Consistent risk management in a changing world: risk equivalence in fisheries and other human activities affecting marine resources and ecosystems

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Summary

This manuscript addresses the need to account for climate change in the management of human activities affecting marine resources and ecosystems. A changing climate makes the evaluation of human impacts on natural systems increasingly uncertain, and affects the risks associated with management decisions. A flexible approach is proposed that involves routine formulation of alternative hypotheses for climate effects and exploration of risk equivalent management options that allow human activities to continue within acceptable risk levels despite shifting or novel conditions. The approach fits within existing risk frameworks and is applicable in all data and knowledge situations where management objectives are specified. Risk equivalence can be achieved either by conditioning the exposure to human pressures on demonstrated, anticipated or projected environmental change, or by conditioning the objectives themselves on a new environmental reality. We exemplify risk equivalence in fisheries management and discuss its applicability to the management of other human activities. Concepts of risk and risk conditioning factors provide a common language and understanding for the inclusion and communication of environmental considerations in management advice. The approach can guide robust and accountable decision-making in a changing world, and facilitate the implementation of ecosystem-based management.

Abstract

Oceans are changing. Departures from known or existing environmental conditions are adding uncertainty in the evaluation of marine resources and ecosystems and impacts from human activities. This uncertainty affects both the achievability and meaning of management objectives used to assess the risks from human pressures. An objectives-based risk framework that explicitly accounts for quantifiable and unquantifiable uncertainty in the evaluation of potential consequences from human activity, can be a powerful tool for timely and consistent incorporation of environmental considerations into management advice. A risk equivalence approach permits a formal treatment of all sources of uncertainty, such that objectives-based

management decisions can be maintained within acceptable risk levels and comparable over time among resources and among management strategies and options. There are two pathways to achieving risk equivalence accounting for the short-term and longer-term impacts of a changing environment: adjusting the degree of exposure to human pressure and adjusting the objectives. The first can be used to operationalise existing data and knowledge to condition management advice on environmental departures from baseline conditions, even in the absence of complete mechanistic understanding. The second concerns the review and update of objectives, reference levels and risk tolerances, so they remain consistent with the potential consequences from human pressures under new biological, ecological and socio-economic realities. A risk equivalence approach is about adapting existing practice to frame environmental considerations within objectives-based risk frameworks, and systematically exploring risk equivalent management options using the available information to condition management advice on environmental status. It is applicable to the management of all human activities impacting biological and ecological systems. Risk conditioning factors and incremental changes in risk provide a single currency (risk) for consistent communication of environmental effects in advice. Risk equivalence can ensure timely delivery of robust advice accounting for demonstrated, anticipated or projected environmental considerations. This can guide management decisions in a changing world, and greatly facilitate the implementation of an ecosystem approach for the management of human activities.

1. Introduction

There is increasing evidence of shifting means and variances in oceanographic variables and of the increasing frequency of extreme events in marine ecosystems (Frölicher and Laufkötter, 2018; Oliver et al., 2018; IPCC, 2019; Rodgers et al., 2019; IPCC, 2021). These changes increase uncertainty in the assessment of human impacts on marine resources and ecosystems and in scientific advice on managing or mitigating such impacts. A risk-based approach combining explicit consideration of scientific uncertainty as it affects the achievability and definition of management objectives is highly relevant in this context. Framing environmental and ecosystem considerations into risk assessment frameworks used to inform objectives-based decisions can serve to readily and systematically condition management advice on observed, anticipated or projected environmental variation and change.

Risk occurs as a result of incomplete knowledge and information, erroneous or incorrect uses of the available data and information, and the inherent stochasticity and non-stationarity of natural systems and processes. In the marine realm, there is pervasive uncertainty in the evaluation of the state of ecosystems and ecosystem components, their responses to human-induced pressures, and how such responses are likely to evolve into the future and in a changing environment. This makes risk assessment methods and risk management frameworks highly relevant to ocean governance (Burgman, 2005; Levin et al., 2009; Burgman and Yemshanov, 2013; Plagányi et al., 2013; Holsman et al., 2017; Hodgson et al., 2019; Ono et al., 2019; Haas et al., 2021). Risk can

facilitate the communication of uncertainty and uptake of scientific results and conclusions at the science-policy interface, especially in situations involving complex and incompletely known cause-effects pathways (Kaplan and Garrick, 1981; Fu et al., 2018; Stelzenmüller et al., 2018; Hodgson et al., 2019). An improved understanding of risk concepts and components can facilitate existing practice in marine conservation and resource use, and enable the extension of existing practice to consider emerging sources of uncertainty and interactions among risk factors.

Risk assessments are conducted to evaluate and communicate the possible consequences of uncertainty on management outcomes (Francis and Shotton, 1997; Harwood, 2000). Risk management is the process of decision-making under uncertainty, which is informed by the risk assessment and conducted in policy environments providing guidance and direction on how to evaluate and manage the risks (Simonovic, 1997; Sethi, 2010; Hobday et al., 2011; Astles, 2015; Gibbs and Browman, 2015). Risk equivalence is about consistency in risk evaluation and management. It is used to maintain the risk associated with management decisions at a level that is consistent with acceptable risk levels. Where management objectives are specified, risk equivalent options can be formulated considering quantifiable as well as unquantified or unquantifiable uncertainty. While not often discussed or explicitly included in conventional risk management frameworks e.g. (ISO, 2018), risk equivalence is implicit, expected and applicable whenever scientific advice is formulated to inform risk-based management decisions. When implemented systematically, the precautionary approach (FAO, 2003) is a form of risk equivalence: its aim is to maintain a consistently low risk of negative impacts from human activities, notwithstanding the evidence basis available and used to assess the risk (i.e. data and information types, their quantity and quality). Similarly, where environmental variation and change contribute additional uncertainty in the risk assessment, risk equivalence can be applied to evaluate whether and to what extent levels of exposure to human pressures and, when necessary, the definition of management objectives should be adjusted in order to maintain a comparable risk aversion in management decisions.

