes to develop effective tools for future mitigation strategies.

This paper was envisioned during the 50th Anniversary Symposium of The Fisheries Society of the British Isles at the University of Exeter, U.K., in July 2017, by a team of 30 biologists who were challenged to consider the greatest threats fish populations are facing and how we might ensure sustainability in the future. The authors discussed ideas focused on what threats fishes face today, what can be learnt from previous successes, and how to best address future challenges. This paper was written as a collaborative endeavour, summarizing the outcomes of both this conference and relevant recent literature. We hope that it provides a useful review of current threats, an encouraging summary of recently-developed innovations and management options, and a forward-looking roadmap detailing future challenges facing fish populations worldwide and potential avenues for effective management and sustainability.

ISSUES FACING FISHES TODAY

Fishes in marine, transitional and freshwater habitats face a multitude of threats ultimately driven by increasing human populations (projected to reach 9·7 billion by 2050; United Nations, 2017) and intensifying resource use including for food provision

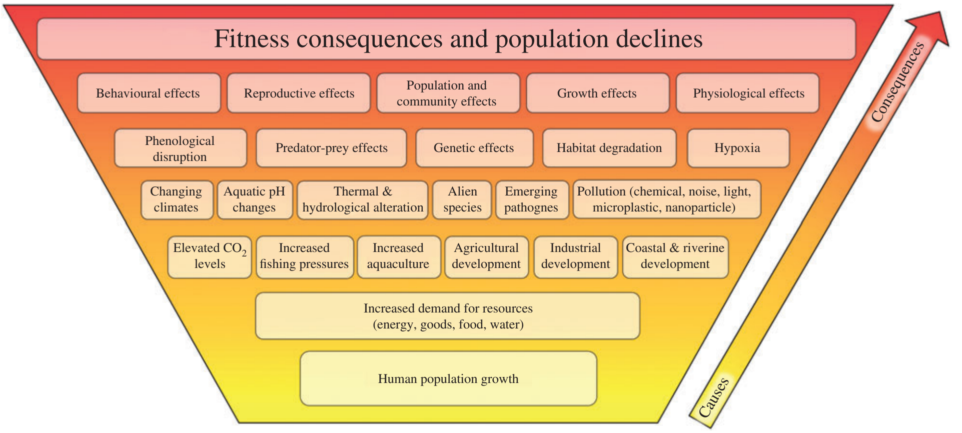

FIG. 1. Hierarchical structure of threats facing fishes globally. Human population growth as a driver leads to altered resource use and subsequently to fitness consequences and population declines by a wide range of varied and inter-linking mechanisms.

(fishing, irrigation, agriculture, livestock production), energy production (hydropower, wind turbines, oil and gas drilling, fracking, biomass harvesting), water usage (drinking, sanitation, industry) and other goods (mining, forestry, river channelling). The accumulation of threats has resulted in unprecedented effects on ecosystems, with widespread population declines of fauna and extinctions across many taxa (Foley *et al.,* 2011; Mueller *et al.,* 2012; Young *et al.,* 2016; Ceballos *et al.,* 2017). These threats are manifested through multiple biological, chemical, physical and climatic mechanisms (Fig. 1). Threats occur across a wide range of spatial and temporal scales, and need to be understood in the context of a combination of local (spatially and temporally variable) and global (large scale, with little spatial and temporal variation) pressures. A combination of local and global mitigation strategies will therefore be required to restore and sustain the health of aquatic systems.

