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Evaluating sustainability of fisheries bycatch mortality for marine megafauna: a review of conservation reference points for data-limited populations

THEMATIC SECTION
Politics, Science and Policy of Reference Points for Resource Management

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SUMMARY

Fisheries bycatch threatens populations of marine megafauna such as marine mammals, turtles, seabirds, sharks and rays, but fisheries impacts on non-target populations are often difficult to assess due to factors such as data limitation, poorly defined management objectives and lack of quantitative bycatch reduction targets. Limit reference points can be used to address these issues and thereby facilitate adoption and implementation of mitigation efforts. Reference points based on catch data and life history analysis can identify sustainability limits for bycatch with respect to defined population goals even when data are quite limited. This can expedite assessments for large numbers of species and enable prioritization of management actions based on mitigation urgency and efficacy. This paper reviews limit reference point estimators for marine megafauna bycatch, with the aim of highlighting their utility in fisheries management and promoting best practices for use. Different estimators share a common basic structure that can be flexibly applied to different contexts depending on species life history and available data types. Information on demographic vital rates and abundance is required; of these, abundance is the most data-dependent and thus most limiting factor for application. There are different approaches for handling management risk stemming from uncertainty in reference point and bycatch estimates. Risk tolerance can be incorporated explicitly into the reference point estimator itself, or probability distributions may be used to describe uncertainties in bycatch and reference point estimates, and risk tolerance may guide how those are factored into the management process. Either approach requires simulation-based performance testing such as management strategy evaluation to ensure that management objectives can be achieved. Factoring potential sources of bias into such evaluations is critical. This paper reviews the technical, operational, and political challenges to widespread application of reference points for management of marine megafauna bycatch, while emphasizing the importance of developing assessment frameworks that can facilitate sustainable fishing practices.

Keywords: bycatch, management strategy evaluation, marine megafauna, reference points, risk, uncertainty

INTRODUCTION

Fisheries bycatch mortality threatens populations of many marine vertebrate taxa worldwide, including marine

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megafauna such as sea turtles, birds, mammals and elasmobranchs (NRC [National Research Council] 1990; Stevens *et al.* 2000; Tasker *et al.* 2000; Lewison *et al.* 2004; Read 2008; Wallace *et al.* 2011). Mitigation efforts have reduced some threats (Hall *et al.* 2000; Werner *et al.* 2006; Cox *et al.* 2007; Moore *et al.* 2009; Dunn *et al.* 2011; Gilman 2011), but mitigation can be expensive (Bisack & Sutinen 2006; Huang & Leung 2007; Gallaway *et al.* 2008) and difficult to implement or enforce (Rodríguez-Quiroz *et al.* 2010; Gilman 2011). As a result, and despite the precautionary management paradigm and bycatch minimization goal agreed to in the Food and Agriculture Organization (FAO) Code of Conduct for Responsible Fisheries (FAO 1995), fishing industry leaders and policy-makers may be reluctant to mandate costly mitigation measures without evidence that fisheries bycatch exceeds safe levels and may be preventing population recovery, contributing to population declines, or substantially altering marine ecosystems (Gilman 2011).

Quantifying the impacts of fisheries on non-target species is thus an important step in building the necessary stakeholder support and political will for changing fishing practices. For example, data analyses that clearly demonstrated the unsustainability of seabird bycatch levels in Atlantic longline fisheries (Tuck *et al.* 2011) were instrumental in advancing recent bycatch mitigation measures such as night setting, line weighting and use of bird-scaring lines, within high seas fisheries managed by the International Commission for the Conservation of Atlantic Tunas (ICCAT [International Commission for the Conservation of Atlantic Tuna] 2011). Quantifying bycatch impacts is also necessary to inform the level of bycatch reduction needed to satisfy management goals. Simply reducing incidental mortality to relatively low levels may not be sufficient, as in the case of rare and highly vulnerable species or when reduced bycatch may simply be the result of declines in population abundance (for example Jaramillo- Legorreta *et al.* 2007; Tuck 2011).

Given the low amount of information typically available for non-target populations, determining the level of bycatch that avoids negative population impacts is challenging. However, several approaches to estimate reference points for data-limited populations can be used to assess sustainability of fisheries bycatch levels relative to defined population goals. Reference points are a fundamental component of sustainable management of target species (Caddy & Mahon 1995; Quinn & Deriso 1999; Garcia & Staples 2000; Garcia & Cochrane 2005; Reuter *et al.* 2010), and the FAO (2010) has called on States and Regional Fishery Management Organizations (RFMOs) to consider establishing mortality limits for bycatch species using a precautionary approach when bycatch is unavoidable. In this review, we focus specifically on limit reference points (in contrast to target reference points), because in a bycatch context we are concerned with ensuring populations do not fall below some minimum acceptable level, rather than intentionally exploiting them to a target level to optimize economic benefit.