In this paper, we illustrate the relevance of risk equivalence for the management of human activities under environmental variation and change. We propose a flexible risk assessment and management framework that incorporates the explicit distinction between quantifiable and unquantifiable uncertainty and application of risk equivalence. We show how risk equivalence can be used to incorporate ecosystem and environmental considerations in scientific advice for fisheries management across temporal scales and over the data and process-knowledge continua. We demonstrate how a risk equivalence approach provides as a unifying concept for handling the short-term aspects of environmental change on the probability of achieving (or not achieving) management objectives, and longer-term aspects relating to the specification of the objectives and the safe operating space within which the risk is managed. Finally, we discuss how this approach can be extended to marine resources and ecosystems management more broadly, whereby risk provides a common currency for handling and communicating all sources and types of uncertainty in a transparent and explicit manner.

For clarity and inclusiveness, throughout this paper, we use the word ‘environment’ to encompass all external factors, drivers or indicators (e.g. ecosystem, climate and physico-chemical variables) that are beyond the control of management systems but likely to affect the risk associated with management decisions.

2. Objectives-based risk assessment and management

Risk assessment methods differ in their scope and level of connection to management actions and outcomes (Hodgson et al., 2019). As a result, the term “risk” in natural resources management is given a variety of meanings that are often confounded and confounding. Risk assessments are commonly used in the marine context to screen risks and prioritise species, ecosystem components and/or human activities for management actions, without explicit quantification of uncertainty and without consideration of management outcomes (Dulvy et al., 2004; Smith et al., 2007; Hobday et al., 2011; Gaichas et al., 2014; Cotter et al., 2015; Knights et al., 2015; Hare et al., 2016; Gaichas et al., 2018; Pedreschi et al., 2019; Muffley et al., 2021). Such contextual risk assessments involve identifying relevant pressures arising from human activity, mapping how they relate to individual resource, ecosystem components or ecological characteristics (pressure-effects pathways) and using available knowledge and information to identify, approximate and rank relative risks.

Contextual risk assessments are often precursors or complementary to objectives-based risk assessments, where risks are assessed in relation to biological, ecological and social and economic thresholds or reference levels expressing the potential consequences from human-induced pressures. These reference levels are tied to management objectives representing long-term goals for the state of the resource, ecosystem and/or human activity sector and societal welfare. The specification of objectives is aspirational and guided by science, policy, regulations and legislation, addressing considerations such as maximising benefits from resource use to human societies and minimising harm to the resource, the ecosystem service, or the entire ecosystem (Barber and Taylor, 1990). The assessment of the risk associated with not meeting the objectives given the uncertainties encountered in managing human activities, is operational. All natural resource use and conservation management is ultimately objectives-based, with objectives ideally specified explicitly rather than implicitly (Rice, 1999; McDaniels, 2000; Game et al., 2013). In objectives-based risk assessments, the link between risk and anticipated management outcomes is explicit, as is the quantification and propagation of uncertainty.

Understanding the roles and opportunities provided by objectives-based risk frameworks is a critical step toward using risk equivalence to account for environmental variation and change in scientific advice. Objectives-based risk management consists of defining a ‘safe operating space’ or ‘sustainability domain’ bounded by reference levels and objectives (each with a specified risk tolerance), and choosing management options that are as robust as possible for maintaining the system within the safe operating space, taking uncertainties into account. The risk assessment has a crucial role in linking these steps. Objectives-based risk assessments involve 1) identifying the pressure(s) resulting from human activity and their potential consequence(s) considering resource, ecosystem or activity sector sensitivity (risk identification); 2) estimating the likelihood

or probability that these pressures will lead to consequences of varying severity (i.e. the probability of not achieving objectives) given sensitivity and levels of exposure to each pressure (risk analysis); and 3) evaluating the incremental changes in risk and possible trade-offs among management options in relation to acceptable risk levels (risk evaluation) (Figure 1). Together, sensitivity and exposure determine the magnitude of possible impacts. Sensitivity expresses resource or ecosystem resilience and adaptive capacity, as determined by productivity traits and intrinsic dynamics. Exposure captures the various aspects of human activity that can be managed, as well as aspects of resource or ecosystem vulnerability to human activity (e.g. spatial extent or distribution, habitat use or heterogeneity, and ontogenetic or seasonal migrations). There will be uncertainty in various aspects of sensitivity and exposure that will be quantified and propagated in the risk analysis. Yet no matter how intensively sampling is done, and however sophisticated the risk analysis, unquantified or unquantifiable uncertainty will also occur in the assessment and affect the risk of not achieving objectives.

This explicit distinction between quantified and unquantified or unquantifiable uncertainty is central to the application of risk equivalence in risk evaluation and management (Figure 1). Uncertainty can arise from multiple sources including stochastic variability and non-stationarity inherent to the natural world, oversimplification, incomplete sampling or understanding, and institutional constraints. In particular for natural resources and ecosystems management, key biological and ecological processes are often poorly understood or can be described adequately by multiple rival models (Harwood and Stokes, 2003). Francis and Shotton (1997) and Simonovic (1997) provide detailed descriptions of sources of uncertainty in fisheries and aquatic resources management. However, until now, risk assessment and management frameworks have commonly ignored unquantified uncertainty, by assuming it does not exist or has a null value; an assumption that has been demonstrated to be clearly invalid in fisheries assessments (Punt et al., 2012). Models including random effects, process and observation errors are good at capturing and propagating uncertainty without necessarily understanding its underlying cause (Thorson and Minto, 2015), which may relegate such uncertainty as irreducible. Failure to recognise that a fraction of the uncertainty in the evaluation of the risk from human activities to natural systems is not captured in standard practice, can lead to unexpected and undesirable outcomes from management decisions.

We propose a conceptual framework for objectives-based risk assessment and management that includes the explicit distinction between quantifiable uncertainty, which is handled in risk analyses, and unquantifiable uncertainty, which is handled in risk evaluation by investigating and formulating risk equivalent scenarios and management options (Figure 1). This framework can be developed and tailored to all human activity sectors for formulation of consistent and accountable decisions under a changing environment.