Physical threats to aquatic systems include habitat degradation, fragmentation or destruction (Valiela *et al.,* 2001; Waycott *et al.,* 2009) and flow modification (*e.g.* water or sand extraction for societal use), caused by developments of energy infrastructure (*e.g.* dams for hydropower) and changes in land use (Dudgeon *et al.,* 2006; Ziv *et al.,* 2012; Pittock *et al.,* 2015). Overexploitation of fish stocks beyond sustainable limits is one of the most severe threats to fish populations (Pauly *et al.,* 1998; Allan *et al.,* 2005; Pauly & Zeller, 2016), with direct effects ranging from mortality through to fishing-induced life-history changes on populations (Jørgensen *et al.,* 2007; Kuparinen & Festa-Bianchet, 2017). Aquaculture of fish and other organisms may relieve pressure on natural fish stocks, but also has the potential to cause damage through proliferation of pathogens, destruction of natural habitat, localized pollution and distortion of native gene pools through escapes of strains selected for performance in captive conditions (Naylor *et al.,* 2000; Tornero & Hanke, 2016). Water pollution is another major threat, acting *via* a diverse array of mechanisms. Chemicals from industrial and domestic wastewater discharges and run-off from urban areas, agriculture and aquaculture can persist in aquatic environments and have a wide range of biological consequences for organisms and populations, ranging from lethal effects to non-lethal physiological changes such as disruption of the endocrine system (Jobling *et al.,* 1998; Jones & de Voogt, 1999; Hamilton *et al.,* 2016). Additionally, agricultural and aquacultural run-off can cause eutrophication of aquatic systems leading to local reductions in oxygen concentrations, which may be further exacerbated by climatic changes (Smith *et al.,* 1999; Jenny *et al.,* 2016). Expansion of severely hypoxic water masses ($<0{\cdot}5$ ml l^{-1} O_2) compresses habitable areas for fishes and causes concerning lethal and sub-lethal effects (Diaz & Rosenberg, 2008; Gallo & Levin, 2016; Townhill *et al.,* 2017). Further, human disruption of river continuity (for example for hydroelectricity production or water supply), coupled with stocking of migratory fishes, can cause shortages in nutrient availability (Nislow *et al.,* 2004). Stressors such as anthropogenic noise (*e.g.* commercial shipping, recreational motorboats) can affect both the physiology and behaviour of fish and have direct effects on fitness (Slabbekoorn *et al.,* 2010; Simpson *et al.,* 2016). Biological threats, including non-native species and aquaculture, have also emerged as significant pressures on biodiversity in aquatic environments and can have profound ecological consequences both directly (*e.g.* predation) and indirectly (*e.g.* habitat alterations, pathogens) (Middlemas *et al.,* 2013; Gallardo *et al.,* 2015). All of these human-induced biological changes may persist over time through a range of genetic and epigenetic mechanisms (Feil & Fraga, 2012; Paris *et al.,* 2015; Uusi-Heikkilä *et al.,* 2017).

Threats that are temporally persistent and geographically extensive will have the most widespread effecs on ecosystems. For instance, rising atmospheric CO_2 levels and associated acidification, together with warming and expansion of hypoxic zones in aquatic environments, have a range of individual, population, community and ecosystem-level effects on fishes globally (Perry *et al.,* 2005; Deutsch *et al.,* 2011; Stramma *et al.,* 2012; Jenny *et al.,* 2016). Associated reductions in pH and carbonate levels cause physiological and behavioural changes that may have severe consequences for both marine and freshwater populations (Simpson *et al.,* 2011*b*; Munday *et al.,* 2012; Stiasny *et al.,* 2016; Tix *et al.,* 2017). Some organisms can adapt behaviourally, physiologically or morphologically, whereas others are more intolerant and may be more susceptible to threats (Gallo & Levin, 2016). Mobile marine fishes may be more resilient to changes in temperature due to their potential for poleward range shifts (Simpson *et al.,* 2011*a*; Fossheim *et al.,* 2015), whilst non-diadromous freshwater fishes are more likely to be constrained by enclosed ecosystems, making such compensatory range shifts less feasible (Strayer & Dudgeon, 2010; Rolls *et al.,* 2017). Climate change-related effects on hydrological regimes and increased frequency and intensity of droughts and floods can dramatically affect riverine fish distributions and abundance (Milly *et al.,* 2005; Arthington *et al.,* 2010; Reynard *et al.,* 2017). Additionally, increasing mismatches between seasonal temperature patterns and photoperiodic cues can have population and ecosystem-wide effects in high latitude areas where daylight length changes with seasons (Jørgensen & Johnsen, 2014; Stevenson *et al.,* 2015).