Methods to estimate reference points for data-poor populations have been developed for several vertebrate groups of conservation concern, but their application to inform management of bycatch is uncommon. To facilitate wider use of these tools and maximize their effectiveness in fisheries management contexts, a synthesis of available methods and recommendations for application is needed. We review a set of complementary approaches for estimating sustainable impact levels (namely reference point estimators) for marine vertebrate taxa, highlighting their similarities and differences in data requirements and assumptions. We compare different approaches for considering risk due to uncertainty in indicator and reference point estimates (probability of incorrectly inferring that bycatch levels are sufficiently low with respect to management goals). We emphasize the role of simulation-based management strategy evaluation (MSE; Smith 1994) to assess the effectiveness of reference point estimators and optimize their performance in the face of limited data and high uncertainty in population parameters. We highlight the value of applying these methods within broader risk assessment frameworks to facilitate assessment of large numbers of species. Finally, we discuss challenges facing implementation of reference points as tools to guide bycatch management and offer suggestions to address these. Through this review, we aim to highlight the value of using reference points to inform management of bycatch impacts on marine megafauna, elucidate their construction and estimation, and provide guidance for their effective application and implementation across diverse fisheries contexts.

Reference point estimators for bycatch mortality

Relationship between reference points for population status and fisheries impacts

Of the many examples of reference points in fisheries (for example Restrepo *et al.* 1998; Quinn & Deriso 1999; Hall & Mainprize 2004; Zhou *et al.* 2012*b*), we differentiate two broad classes: (1) those relating to the status of the population itself (for example a benchmark level for population abundance), which we refer to as population reference points; and (2) those relating to the level of anthropogenic impact occurring to the population (for example a limit to bycatch mortality), which we refer to as impact reference points. Because information about population status is lacking for many of the bycatch species discussed in this review, we focus primarily on estimating impact reference points, against which to compare a measurable and manageable indicator such as bycatch mortality. However, the two classes of reference points are inextricably linked. The impact reference point represents the level of mortality that would theoretically cause a population to eventually equilibrate to the associated population reference point level (Fig. 1; also see fig. 3 in Zhou *et al.* 2011). Thus, management based on reference points requires both types to be defined, even though it may only be the impact reference point that is used in the management process. For example, under the US Marine Mammal Protection Act

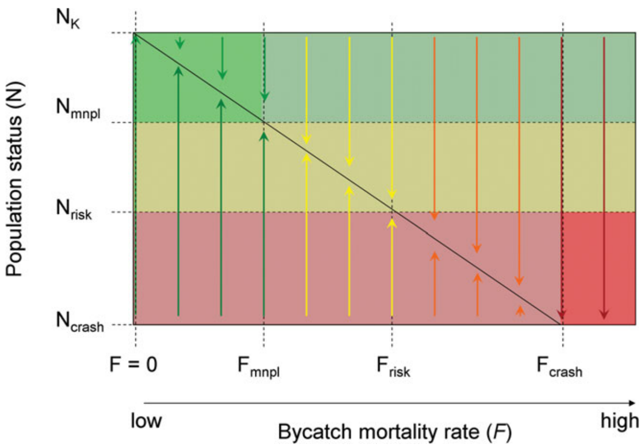

Figure 1 Relationship between impact (*x*-axis) and population reference points (*y*-axis). Subscripts: K = carrying capacity; MNPL = maximum net productivity level; crash = highly critical level (population abundance N is small but > 0) associated with irreversible damage to the population or ecosystem, or a high risk of eventual extinction; risk = early warning level between a limit reference point such as MNPL and a critical limit point such as crash. Vertical arrows indicate direction (net force) of change in population abundance (N) given F (fishery mortality) and initial N. Diagonal represents equilibria between F and N. Populations in the upper left box (bright green) are of low concern. Populations in the lower right box (bright red) are in dire circumstances. For many populations, population status is unknown, so management is limited to information about F relative to various F_{lim}. Vertical arrow colours depict relative concern level (green = low; red = urgent) associated with the level of F.