3. Fisheries management is objectives-based risk management

Objectives-based risk management is well exemplified in fisheries, where structured frameworks for considering risk in fisheries advice and decision-making have been adopted in several jurisdictions e.g. Canada (DFO, 2006), ICES/EU (ICES, 2021a), New Zealand (Ministry of

Fisheries, 2008), and the US (USDC, 2007). Fisheries risk assessments are used for exploring and identifying management options enabling fishery objectives to be met at the acceptable risk level, given quantifiable scientific uncertainty (namely, observation and process error variability). Fishing exerts multiple pressures on marine ecosystems, a primary one being the selective removal and possible depletion of targeted fish stocks. Depleting a fish stock to a level of impaired productivity is a potential biological consequence of fishing. This consequence is inconsistent with the application of precaution in fisheries management. Avoidance of that consequence is therefore operationalised as a limit biomass reference point such as B_{lim} . The limit reference point delineates the lower boundary of the safe operating space for the fishery, where the risk of serious or irreversible biological harm to the stock has become unacceptable. This risk is estimated as the probability of stock size (usually spawning stock biomass, SSB) falling below B_{lim} and thus, not achieving the objective. It is adjusted by considering stock sensitivity to fishing pressure (e.g. how productivity attributes and dynamics including individual growth, natural mortality and recruitment vary with SSB) and after applying management options corresponding to varying degrees of exposure to fishing pressure (e.g. varying effort and harvest levels). If the management aim is to avoid potentially serious or irreversible consequences to the stock, such as inability to recover to previously observed levels, the risk should be kept low (e.g. $< 5\%$), corresponding to a low risk tolerance or high risk aversion.

Sets of reference levels relating to potential biological, ecological and socio-economic consequences of varying severity are used in fisheries risk frameworks. These include biological and exposure limits intended to delimit the true domain of sustainability (e.g. B_{lim} and F_{lim} (ICES, 2021a), Canada's Lower Reference Point LRP (DFO, 2006), and the Overfishing Level OFL in the US (USDC, 2007)), as well as precautionary, early-warning or trigger reference points taking into account uncertainty in limit estimates (e.g. B_{pa} and F_{pa} (ICES, 2021a). Upper reference levels also may be defined. These are tied to management objectives reflecting long-term aspirational goals for the state of the stock and fishery, usually corresponding to economic targets and potential consequences arising from missed fishing opportunities (e.g. F_{MSY} and B_{MSY} (USDC, 2007; Ministry of Fisheries, 2008; ICES, 2021a) and Canada's Upper Stock Reference USR (DFO, 2006)). However, upper reference levels may also be defined as limits for biological and ecological consequences on other species or ecosystem components within a viability kernel/ecosystem approach (Cury et al., 2005).

Measurable reference levels are estimated using historical (sometimes truncated) time series of fish productivity dynamics that are assumed to reflect stock responses to long term average 'baseline' environmental conditions (Smith et al., 1993; Schijns and Pauly, 2021). In linking management objectives and acceptable risk levels, reference levels are used to delimit the safe operating space within which fishery managers can make decisions for maintaining both healthy and economically viable fisheries. The safe operating space and risk assessment are thereby conditional on one or more assumption(s) about the state of the environment.

There is an expectation that fisheries risks will be managed consistently among stocks within a jurisdiction and over time for individual stocks i.e. that risk equivalence is applied when formulating management options for fisheries (Fulton et al., 2016). The risk of stock productivity

impairment, for example, is expected to be maintained at an acceptable low risk level, regardless of differences in data availability, assessment methods, productivity dynamics, or external factors. However, deviations from baseline environmental conditions, including directional or trending environmental change, will contribute additional uncertainty that may not be captured in the conventional risk assessment. These deviations may take the system beyond the boundaries used to delineate the safe operating space for managing risks, thus no longer enabling consistent risk management under the changed environmental conditions.

4. Risk equivalence: consistency in practice

Risk equivalence is a fundamental concept in risk evaluation and management that has been largely overlooked to date. It permits a formal treatment of all sources and types of uncertainty in the assessment of the risk from human activities to natural resources and ecosystems, such that objectives-based management decisions remain within specified risk aversion, acceptability or tolerance, and comparable over time among resources and among management strategies and options.

Practical examples of the application of risk equivalence are found in fisheries management jurisdictions that have implemented data and assessment tiers and associated buffer systems to ensure comparable risks among data-rich and data-limited stocks (Smith et al., 2009; Punt et al., 2012; Dichmont et al., 2016; Fulton et al., 2016; ICES, 2017; Mildenerger et al., 2021). For stocks with comparable life histories, fisheries assessments based on fewer data are more uncertain than data-rich assessments. Low information stocks have high levels of unquantified uncertainty and may exhibit greater inaccuracies in estimates of variance, kurtosis or cumulative probability density functions. Thus, if results from low-information assessments are used to inform decision-making in the same way as results from high-information assessments, there is an increased risk that decisions would allow serious or irreversible consequences from fisheries in data-limited situations. If not accounted for, this difference in risk equates to different degrees of precaution (or risk tolerance) in the management of data-rich and data-limited stocks, with the management of data-limited stocks being less precautionary. To avoid this, precautionary buffers are applied to the advised property (usually but not necessarily the catch advice or harvest control rule) to reduce fishery exposure in data-limited situations. Precautionary buffers are adjustment factors applied to the exposure (or any advised property used to manage the degree of exposure to fishing pressure) to recalibrate the risk and maintain a comparable level of precaution among data tiers or stock categories. They can be expressed numerically as the ratio of the adjusted exposure to the status quo exposure (Fulton et al., 2016). Applied at a jurisdictional scale, buffers are intended to ensure that all fisheries are managed consistently, i.e. that all fish stocks have an intended and comparably low probability of biological harm, despite differences in assessment methods and data availability. The delineation of buffers can be subjective or partly quantitative. Those currently in use have been simulation tested and found to be appropriate for formulating risk equivalent advice for fisheries (Fulton et al., 2016; ICES, 2017; Mildenerger et al., 2021). Most importantly, even buffers largely based on expert opinion have been demonstrated to be an improvement over the assumption that additional, unquantified uncertainty does not exist (Punt et al., 2012).