The threats faced by fishes are rarely, if ever, experienced in isolation (Halpern *et al.,* 2008). Threats to aquatic ecosystems can occur concurrently or consecutively within the lifetime of a fish, with resulting antagonistic, additive or synergistic effects which may significantly alter the consequences of the individual stressors (Crain *et al.,* 2008; Darling & Côté, 2008). The consequences of such exposures to multiple stressors are often highly complex and context dependent. For example, coral-reef habitats and the fishes that occupy them are simultaneously threatened by both local overfishing and pollution as well as changes to global ocean pH and temperatures (Hughes *et al.,* 2017).

Additionally, temperature changes and hypoxia can act synergistically, such that small shifts in one stressor result in large effects on organismal performance when fish are exposed to both in combination (McBryan *et al.,* 2013). In contrast, a stressor can also act to reduce the effects of other stressors when acting in combination or its effects may be dependent on life stage. For example, hypoxia was shown to protect fishes from copper toxicity during embryonic development, but this effect was reversed after hatching (Fitzgerald *et al.,* 2016, 2017). In freshwater lakes, climate-change induced increases in temperature and precipitation influence both eutrophication and deep-water hypoxia, altering habitat availability for many fish species (Graham & Harrod, 2009; Rolls *et al.,* 2017). The increasing frequency of droughts can have a synergistic effect with other anthropogenic stressors; *e.g.* by increasing the concentration of chemical pollutants in fresh waters (Woodward *et al.,* 2010). Additionally, symbiotic interactions further complicate the consequences of ecosystem threats, as sub-lethal effects on one species can affect sublethally another species with which it interacts (Mills & Reynolds, 2004; Beldade *et al.,* 2017). Such interactions introduce considerable complexity to the analysis of the issues that fishes face, increasing the difficulty to predict levels of threat, causal relationships and likely consequences for survival.

LEARNING FROM PREVIOUS SUCCESSES

In confronting the significant challenges faced by fishes in globally changing ecosystems, it is important to reflect on the significant progress that has been made in addressing such issues over past decades. Revolutionary new conceptual, experimental, computational and technological advances have dramatically changed approaches in aquatic ecology, facilitating the development of strategies for dealing with future challenges. For example, modern genetics and genomics methods have revealed the fine-scale genetic diversity within and among fish populations, advanced modelling tools have allowed incorporating multiple individual-level processes in simulation models used to address realistic large-scale management scenarios, and technological developments in survey equipment have enhanced our ability to study and conserve deep-water ecosystems and species of particular concern (Dunlop *et al.,* 2009; Favaro *et al.,* 2011; Beguer-Pon *et al.,* 2015; Fernandes *et al.,* 2016; Valenzuela-Quiñonez, 2016). The following examples are not intended to be comprehensive, but provide case studies of how increases in understanding or new technologies have improved the management of fish populations.

CHEMICAL POLLUTION

Advances in ecotoxicology have demonstrated that even very small concentrations of pharmaceutical and industrial chemicals can have extensive consequences for fish populations through sub-lethal effects (Hamilton *et al.,* 2016). For example, synthetic oestrogens present in waste waters can result in widespread endocrine disruption in wild fish, with potentially negative implications for populations (Jobling *et al.,* 1998, 2006; Kidd *et al.,* 2007). Further, lessons from large oil spills (*e.g.* M.V. *Exxon Valdez* in 1989; M.V. *Deepwater Horizon* in 2010) have revealed variability across life-stages in the response of fishes to pollutants, in the time scales associated with stock recovery, the time lags associated with secondary effects such as disease and malnutrition, and the interactions of oil pollutants with natural environmental conditions (Pearson *et al.,* 1999; Thorne & Thomas, 2008; Whitehead, 2013; Incardona *et al.,* 2014). Additionally, recent experimental findings show that hydrocarbon-based pollutants at environmentally-relevant concentrations disrupt behaviours that are crucial to larval survival and settlement in coral-reef fishes (Johansen *et al.,* 2017). These recent developments in our understanding of the consequences of exposure to pollutants enhance our ability to predict and mitigate the effects of such events in the future. This ability has important implications for governmental decision-making, *e.g.* regarding waste water treatments, oil exploration, drilling and construction near sensitive ecosystems. Indeed, several examples of ecosystem recovery have been reported following introduction of improved treatment of wastewaters and reduction of discharges [*e.g.* the River Aire (Sheahan *et al.,* 2002) and the Mersey estuary (Jones, 2006) in the U.K.], effectively demonstrating the benefits of improved wastewater management strategies.