(MMPA), anthropogenic mortality limits to marine mammals are represented by the 'potential biological removal' (PBR), and management actions are based on whether annual human-caused mortality exceeds this impact reference point. PBR is linked mathematically to a population reference point called the maximum net productivity level (N_{MNPL}), which is analogous to a maximum sustainable yield biomass or abundance level (B_{MSY} or N_{MSY}), but direct evaluation of marine mammal population levels with respect to MNPL is usually not feasible and is rarely attempted (Taylor *et al.* 2000). Rather, it is assumed that if bycatch mortality remains below PBR, then the goal of maintaining populations above N_{MNPL} will be met or eventually achieved.

Ingredients of impact reference point estimators

Understanding the general architecture of impact reference points for total bycatch can be useful for developing context-specific estimators. Most estimators for impact reference points consist of two essential ingredients. The first is an estimate of the human-added mortality rate that the population can sustain without being driven below the desired population reference point level (Fig. 1). This mortality rate is itself an impact reference point, which we generically call F_{lim}, determined by the life history of the species (we use 'lim' as a generic subscript for a limit reference point; a specific example would be F_{MNPL}, the level of fisheries mortality that maintains a population above N_{MNPL}). The second ingredient is an estimate of population size (for example abundance or biomass), so that F_{lim} may be scaled to an absolute removal level. Differences among existing estimators for the mortality limit largely reflect how the input quantities are derived, which depends on available data types, life histories and population-dynamics assumptions for the population in question, but all the estimators can ultimately be expressed as variations of each other (Table 1).

Mortality rate. F_{lim} is rarely known or precisely estimable. Proxies or default values are typically based on life-history theory, expert judgment, information from conspecifics or congeners, or empirical meta-analyses. This is possible because, for long-lived late-maturing species, life history constrains the possible values of F_{lim} to a relatively narrow range once some vital rates are known (see Reilly & Barlow 1986; Forrest & Walters 2009; Dillingham & Fletcher 2011). Underlying the input for F_{lim} are two types of information: the density-dependent population growth function and the maximum potential population growth rate. For example, the PBR estimator for marine mammals implicitly derives F_{MNPL} from an assumption of a simple logistic population growth model (namely $\theta = 1$ in a theta-logistic equation, implying linear decline in per caput population growth rate as abundance increases) and default estimates for maximum productivity (R_{max}) of 0.04 for cetaceans and 0.12 for pinnipeds (Wade 1998). For seabirds, Dillingham and Fletcher (2011) also assumed simple logistic population growth, but calculated R_{max} from estimates of adult survival and age of first reproduction based on allometric methods (Niel & Lebreton 2005; Dillingham 2010). Curtis and Moore (2013) used an age-structured model with logistic-type density-dependent response in vital rates for sea turtles. The true shape of the density-dependent function for all these taxa is typically unknown, but it may be assumed based on life history arguments that most of the density-dependent response occurs relatively close to carrying capacity for long-lived late-maturing species such as those considered here ($\theta > 1$ in a theta-logistic model; the decline in per caput population growth rate with increasing abundance is a convex function viewed from above) (Fowler 1981, 1988; Taylor & DeMaster 1993). Assuming a simple logistic response for these species should result in precautionary estimates for bycatch limit reference points compared to a model that uses a skewed function (Wade 1998; Curtis & Moore 2013). This is because the reference point based on a simple logistic growth assumption uses an underestimate of the depleted population's growth potential.

Assigning reasonable proxies for F_{lim} is arguably more challenging for sharks and rays (collectively, elasmobranchs) than air-breathing marine megafauna because they encompass a broader array of life history types along the 'fast' to 'slow' spectrum (Cortés 2002) and direct empirical estimates of life

Table 1 Comparison of bycatch mortality limit estimators for marine megafauna that use direct estimates of abundance (PBR = potential biological removal, Wade 1998; PBR for seabirds, Dillingham & Fletcher 2011; RVLL = reproductive value loss limit, Curtis & Moore 2013; SAFE = sustainability assessment of fishing effects, Zhou *et al.* 2008, 2011). All can be adapted to different population goals and may be applicable to other taxa. For additional explanations, see caption of Figure 1.