The buffer approach can be extended to handle external factors that are beyond the control of the decision makers but likely to affect the risk associated with management decisions and thus, management outcomes. Like precautionary buffers, ecosystem or environmental conditioning factors (ECFs) can be developed to measure the change in exposure to human pressures required to maintain a constant risk in an increasingly variable or changing environment (Figure 2). Short term stochastic environmental variation contributes process uncertainty in the evaluation of resource or ecosystem status in response to human pressures. This uncertainty can be quantified in the risk assessment, providing there are sufficient data and mechanistic knowledge to be implemented in a dynamic model of resource or ecosystem response to both human activities and environmental drivers. Such models remain relatively rare and most are used in fisheries (King et al., 2015; Sagarese et al., 2015; Skern-Mauritzen et al., 2016; Marshall et al., 2019; Satterthwaite et al., 2020). Models including mechanistic relationships for environmental effects are complex and time-consuming to develop, and seldom robust over time or as circumstances change. As a result, most analytical assessments still rely on assumptions of stationarity or that environmental variation is purely stochastic within known bounds. These assumptions are invalidated where environmental conditions are shifting abruptly or trending progressively outside the long term means and variances used as the basis for specifying the reference levels and objectives in risk management frameworks. Such departures from baseline environmental conditions contribute additional uncertainty in the assessment that is rarely quantifiable within the timeframes available for providing management advice. This additional uncertainty can quickly alter the risks of biological, ecological and socio-economic consequences from management actions (or lack thereof). Accounting for such changes in risk is essential to inform management decisions intended to deliver outcomes that are consistent with objectives and anticipated consequences from human activity in a changing environment. Risk equivalence provides a foundation for consistency in the handling of uncertainty arising from the full range of environmental variation and change.

There are two pathways to achieving risk equivalence in a changing world: adjusting the degree of exposure to human pressures (conditioning of exposure) or adjusting the objectives, reference levels and risk tolerances used to manage the risk (conditioning of objectives) (Figure 1). The first concerns the probability of not achieving objectives within acceptable risk levels. The second concerns the delineation of the ‘safe operating space’ used for providing risk-based advice. These pathways are complementary and can be implemented sequentially to handle both the short-term (tactical) and longer-term (strategic) aspects of natural resources management in a changing environment (Box 1).

Conditioning of exposure involves exploring a range of management options that allow objectives to be achieved within specified risk tolerances, under alternative assumptions about the state of the environment and its potential or demonstrated effects on resource responses to human pressures. Risk equivalent management options will be an increase or decrease in some advice property used to manage the degree of exposure to human pressure (e.g. recommended effort or harvest levels in fisheries). The ratio of the advice adjusted for environmental change to the status quo advice assuming a constant or randomly varying environment is the ecosystem or environmental conditioning factor (ECF). ECFs measure the change in exposure to a human

pressure that is required to maintain a comparable risk. They can be investigated in risk analyses considering resource or ecosystem sensitivity to environmental variables and the magnitude of departures from baseline environmental conditions. Most importantly, ECFs can be operationalised across the data and process-knowledge continuum (Figure 3), providing a consistent metric for handling and communicating the incremental risks that can arise from environmental considerations either explicitly or not explicitly considered and quantified in the assessment. In data and process-knowledge rich situations, where environmental signals can be reliably incorporated within the analytical model used for providing advice, ECFs can be estimated by forecasting the dynamic responses of the resource or ecosystem to varying degrees of exposure to human pressure under observed and/or projected environmental change scenarios, using tools such as management strategy evaluation (MSE) (Plagányi et al., 2013) and/or models of intermediate complexity (MICE) (Plagányi et al., 2014). In circumstances where data are available but the mechanistic understanding for environmental effects remains limited, ECFs can be investigated and estimated in an empirical process that is parallel and external to the assessment (Duplisea et al., 2021). In situations where both data and process knowledge are limiting, ECFs can be approximated as relative risk scores using qualitative or semi-quantitative information and scoring methods, and applied *a posteriori* to condition the advice on external conditions not considered within the assessment e.g. (Dorn and Zador, 2020). This approach recognises that where there is evidence of departures from known or baseline environmental conditions, even qualitative ECFs based on expert knowledge can be an improvement over the assumption that the environment is stationary. The idea is to use existing data and knowledge to explore alternative assumptions about environmental status, and formulate risk equivalent options that explicitly consider these alternative assumptions in relation to the status quo (e.g. stationary, baseline average, or randomly varying environment within the range of existing

observations). ECFs can have positive or negative values, indicating potential for increases in resource use when conditions are favourable, or decreases when conditions are unfavourable.

Over time, recurring environmental deviations from baseline conditions or persistent directional change will alter resource or ecosystem sensitivity and exposure to human pressures, human practice, and the meaning of reference levels and objectives. Conditioning the objectives and reference levels on a new environmental norm is then required to maintain risk equivalency. This can range from updating the biological limits for sustainability to ensure the advice remains precautionary, to reviewing and adjusting an appropriate combination of management objectives, reference levels, and risk tolerances, to reflect new biological, ecological and/or socio-economic realities.

Box 1. Risk equivalence driving tactical decisions vs risk equivalence guiding when and how to alter risk management frameworks

In objectives-based risk frameworks, there are two pathways to formulating risk equivalent options for the management of human activities impacting marine resources and ecosystems:

The first consists of **adjusting the degree of exposure to a human pressure** considering varying levels of quantifiable and unquantifiable uncertainty in the assessment. Unquantified uncertainty can arise from differences in resource sensitivity and the evidence basis for assessment (e.g. data availability and assessment methods), and external factors not explicitly considered in risk analyses, namely socio-economics and environmental and ecosystem drivers. Conditioning of exposure or any advice property used to manage the degree of exposure to human pressure, will involve risk adjustment factors expressing the change in exposure required to maintain a comparable risk. Risk equivalent options achieved by conditioning the exposure allow for the measurable and potential consequences from human pressures to remain within acceptable risk levels, consistent with reference levels and objectives, over the lifespan of the advice.

The second pathway consists of **adjusting the objectives** themselves considering persistent, directional change in external factors (e.g. socio-economics or environmental and ecosystem drivers) affecting the definition of the potential consequences from human pressures on a resource or ecosystem. Conditioning the reference levels, objectives and risk tolerance on a new reality, allows maintaining the safe operating space for managing risks consistent with the anticipated consequences from human activity and desired outcomes from management decisions.

Together, conditioning the degree of exposure to human pressure and conditioning the objectives on alternative assumptions about the state of the environment, provide complementary and incremental mechanisms to account for the short-term and longer-term impacts of a changing environment in scientific advice for the management of human activities.