CLIMATE CHANGE

Growing concerns surrounding the consequences of anthropogenic climate change have resulted in a dramatic increase in related research. For example, a recent wealth of predictive models has been developed to help determine future patterns of fish distribution and productivity, with increasing competitive abilities and physiological challenges (Cheung *et al.,* 2010, 2013; Piou *et al.,* 2015). Furthermore, despite the problem of ocean acidification having only been recognized within the past decade or so, there is now significant progress towards understanding the effects of temperature and changing ocean pH, both as individual stressors and in the context of a complex suite of other environmental pressures (Orr *et al.,* 2005; Kroeker *et al.,* 2017). Additionally, our understanding of the ability of fish in riverine systems to shift their spatial distributions with changing isotherms has increased (Comte & Grenouillet, 2013). Previously, research had centred upon spatial predictions and exposure; recent progress now facilitates detailed analysis of vulnerability frameworks (including species-specific sensitivities, adaptive capacity and exposure) to aid in the conservation and management of fish populations by determining the best strategy and the urgency with which it should be applied (Dawson *et al.,* 2011). For example, understanding a species' vulnerability may inform managers that an intensive approach is required involving assisted migrations outside of a species' native range (Dawson *et al.,* 2011; Lunt *et al.,* 2013); although such assistance is still debated due to potential unintended consequences (Ricciardi & Simberloff, 2009). Within freshwater environments there is also potential for mitigation against thermal increase, for example by planting trees to provide shading where temperatures are predicted to exceed optimum or reach critically high levels for growth and survival of fish populations (Jackson *et al.,* 2016). Understanding the capacity of farmed species to cope with changes to the environment (Castanheira *et al.,* 2017) and the potential to select species suited to future conditions (Callaway *et al.,* 2012) could buffer some of the detrimental consequences of climate change both on food production and the environment. Active research in these areas will enable management of associated risks.

OVEREXPLOITATION

Overexploitation of fish stocks, in addition to the removal of individuals, can induce phenotypic shifts in life-history traits of remaining fish and thus disrupt size-dependent community and ecosystem functioning (Pauly *et al.,* 1998; Branch *et al.,* 2010; Kuparinen *et al.,* 2016; Graham *et al.,* 2017). To achieve more ecologically and socially sustainable management schemes, especially in the wider context of increasing climate-induced pressures, balanced harvesting strategies (Garcia *et al.,* 2012) and spatially or evolutionarily explicit, ecosystem-based approaches have emerged as alternatives to traditional individual-species management (Pikitch *et al.,* 2004; Laugen *et al.,* 2014; Möllmann *et al.,* 2014; Patrick & Link, 2015). These ecosystem-based approaches are designed to prioritize management of the ecosystem through defined biological and societal objectives, ultimately supporting target fisheries (Pikitch *et al.,* 2004; Garcia & Cochrane, 2005; Ruckelshaus *et al.,* 2008). While these approaches remain largely in their infancy and challenges regarding implementation still remain, recent models show that such approaches can be very effective management strategies to achieve multiple social, economic and ecological objectives simultaneously (Fulton *et al.,* 2014). The adoption of ecosystem-based management regimes represents the best option for sustainable management, but is a complex process involving many organizations, communities and stakeholders. Implementation is therefore challenging, but it has been shown to be achievable (Garcia & Cochrane, 2005; Olsson *et al.,* 2008). For example, management of the Great Barrier Reef Marine Park in Australia transitioned from protection of individual reefs to the wider-scale seascape through reorganization of the park authority, which enabled better collaboration with scientists and increased public awareness of threats (Olsson *et al.,* 2008; Reef Water Quality Protection Plan Secretariat, 2013).