	PBR	*PBR for seabirds*	*RVLL*	*SAFE*
Taxonomic group(s)	Marine mammals	Seabirds	Marine turtles	Sharks and rays, sea snakes, teleosts
Population goal	$N \geq N_{MNPL}$	$N \geq N_{MNPL}$	$N' \geq N'_{MNPL}$; N' = total abundance scaled by reproductive value	various, e.g. $N \geq N_{crash}$; $N \geq 0.5N_{MNPL}$; $N \geq N_{MNPL}$
Estimator for bycatch limit	$0.5R_{max}N_{min}F_r$	τBF_r; where $\tau = 0.5R_{max}m$	$0.5R_{max}\,N'_{min}F_u$	$F_{lim} \cdot N$; see next row
F_{lim}	$F_{MNPL} = 0.5R_{max}$	$F_{MNPL} = \tau/m = 0.5R_{max}$, where m is a conversion factor for breeding pairs (B) to N	$F'_{MNPL} = 0.5R_{max}$, where F' = mortality rate in terms of fraction of N' removed	$F_{crash} = R_{max}$; $F_{crash} = 2\omega M$; $F_{risk} = 0.75R_{max}$; $F_{risk} = 1.5\omega M$; $F_{MNPL} = 0.5R_{max}$; $F_{MNPL} = \omega M$; where ω = ratio of F_{MNPL} to M
Density-dependence assumed	Logistic	Logistic	Age-structured 'logistic'	Graham-Schaefer (logistic)
Fishing-selectivity assumed	Age-independent	Age-independent	Age-dependent (implemented as increasing with age)	Age-independent
How F_{lim} parameters estimated	Default R_{max} if not estimable	R_{max} estimated from age-of-first reproduction and adult survival rate; m estimated from population model	Allometry-based estimates of R_{max} if not estimable, or drawn from conspecific population(s)	estimates of R_{max} or M from literature, or allometry-based estimates of M; empirical proxies for ω
How N estimated	In-water abundance surveys	Surveys for breeding pairs	Surveys for nests or nesting females, use estimated population matrix to derive N' from survey data	trawl surveys for total abundance and spatial distribution
Risk incorporated in estimator?	Yes	Yes, assumed same criteria and parameterization as PBR	Yes, assumed same criteria as PBR	No

history parameters for elasmobranchs are particularly rare (Cortés *et al.* 2012). Zhou *et al.* (2008, 2011, 2012*a*) estimated various F_{lim} by first using indirect methods to estimate natural mortality (*M*) (for example based on correlations with body size), from which the F_{lim} were derived based on empirical relationships and the assumption of a logistic (Graham-Schaefer) production model (Zhou *et al.* 2012*b*). However, the indirect methods to estimate M have been derived using data mainly from teleost fishes (for example see Hoenig 1983; Peterson & Wroblewski 1984; Chen & Watanabe 1989), and experts warn against the use of simple production models for species that experience strongly age-structured selectivity by a fishery (Maunder 2003), which is the case for sea turtles (Curtis & Moore 2013) and elasmobranchs (Gallucci *et al.* 2006). Brooks *et al.* (2010) developed an analytical method to estimate fishing mortality reference points based on Beverton-Holt (B-H) and Ricker stock-recruit relationships, although some argue that these production models may not be appropriate for species that have highly constrained fecundity (for example litter sizes of just a few individuals, as in sharks) or that exhibit peak population productivity at biomass or abundance >0.5 carrying capacity (Dick & MacCall 2011; Taylor *et al.* 2012). More research is urgently needed to determine suitable estimates or proxies of F_{lim} to use in reference point estimators for elasmobranchs.

Population abundance. Whereas life history constraints may permit reasonable proxies to be derived for F_{lim} in many cases, population abundance cannot be inferred from proxy information and is therefore the most limiting factor in estimating a reference point for bycatch. For many, but not all marine mammals, abundance can be estimated directly by aerial or vessel line-transect surveys, although for many pinniped species surveys are limited to counting reproductive adults or pups. For seabirds, numbers of breeding pairs in a year is the typically observed quantity; Dillingham and Fletcher (2011) re-parameterized the marine mammal PBR equation based on a simple age-structured population growth model to accommodate this input and to account for uncertainty in converting from breeding pairs to total population size. In-water abundance surveys of sea turtles are rarely practical, but annual numbers of nests or nesting females can be counted for many populations. Extrapolation of population size from index counts of abundance can be highly uncertain, however, especially when the breeding adults are a relatively small proportion of population size and are not the primary life stage in the bycatch (Richards *et al.* 2011). The RVLL (reproductive value loss limit) estimator of Curtis and Moore (2013) uses an estimated population transition matrix to convert adult female or nest survey data to into population estimates rescaled by reproductive value, which is presented as the more appropriate currency to manage given large ontogenetic change in relative reproductive value and in fishery selectivity. Gallucci *et al.* (2006) demonstrated the importance of management based on reproductive value for exploited shark populations.