Conditioning the objectives will ensure that management decisions continue to deliver outcomes consistent with expectations i.e. allow avoiding comparable negative/unwanted consequences and achieving comparable long-term aspirational goals for the resource, ecosystem and human activity sector. We note that in complex, multi-objectives management frameworks, new environmental conditions may require different prioritisations and trade-offs among objectives. Seeking risk equivalence under new environmental realities by adjusting the safe operating space used to inform risk-based decisions in the past, allows discussions not just of whether resources now need to be managed at a higher or lower status given expanded or reduced opportunities for human activities, but whether the risks to the resource, ecosystem and communities of users have

changed. Exploring risk equivalence in this way may allow a much more constructive public policy dialogue.

A risk equivalence approach accounting for environmental considerations is applicable to all scientific advice aimed at assessing potential impacts from human activities and evaluating the risks associated with different management strategies and options. Conditioning of advice on environmental status can relax the short-term need to assume a greater mechanistic understanding of environmental effects than actually is known, instead focusing on the uncertainty and incremental risks contributed by a changing environment, their magnitude and direction, temporal patterns, and directionality. This can facilitate timely delivery of robust management advice in the absence of complete knowledge and understanding. A risk equivalent approach meets the call for more flexible and adaptable management and policy frameworks in a changing world (Schindler and Hilborn, 2015).

Pathways to risk equivalence are complementary and can be implemented sequentially to enable consistent risk management. Conditioning of exposure on environmental status requires routine monitoring and consideration of environmental conditions likely affecting the response of resources or ecosystems to human pressure. This can improve the detection of repeated environmental deviations from background conditions and incremental changes in risk. As such, repeated conditioning of exposure can serve as a trigger for conditioning the objectives: it can inform the definition of thresholds (e.g. maximal recurrence or amplitude of environmental deviations into improbable risk space, or maximal incremental change in risk), beyond which a review and update of the reference levels and objectives is necessary for management decisions to remain risk equivalent. Alternatively, the point at which no level of exposure to human pressure can achieve one or more objectives within the acceptable risk level, can be the point at which conditioning the objectives on a new reality is required to continue formulating robust advice for feasible actions. In recurring advice, the exploration and provision of risk equivalent management options can be iterative and adaptive, allowing it to consistently operate within acceptable risk levels whilst incrementally improving the evidence basis for environmental effects for the management of human activities (Figure 4).

5. Risk equivalent advice for fisheries in a changing environment

Fisheries have long sought to achieve risk equivalence between current and future stock status by regulating the exposure to fishing pressure with the intent of maintaining risks within acceptable levels. This is operationalised in advice that is updated annually or on short multiyear cycles, by adjusting the advised catch (or some other component of fishery exposure that is subject to management actions), such that biological or fishery reference points are met within a specified risk tolerance. However, this strategy *de facto* treats the uncertainties quantified in the analytical (or other) assessment as fully capturing the risks. Most conventional assessment methods do not account for environmental departures from reference or baseline conditions, even though such departures will often affect the dynamic responses of fish stocks to fishing pressure, through changes in fishing practice, spatial distribution, or in the timing of seasonal or ontogenetic migrations (fishery exposure) and/or changes in stock productivity. Such changes are

increasingly common (McFarlane et al., 2000; Pecl et al., 2017; Cheung, 2018; Schickele et al., 2021). However, most stock assessments still lump any changes in stock status that have resulted from productivity responses to environmental conditions with overall “uncertainty”, without taking into account the change in risks of fishery management decisions that may result from operating outside the domain of known environmental conditions.

A changing climate requires predictions of what can happen when fishing takes place outside the distribution of existing observations. This entails the development of robust mechanistic understanding of the complex relationships among fish stocks, fishing pressures and environmental factors, and the use of heavy-tailed probability distributions (Anderson et al., 2017). Stock assessment models using random processes or time-varying parameters can be used to provide fishery options that consider changing stock productivity (Thorson and Minto, 2015; Miller et al., 2016; Holt and Michielsens, 2020; Stock and Miller, 2021). These models are relatively simple to develop and implement because they avoid the need to specify a mechanistic relationship for the effects of one or more environmental variables on stock productivity. However, projecting such models to investigate future plausible environmental status will typically result in a variance window so large as to make all future outcomes plausible (Duplisea et al., 2021). Hence, there is a sweet spot in defining model complexity in the face of uncertainty (Collie et al., 2016). Regular updating of fishery objectives and associated reference levels (e.g. F_{MSY} and B_{lim}) can be used to keep fisheries management decisions attuned to current environmental status and short-term variation reflected in stock productivity characteristics examined through, for example, the benchmarking process in ICES (ICES, 2013). However, such a strategy requires both an analytical model that reliably links stock productivity to environmental conditions, and an efficient consultation and policy decision process for altering objectives and reference points. Currently neither are readily feasible nor widely applicable because the majority of fishery resources remain data-limited and do not have a robust analytical assessment (FAO, 2020). Few assessment models treat environmental influences on stocks and fisheries dynamically, and consultation processes can be lengthy and cumbersome when dealing with areas of high knowledge uncertainty.

The formulation of risk equivalent fisheries options offers a practical, broadly applicable, and readily operational approach. Manageable aspects of fishery exposure can be readily conditioned on environment status in a process that is transparent, adaptive and iterative, allowing for timely delivery of reliable advice consistent with fishery objectives and risk tolerances. Existing tools such as random process models can be used to develop ECFs, for example as the ratio of the advised property (e.g. recommended harvest level) in a scenario fitted with time-varying productivity, to the same property in a scenario fitted assuming a constant productivity. This would enable investigation and communication of the change in risk that can be expected under alternative assumptions for environment effects, although not solving the problem of inflated variance in mid- to long-term projections. A multi-model approach focusing on ensemble means and variance within and between models may be used to explore risk equivalent management strategies under climate forcing (Hollowed et al., 2020). Another alternative is to estimate ECF values and explore risk equivalent options in an empirical process that is parallel and external to the stock assessment. Duplisea et al. (2021) used an empirical model of stock productivity

dependence on an environmental variable to investigate the incremental change in risk that can be expected under various environmental change scenarios, and the adjustments to fishery exposure (ECFs) that would be required to maintain a constant risk of not achieving a fishery objective. This approach has the advantage over the use of random processes to enable exploration of a range of falsifiable hypotheses for environmental effects onto fish stocks. Similar empirical models could be developed to explore the ECFs required to maintain a constant risk when environmental change alters the spatial distribution of a fish stock and thus, its availability to the fishing gear. In data-limited fisheries, existing data and information on stock sensitivity and exposure to changes in environmental variables can be used to approximate an ECF as a relative risk score, which is then applied to the status quo advice or management strategy (e.g. previous years catch or harvest control rule) to provide a risk equivalent option (see example in Supplementary Material).