PROTECTED AREAS

Marine and freshwater protected areas (*i.e.* aquatic areas where fishing or other activities are limited or prohibited) represent an important tool for recovery and replenishment of exploited stocks and facilitation of adaptation to climate change if implemented, managed and enforced appropriately (Huntington *et al.,* 2010; Edgar *et al.,* 2014; Gill *et al.,* 2017; Roberts *et al.,* 2017). Development in the design and implementation of aquatic protected areas has focused on integrating and improving resilience to climate change and enhancing socio-ecological capacities (Cinner *et al.,* 2009). Additionally, an improvement in reserve design and consideration of global marine reserve connectivity and larval supply can serve to better direct reserve benefits to both people and the environment (Chollett *et al.,* 2016; Andrello *et al.,* 2017; Krueck *et al.,* 2017*a*). This can optimize the trade-off between conservation and fisheries production (Gaines *et al.,* 2010; Brown *et al.,* 2015; Chollett *et al.,* 2016). Similarly, in freshwater systems, improvements in management using protected areas have enhanced the connectivity of important sections of rivers, lakes and estuaries (Pittock *et al.,* 2015; Harrison *et al.,* 2016).

EMERGING ANALYTICAL BIOTECHNOLOGIES

Rapid technological and computational developments have resulted in the development and improvement of technologies for understanding, monitoring and protecting fish populations (Paris *et al.,* 2018). For example, microchemical analyses of both otoliths and other calcified structures in fishes are widely used as valuable tools for understanding the age structures, life histories, habitat use, migration routes and dietary patterns of many fish populations (Campana, 2005; Tzadik *et al.,* 2017), and have contributed significantly to population management and conservation over time.

In recent decades, genetic sequencing technologies have undergone dramatic development, resulting in major advances in all areas of biology, including for fish biology. The resulting ease of generating and interpreting sequence information for many fish species has increased our knowledge of their evolutionary biology and adaptive physiology, as well as our understanding of how these features change for populations under environmental stress (Uren Webster *et al.,* 2013 and Paris *et al.,* 2015 for examples regarding populations of fish living in metal contaminated rivers). Further, DNA barcoding now allows global tracking of seafood fraud (Pardo *et al.,* 2016), and next-generation sequencing-based eDNA metabarcoding can be used to effectively detect non-native and endangered species when this was hitherto impractical (Bohmann *et al.,* 2014). Use of eDNA is arguably on the verge of revolutionizing fish community monitoring (Valentini *et al.,* 2016) and is becoming an effective tool for monitoring the health of aquatic ecosystems (Chariton *et al.,* 2015; Aylagas *et al.,* 2016). For example, in an Australian riverine system, eDNA has been used to improve management and control of the invasive Eurasian perch *Perca fluviatilis* L. 1758 through high sensitivity of detection, allowing more accurate placement of exclusion barriers (Bylemans *et al.,* 2016). As technologies develop and their associated costs decrease, it is envisaged that sequencing will become progressively more powerful and widely used in managing fish populations worldwide. Together, the development of new technologies and improvements in well-established techniques are contributing significantly to better understand fish populations and improved management of fish and fisheries.

BIG DATA

The growing availability of free or low-cost data from a wide range of remote sensing platforms, combined with miniaturization of data-storage devices, has provided the ability to collect large amounts of data that can be shared internationally between multi-disciplinary groups (Sbrocco & Barber, 2013, Yeager *et al.,* 2017). This is allowing development of big-data approaches in fish science, which have the potential to help tackle issues related to monitoring and mitigating changes in large-scale systems (Hampton *et al.,* 2013; Dafforn *et al.,* 2015). Future technological developments may lead to further dramatic improvements in the ability of scientists and environmental managers to assess and manage the effects of global change on fishes and fisheries.

MODELLING

Major progress has been made in advanced modelling techniques, allowing society to transfer understanding of effects of environmental change on individual fish to population and community levels. For example, developments in computing and software have allowed for a range of food-web models, such as Ecopath (Christensen & Walters, 2004; Moloney *et al.,* 2005). Fisheries models are now expanding to include multiple trophic levels, allowing more informative predictions about the potential consequences of management strategies (Bozec *et al.,* 2016). Further, advanced modelling techniques facilitate greater understanding of key features of population dynamics, including energy budgets, reproduction, larval dispersal, recruitment, genetic changes and productivity of fisheries (Dunlop *et al.,* 2009; Cheung *et al.,* 2010; Sibly *et al.,* 2013; Krueck *et al.,* 2017*a*), leading to improved utility for management and conservation. This potentially allows scientific advice to play a greater role in policy, as seen with successes such as the establishment of multi-disciplinary management indicators adopted by the E.U. Water Framework Directive (EC, 2016). Nevertheless, much of this advice can be further improved. The use of mandatory environmental impact assessments (EIA) in Europe has extended to many forms of aquatic development planning. Yet, the ability to predict robustly the outcomes of development and to engage effectively in post-scheme monitoring and adaptive management still constrain the practical application of EIA (Rose, 2000; Milner, 2015). Hydrological and ecological models have been used successfully in restoration of riverine habitats that have been affected by water extraction and associated altered flow regimes, which bodes well for future uses in similar systems (Webb *et al.,* 2017). Such models, combined with empirical research, were used to inform management decisions on flow regulation to increase fish spawning and recruitment on a flood plain on the River Murray, Australia (Arthington *et al.,* 2010; King *et al.,* 2010), demonstrating the potential of these approaches to improve the sustainability of fish populations.

INTERDISCIPLINARY AND HOLISTIC THINKING

The severity of problems facing fishes and the difficulty of studying long-term anthropogenic changes have necessitated the development of new integrative and holistic ways of thinking in environmental biology. Multi-disciplinary, ecosystem-based approaches have emerged as particularly promising novel frameworks, resulting in significant advances in both research and management applications. For instance, local societal and ecological changes have been linked to global climate change (Karnauskas *et al.,* 2015), biophysical modelling has been integrated with population genetics (Selkoe *et al.,* 2008), ecosystem service ideas have been expanded to include relational values (Chan *et al.,* 2016), and fisheries sustainability has been added to biodiversity in considering the effectiveness of marine protected areas (Krueck *et al.,* 2017*b*). Furthermore, recent ideas promote decision-making based upon expected future ecosystem states, as opposed to past baselines, to increase the efficacy of future management strategies (Rogers *et al.,* 2015). Calls for anticipative management of this nature have led to increased understanding of the subtle variations characterizing degraded environments as well as the novel fish assemblages that arise from warming-induced range shifts and abundance changes (Harborne & Mumby, 2011; Simpson *et al.,* 2011*a*; Salvanes *et al.,* 2015; Mumby, 2017) and have the potential to prevent problems before they occur.

ADDRESSING FUTURE CHALLENGES

Despite significant recent advances in assessing the responses of fishes to global change, key challenges remain. Ultimately, many of the most pervasive problems facing global fish populations can only be mitigated through collaborative efforts involving both scientists and wider society (Sutherland *et al.,* 2006; Lynch *et al.,* 2015). Future efforts must, therefore, use both scientific and societal approaches in order to most effectively secure a future for fishes worldwide (Cooke *et al.,* 2016).