The ECFs offer a common metric that can be derived for all stocks and any manageable aspect of fishery exposure, including harvest or effort levels, seasonal closures or openings, fishing gear configurations, and fleet allocations. The process of estimating or approximating ECFs can enable existing knowledge and information to be engaged in the definition of harvest strategies and productivity scenarios consistent with acceptable risk levels, as proposed by (King and McFarlane, 2006) and (King et al., 2015). An important distinction between an ECF and precautionary buffer used to achieve risk equivalence among stocks within a jurisdiction, is that ECFs can both increase and decrease fishery exposure, thus increasing fishing opportunities when environmental conditions are good for fish production, and reducing them when conditions are poor. In both cases, the ECFs will serve to maintain a consistently high probability of achieving economic targets, and a consistently low biological risk of depleting fish stocks. ECFs may similarly accommodate other types of targets that may be adopted in the future, such as employment or livelihoods supported targets. Systematic conditioning of fisheries advice to account for the uncertainty arising from environmental variation and change (whether quantified, externally quantified, or yet unquantified), can ensure the advice remains robust, defensible and reproducible in a changing environment.

Practical examples of the application of risk equivalence to account for environmental change in fisheries advice have emerged in recent years. These are used to handle environmental variation that is not quantified (or fully quantified) within the assessment model, but likely to affect the risk associated with management decisions over the lifespan of the advice. Plaganyi et al. (2013) combined a qualitative risk assessment using expert knowledge with a spatial management strategy evaluation (MSE) tool to evaluate the performance of alternative harvest strategies in meeting objectives under posited climate change relative to equivalent no-fishing, no-climate change scenarios. The MSE simulations served to quantify and communicate anticipated climate change impacts on fisheries production as incremental changes in risk. Other recent examples include the risk table framework implemented in the USA to adjust fisheries harvest recommendations for concerns external to the stock assessment (Dorn and Zador, 2020), and the F_{eco} approach proposed for including ecosystem considerations in fisheries management advice in the Irish Sea (Bentley et al., 2021; Howell et al., 2021). The risk table framework is an extension of the existing buffer system. It uses a scoring approach to evaluate whether

environmental factors not explicitly considered in the stock assessment would justify a further reduction of the acceptable biological catch (ABC) to account for additional uncertainty and risk (Dorn and Zador, 2020). This approach is consistent with approximating ECFs in data and process knowledge limited space, making use of the best available scientific understanding and information to formulate risk equivalent fishery options (Figure 3). However, the risk table framework has only been applied unidirectionally, to ensure that the advice remains precautionary when environmental conditions are unfavourable. The Feco approach, by contrast, relies on the status of a relevant ecosystem indicator in relation to its long-term range to condition the advice in both directions, accounting for favourable as well as unfavourable conditions (Bentley et al., 2021). The Feco is set in the lower F_{msy} range when conditions are poor and in the upper range when conditions are good. The F_{msy} range is estimated by the stock assessment model, while a whole-ecosystem model (EwE) is used to identify an ecosystem indicator relevant to the stock trajectory in a process that is parallel to the stock assessment (Howell et al., 2021). This approach is consistent with exploring model-based ECFs using external forecasting (in this case in empirical, multivariate space) to provide a presumptively risk equivalent option (Feco) that takes into account ecosystem information (Figure 3). Bentley et al. (2021) also used retrospective simulations to demonstrate that adjusting fisheries advice to account for ecosystem variables (by applying Feco), could have supported more productive cod and whiting stocks in the Irish Sea in comparison with status quo advice (median F_{msy}). These results suggest that routine conditioning of fisheries advice on environmental variation may hold both short and longer-term benefits for fisheries management. However these approaches generally treat the fisheries objectives as being fixed in time.

Conditioning of fishery objectives to maintain risk equivalence is required when the available evidence indicates that environmental conditions affecting the stock and its response to the fishery have changed sufficiently that the data used to set the initial objectives, reference levels and risk tolerances (i.e. to delimit the safe operating space for managing risks), no longer reflect the same biological, ecological or socio-economic realities. Climate change will see fishery management systems striving to achieve static objectives which are no longer attainable, including exposure (fishing mortality-based) reference points that may allow excessive removals or be overly restrictive as environmental changes make stocks less or more productive; and stock status (biomass-based) reference points that could be either not risk averse enough (in cases where a larger biomass is needed to produce adequate eggs and larvae) or too restrictive (if the suitable habitat has been reduced so overall carrying capacity is now lower and can be saturated by a smaller spawner population). Correspondingly, substantial effort is currently being directed at developing methods that can better account for biological and environmental realism in fisheries reference points estimation. This includes recalculating reference points values with more recent data, estimation of time-varying or ‘dynamic’ reference points, and other analytical methods for propagating model, estimation, and process error uncertainties in reference points estimation (O’Leary et al., 2020). Evidence of a stable and lasting change in the environment is difficult to assemble and establish. Using transient reference points in a system in transition may not result in consistent or effective risk management (Travers-Trolet et al., 2020), but may be better suited to simulation testing management strategies (Berger, 2019). Amending objectives

too often or without clear rationales for actual biological, ecological or socio-economic changes, undermines both the effectiveness and credibility of entire objectives-based fisheries management plans. When management objectives do change, they must reflect decisions to maintain all dimensions of fishing practice (biological, ecological and socio-economic) in line with the potential consequences from fishing activity and long-term sustainability goals, and not merely a wish to either avoid substantial harvest reductions (which will result in chasing stocks decline) or maintain a specific stock biomass in a changing ecosystem. Routine conditioning of fishery exposure and provision of risk equivalent advice that account for environmental variation and change, can assist with determining when conditioning the objectives and reference points is necessary, either because the objectives are no longer achievable or because the search for risk equivalence has indicated recurring departures into improbable (and possibly unacceptable) risk spaces.

6. Risk equivalent advice beyond fisheries management

The management of all human activities that directly or indirectly exert pressures on marine resources and ecosystems, involves dealing with uncertainty in resource and impact evaluation (whether quantifiable or not) and increasingly includes objectives, which are either proposed or rooted in policy (Table 1). Although these objectives may not be expressed explicitly in some governance settings, advisory and decision processes should apply consistent, objectives-based risk management in accordance with jurisdictional policy. This requires specification of not only the objectives but also the biological, ecological and socio-economic reference levels associated with the objectives and their acceptable risk level. As objectives-based management frameworks mature, they make risk equivalence approaches appropriate and applicable for effectively managing human activities in a changing ocean. We illustrate this in two hypothetical examples below: one for management of essential fish habitat, the other for marine protected areas. In all cases, a risk equivalent approach will involve:

- 1) Specifying objectives, reference levels, and acceptable risk tolerances i.e. delineating a safe operating space for assessing the performance of alternative management options in meeting objectives and formulating robust and consistent management decisions under uncertainty.
- 2) Mapping all relevant sources and types of uncertainty (quantifiable and unquantifiable) in the assessment of human pressure effects on ecosystem components
- 3) Conditioning of exposure: formulating risk equivalent management options that enable objectives to be met at the acceptable risk level, either by a) estimating and propagating quantifiable uncertainty linked to environmental variables within the assessment; b) quantifying the same uncertainty in an empirical process parallel to the assessment; or c) approximating the relative change in risk that can arise from environmental variables considering resource sensitivity and exposure to such variables (i.e. suspected but as yet unquantified uncertainty).
- 4) Conditioning of objectives: Reviewing and potentially updating the reference levels and objectives in the context of persistent environmental change, to enable continued formulation of robust management decisions that are consistent with the anticipated

consequences from human pressures and desired management outcomes under an evolving reality.

6.1 Risk equivalence in fish habitat management

Human impacts on fish habitat are typically assessed on a project by project basis and tools such as habitat compensation may be offered as means to offset the risk of exceeding levels of allowable harm. Although not defined, provisions for habitat compensation imply that the risk tolerance associated with allowable harm is not zero. For example, we may consider a projected bridge construction that will permanently alter the flow on a salmon river. There is a limit reference level for the occurrence of low river flow below which harmful impacts to salmon can be expected, and a management objective to prevent damage to salmon habitat. The limit reference was estimated in relation to long-term average environmental variation. The risk associated with constructing the bridge can be evaluated in relation to this reference level, considering intrinsic properties of the river system (sensitivity) and bridge design aspects and proposed compensation measures (exposure factors). However, climate change leading to increasingly variable amounts of local precipitations may alter this risk over time. Unless this is accounted for in the advice, the decision leading to infrastructure development may not be accountable over the next decade(s), i.e. it might allow irreparable harm to the salmon population. Conditioning of exposure to formulate risk equivalent options that account for potential climate change impacts would consist of identifying additional compensation measures and design options to alleviate a future increase in risk. Conditioning of objectives would consist of revisiting and perhaps modifying the reference level to ensure it remains relevant to the river system, salmon population and anticipated impacts from infrastructure development under a new environmental reality.

6.2 Risk equivalence in Marine Protected Areas (MPAs)

MPAs are management tools aimed at achieving a number of potentially competing conservation objectives, educational and awareness-raising objectives, and local socio-economic objectives. Some of these objectives are achieved through granting access to various human activities (e.g. ecotourism, resource extraction and shipping) and managing the degree of exposure and potential impacts from such activities. Consistent risk management in this context requires consideration of the hierarchy of objectives (whether implicit or explicit) and their respective risk tolerances. For example, consider an MPA with a conservation objective of protecting a seabird colony, using a target of maintaining a minimum number of breeding pairs with a high (e.g. 90%) probability. A key ecosystem consideration for the colony is the dynamics of a forage fish population which serves as a main food supply (keystone prey) to the seabirds. If the productivity of the forage fish population declines in response to warming surface waters, its exposure to a human pressure (e.g. fishing activity) could be curtailed by conditioning of fishery exposure through spatial or seasonal closures or effort restrictions. This would provide risk equivalent options aimed at preventing a reduction in the forage fish population and prey availability to seabirds, and thus maintaining a consistently low risk of failing to achieve the breeding pair target at the specified risk tolerance (<10% risk) when ecosystem conditions are

potentially unfavorable to the seabird colony. However, under sustained warming, there will be a point at which no further reduction in exposure to fishing or other pressures resulting from human activity can prevent a decline in the forage fish population and allow the seabird breeding pair objective to be achieved locally, either because the total number of breeding pairs has decreased to a lower level (population-level consequence), or because some breeding pairs have permanently shifted their distribution beyond the MPA boundaries, to areas where prey availability and quality remain favorable (spatial consequence). At this point, conditioning the objective could involve revising the target number of local breeding pairs or, if protecting the seabird colony is the primary conservation objective for the MPA, reassessing and potentially adjusting or displacing the MPA boundaries. The latter points to the need for a clear hierarchy of objectives, as this will ultimately determine pathways for achieving risk equivalence in MPA management.

7. Conclusion

Approaches for handling environmental variation and change in marine resources management have been generally focused on the development of analytical tools and methods allowing to quantify and propagate uncertainty. This is often done without a clear understanding of the mechanistic relationships leading to that uncertainty, i.e. without specifying or exploring the mechanisms linking environmental drivers, human pressures and resulting resource or ecosystem states. In this context, limits of applicability of the analytical methods remain unknown. While complex models with random effects can be useful in propagating error, they often result in inflated parameter variance and are mostly applicable in data-rich circumstances encountered in only a few, high economic value, commercial fish species. The majority of marine resources and ecosystems affected by human activity remain data-limited or data-rich but information poor (DRIP) (Wilding et al., 2017), thus requiring alternative methods to take into account how environmental change may affect their responses to human pressures over space and time.