SCIENTIFIC CHALLENGES

Ultimate consequences

Understanding how individual-level responses to environmental change affect individual fitness, and subsequent population and ecosystem-scale effects, is a major challenge (Rolls *et al.,* 2017; Windsor *et al.,* 2018). This includes the development of suitable techniques for understanding multiple stressor effects in ecologically realistic settings at the broadest scales of biological organization (Dafforn *et al.,* 2015). For example, context-dependent responses to cumulative stressors often lead to uncertainty in predicting the outcomes of ecosystem disturbance. Improving our ability to quantify and model these uncertainties is important in order to increase our understanding of system-level responses to environmental change (Mumby & van Woesik, 2014). Furthermore, identifying and quantifying links between observed ecological effects and provision of ecosystem services is important for demonstrating the relevance of research findings to a wider societal audience and for effective action (Hering *et al.,* 2015).

Indirect effects

Indirect effects of environmental change are important in defining its consequences for ecosystems. For example, the emergence of novel habitats resulting from environmental modification might provide new niches but also serious challenges for fish communities if these modifications impede migration pathways and reduce connectivity among crucial habitats (Acreman *et al.,* 2014; Graham *et al.,* 2014). Predicting the constituents of these altered habitats and the likely responses of existing fish communities to change represents a considerable current knowledge gap.

Understanding acclimation and adaptation

The potential for acclimation and adaptation to environmental change and disturbances is a crucial determinant of population persistence and productivity (Munday *et al.,* 2017). These mechanisms are fundamental to ecosystem resilience, and are therefore central in identifying the actual ecological risks presented by environmental stressors. Intra-specific variation in responses is often overlooked, despite potentially important implications for the ability of fish populations to exhibit short-term and evolutionary responses to stressors (Radford *et al.,* 2016; Ellis *et al.,* 2017). Understanding the mechanisms underpinning population responses and their variability and integrating this knowledge into predictive models (Piou *et al.,* 2015) are important to appropriately manage fish populations and communities under stress.

Long-term datasets

Determining the effects of global change on fishes is problematic without extensive, long-term datasets (Soranno & Schimel, 2014). In many cases, the data required to answer certain macro-scale questions are not available, and expansion of existing data-sharing practices in conjunction with data collection networks is required to facilitate long-term ecosystem-scale analysis (Laney *et al.,* 2015). In cases where technological advances have allowed collection of large datasets, current computational capabilities are not always sufficient for appropriate storage, sharing and analysis of these data (*i.e.*, dealing with a data deluge), and greater investment in infrastructure and computational capacity is required (Hallgren *et al.,* 2016). A further aspect of engaging with big data and tackling large-scale questions revolves around contributing to global, interdisciplinary initiatives (Hampton *et al.,* 2013). For instance, understanding fully the potential environmental risk of microplastics in aquatic environments will require a collaborative effort from multiple disciplines including chemistry, hydrology, ethology and ecotoxicology (Wagner *et al.,* 2014). Similarly, multidisciplinary approaches will be required to address other large-scale threats, including those arising from pollution and climate change. Therefore, fostering collaborations between disciplines is of vital importance for determining the likely consequences of global change upon ecosystems and implementing sustainable solutions for these problems (Holm *et al.,* 2013).

SOCIETAL CHALLENGES

Widening participation

Effective communication of the problems facing fish and fisheries, the scientific solutions and the potential options for the future is of fundamental importance. Public support for research and management can be enhanced by instilling and nurturing an ethos of care and value among communities of people. Promoting the involvement of the non-scientific community in data collection and decision making is important in gaining momentum towards positive change (Wiber *et al.,* 2009). In particular, incorporating indigenous communities' local knowledge and cultural values into ecosystem management strategies is a fundamentally important challenge for improving their success (King & Brown, 2010; Finn & Jackson, 2011). A number of citizen-science projects focussing on data collection for fishes already exist (Hyder *et al.,* 2015). Despite this, the absence of best practice regarding these processes is hindering progress and positive change through public engagement. Improving transparency and feedback within communication pathways between scientists and the public may enhance participation in management of fish populations (Dickinson *et al.,* 2012). Improved stakeholder interaction and better use of citizen science also requires development of novel information technology tools and mobile applications that allow for the collection and use of data by the public (Hyder *et al.,* 2015).