A consistent approach that builds on existing practice is needed to handle the increasing uncertainty (quantifiable or not) that is contributed by a changing environment in marine resources and ecosystems management, regardless of the state of knowledge and data developments.

Risk equivalence provides a powerful approach for operationalising available data and information in timely and systematic conditioning of management advice on demonstrated, potential or projected environmental change. The implementation of risk equivalence consists of adapting existing practice in order to frame environmental considerations within objectives-based risk frameworks; systematically explore and formulate risk equivalent management options accounting for environmental variation and change; and formalise strategic reviews and updating of entire risk management frameworks under new environmental realities. Risk equivalent advice can guide consistent, robust and accountable management decision-making in a changing world, even in the absence of perfect knowledge. It is applicable to all human activity sectors and can be extended to handle variation and change in economics and governance aspects of management systems, as human societies adapt to change. Concepts of risk and risk

equivalence provide a common language and understanding for consistent communication of environmental and other considerations in management advice as incremental changes in risk.

8. Authors Contributions

MJR led the writing of the manuscript, with contributions and edits from DD, JR and KH. All authors were involved in the development of research and ideas brought forward in the manuscript.

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11. Tables

Table 1. Examples of human activities, selected manageable pressures, potential biological or ecological consequences from such pressures, and examples of management objectives, as would be applicable in objectives-based risk management frameworks. Note that concurring socio-economic consequences and objectives for each of these activities are not presented here. See Annex B in (ICES, 2021b) for pressures definition.

Human activity	Manageable pressure	Potential consequences	Management objectives
Coastal infrastructure development	Abrasion and smothering	Fish habitat alteration and destruction	Avoid and prevent harmful impacts to fish habitat through compensation measures (Fisheries and Oceans Canada, 2019)
Land-based agriculture	Nutrient and organic enrichment	Coastal eutrophication	Clear water, concentrations of nutrients close to natural levels, natural levels of algal blooms, natural oxygen levels (HELCOM, 2007)
Tourism and recreation	Noise	Disturbance of protected or endangered marine mammals	Use of sanctuaries to reduce or eliminate physical and acoustic disturbance (Williams et al., 2014)
Offshore windfarms	Substrate loss and abrasion	Habitat alteration, fragmentation and destruction	Maintaining ecosystem-service-provision by benthos (e.g. sediment-based nutrient processing) (Wilding et al., 2017)
Shipping	Marine litter	Mortality of protected or endangered marine life (e.g. sea turtles)	Prevent and reduce to the minimum marine litter pollution (UNEP, 2013)

12. Figures Legends

Figure 1. A conceptual framework for objectives-based assessment and management of the risks posed by human activities to natural systems, with explicit consideration and application of risk equivalence. Management objectives are identified in relation to potential consequences from human-induced pressures. The risk assessment involves risks identification (pressures and potential consequences definition), risk analysis (estimation of the probability that pressures lead to consequences considering quantifiable scientific uncertainty), risk evaluation (exploration of alternative management options in relation to acceptable risk levels and potential trade-offs), and the explicit investigation and accounting for unquantified or unquantifiable sources of uncertainty. There are two pathways to formulating risk equivalent management options (red boxes and arrows): conditioning the exposure and conditioning the reference levels and objectives. Note that a single human activity will usually generate multiple pressures, each with potential biological, ecological and socio-economic consequences for various ecosystem components, requiring separate and complementary or cumulative objectives-based risk assessments and management.

Figure 2. Illustration of risk equivalence in resource status evaluation in response to a human pressure (modified from Fay et al. 2013). The red dashed line is a limit reference level and objective for resource status. Given the same degree of exposure to the pressure, the risk of resource status being below the limit reference level increases with decreasing data availability and quality or an increasingly variable environment away from baseline conditions (from left to right). Precautionary buffers or environmental conditioning factors (ECFs), expressing the change in exposure required to maintain a comparable risk, can be developed and applied to deliver risk equivalent outcomes i.e. the grey dots corresponding to resource status estimates having the same probability of not meeting the objective, despite differences in the evidence base for assessment and environmental departures from baseline conditions. The adjusted exposure (not showed) is the risk equivalent management option. The numerical value of the buffer or ECF is the ratio of the adjusted to status quo exposure ignoring additional uncertainty in the assessment (or assuming it has a null value).

Figure 3. Degree of quantified uncertainty in ECFs as a function of the evidence base for environmental effects. ECFs express the change in exposure to human pressure required to maintain a constant risk in a changing environment. Where data and mechanistic knowledge are limited, ECFs can be approximated as relative risk scores using qualitative and experiential information (e.g. expert knowledge) and empirical evidence such as results from laboratory studies or information inferred from other, relevant studies. Where there is sufficient empirical or mechanistic evidence, ECFs can be derived empirically or analytically from model outputs as the ratio of management options allowing to meet objectives in model scenarios with environmental change, to status quo management option assuming a constant of randomly varying environment within known bounds. In the absence of mechanistic understanding, empirical models can be used to explore risk equivalent management options and ECFs. Full quantification of uncertainty is only achievable where there is mechanistic evidence for both human pressure and environmental effects implemented in an analytical assessment model.

Figure 4. A risk equivalence approach accounting for the influence of environmental variation and change in scientific advice for the management of human activities. Conditioning the degree of exposure to human pressures on environmental status, requires to monitor and prioritise environmental indicators most relevant to the resource or ecosystem and human activity under assessment. Depending on the evidence basis for environmental effects, ECFs expressing the change in exposure required to maintain a constant risk, will be used to formulate risk equivalent management options accounting for yet unquantified, partly quantified or fully quantified and propagated uncertainty linked to a changing environment. In recurring advice, routine conditioning of exposure can assist with incrementally building the knowledge basis and mechanistic understanding required to fully quantify environmental effects on management advice. It can also assist with detecting directional change leading to a new environmental reality requiring to review and update the management objectives, reference levels, and risk tolerances (conditioning of objectives) for advice to remain consistent with the potential consequences from management decisions and long-term aspirational goals for the state of the resource, ecosystem and human activity sector. Risk equivalent advice enables consistent handling and communicating of the uncertainty arising from environmental variation and change.

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1002