Spatial boundaries

Practical solutions are necessary to overcome existing issues regarding the use of ecologically arbitrary spatial boundaries to separate the dynamic environment of open water bodies (*e.g.* exclusive economic zones), which can prevent current management strategies from reaching their full potential (Song *et al.,* 2017). Ultimately, sympathetic and inclusive management measures at a range of spatial scales (local, international or global) are required, and this can aid with compliance in strategy implementation (Ramírez-Monsalve *et al.,* 2016).

Political landscapes

The global political landscape provides a major challenge to researching and managing fish populations. Destabilization of both domestic and international politics affects the international scientific community worldwide and the translation of discoveries into effective management; examples include uncertainty surrounding the consequences of the U.K. cancelling its membership of the E.U. on fisheries and nature conservation policies (Rush & Solandt, 2017), potential changes in European marine environmental protection policy (Boyes & Elliott, 2016) and breakdowns in transboundary agreements regarding the management of South China Sea fish stocks (Teh *et al.,* 2017). The world currently faces dramatic changes to ecological, societal and political environments. Maintaining consistency and employing robust management strategies such that political uncertainty does not result in degraded ecosystems is, and will continue to be, a major challenge for the future.

Public concern for fish welfare

Public concern for fish welfare in aquaculture (*e.g.* the presence of sea lice) and both commercial and recreational fishing appears to lag behind that for terrestrial farming, but voices of concern are growing and evidence is accumulating on this contentious and challenging issue (Huntingford & Kadri, 2014; Brown, 2015; Stevens *et al.,* 2017). However, current data and knowledge are insufficient for representatively assessing the current state of fish welfare and supporting significant improvements in this area (Röcklinsberg, 2015). Continued research on fish welfare topics is required to address this knowledge gap, and public engagement needs to become a priority for changing attitudes and implementing positive action in this area.

Prioritization of resources

It may be necessary to prioritize specific avenues for research, management or regulation in the face of a rapidly changing global environment and limited resources. Problem areas that may benefit from rapid intervention to address emergent threats should be given a higher priority compared with others where immediate action may not be necessary or effective. Such prioritization should be based not only on scientific merit, but also inclusion of societal requirements, conservation and management strategies (Gullestad *et al.,* 2017). For example, proposed habitat developments (*e.g.* hydropower) should increasingly weigh up the cost to biodiversity and fish productivity against societal requirements, to avoid negative consequences for aquatic conservation and ecosystem services (Ziv *et al.,* 2012; Winemiller *et al.,* 2016). Alternatively, aquatic infrastructure can potentially be eco-engineered to minimize adverse impacts and provide benefits to a range of taxa (Perkins *et al.,* 2015). Increasingly, compromises must be made between the amount of scientific evidence required to competently answer research problems and the need to provide timely advice to inform decision-making and management (*i.e.* a quest for perfection should not be an enemy of plain good). There is increasing concern regarding the rate of global change and the risk of overly cautious scientific conclusions limiting the onset, speed and potential benefits of effective management decisions. Some management decisions need to be made on priority issues with best current knowledge using precautionary principles, rather than waiting for complete datasets to be generated, in the knowledge that in the future decisions may be adjusted as new data emerge. This bolder management approach can accelerate the management of new challenges and prevent deterioration of the environment.

CONCLUSION

Fish populations worldwide face a multitude of threats ultimately stemming from human population growth and altered resource use. These threats present dramatic challenges for both science and society today, but a range of successes over past decades provide a roadmap for many of these challenges to be met effectively. For example, major scientific, technological and conceptual advances associated with big data and new computational and genetic techniques have increased our ability to manage fish populations effectively, at least in more economically developed nations. However, significant ecological, political and societal challenges must still be met to secure a future for the world's fishes (and in doing so, their entire supporting ecosystems). This requires global and collaborative efforts to achieve effective solutions for sustainable fisheries and ecosystems. The rate of global change threatening fishes worldwide is such that time has become the most precious commodity in mitigating the threats faced by fish populations. Urgent and bolder action is needed for the effective protection of ecosystems and the services they provide for human populations across the globe.

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