Abundance estimation for many non-target elasmobranchs is more challenging in general, particularly for highly migratory species, because they are not forced to the surface to breathe and do not give birth or lay eggs on dry land. For coastal or resident populations, abundance or biomass may be estimated using fishery-independent data, such as from trawl surveys (Zhou *et al.* 2008, 2011, 2012*a*) or diver-collected data (Ward-Paige & Lotze 2011). Alternatively, catch histories may be used to estimate population abundance and thus limit reference points for data-poor populations (MacCall 2009; Berkson *et al.* 2011; Dick & MacCall 2011; Little *et al.* 2011; Martell & Froese 2012; Cope 2013), but most catch-based methods rely on relatively complete historical time series of catches, which are unavailable for most non-target species. Moreover, catch-history methods generally rely on assumptions that fishery selectivity and relative catchability of fish are constant over time, as well as on assumptions about the status of the population relative to its unfished state, which may underestimate pristine population size and overestimate limits (for example see Wetzel & Punt 2011).

Given the difficulty of estimating abundance and reference points for total bycatch, methods that evaluate relative rather than absolute levels of potential impact from fisheries may be valuable for data-poor species. Productivity susceptibility analyses that compare life history characteristics and susceptibility to fisheries across multiple species have therefore been applied as bycatch assessment tools for elasmobranchs and other marine megafauna groups (Stobutzki *et al.* 2002; Cortés *et al.* 2009; Patrick *et al.* 2010; Arrizabalaga *et al.* 2011; Cope *et al.* 2011). Another alternative, proposed by Le Quesne and Jennings (2012), is to use estimates of F for target species as proxies for non-target species, enabling direct comparison of the indicator (F) to the reference point (F_{lim}) and circumventing the need to estimate population abundance. Invoking 'Pope's postulate', Le Quesne and Jennings (2012) suggested that target species F may usually be taken as a maximum estimate of non-target F (also see Pope *et al.* 2000). This assumption needs to be critically evaluated if the approach is to be used in practice.

Dealing with uncertainty and risk

Reference points and indicators are both estimated with error, which is often substantial but difficult to quantify (Faunce & Barbeaux 2011; Warden & Murray 2011). If management is based simply on comparing point estimates of the indicator and reference point, the likelihood of management error (risk probability) can be fairly high. Error in the bycatch mortality estimate or incorrectly setting the reference point could lead to an overly optimistic assessment, such that bycatch mortality may be allowed to continue at a level too high to achieve the desired population status. Risk tolerance might depend on a population's current status (if known) or the equilibrium population status associated with different levels of F_{lim}. For example, for protected, endangered, declining or depleted populations (such as those below a level described in Fig. 1 as N_{risk}), managers would likely strive for higher certainty of maintaining bycatch levels below a particular F_{lim} than for species of lesser concern. And while managers might try to ensure that bycatch does not exceed dire limits (such as represented in Fig. 1 by F_{crash}), some level of risk of bycatch being above a limit like F_{MNPL} might be more acceptable. Below, we discuss how risk management can be built explicitly into the reference point estimators or handled apart from the estimation of limits. We then discuss the role of simulation based performance-testing, such as MSE, in assessing the effectiveness of whichever type of management approach is taken to deal with uncertainty and risk in terms of its ability to help achieve management goals.

Incorporating risk into reference point estimators

The PBR reference point used under the MMPA provides an excellent example of explicitly incorporating risk management into the estimator itself. The goal of the PBR management framework is to maintain or recover populations to a level at or above MNPL, and to do so with probability ≥ 0.95 given estimated error (i.e., coefficient of variation [CV]) in the abundance estimates and presumed levels of plausible bias in various factors related to the reference point and indicator estimates. Based on extensive simulation trials, Wade (1998) tuned the estimator to use a 20th percentile estimate of abundance to account for a range of levels of estimation precision and then tuned a separate parameter (the 'recovery factor') to account for plausible scenarios of bias. Curtis and Moore (2013) followed this example in developing their RVLL estimator for sea turtles.

As implemented or evaluated to date, PBR and RVLL are precautionary; they aim to ensure relatively high population levels or rapid recovery with high probability. Alternatively, Zhou *et al.* (2008) suggested that for unprotected species of low economic or cultural value, depletion to lower abundance relative to carrying capacity or accepting higher levels of risk might be reasonable. Thus, as suggested by Curtis and Moore (2013), simulations like those for PBR or RVLL may be repeated to identify percentile levels of the abundance estimate or a value of the tuning parameter that correspond to a less ambitious population goal than MNPL or a lower acceptable probability of achieving the desired population goal. Williams *et al.* (2008) provided an example of using simulations to retune the PBR estimator to achieve

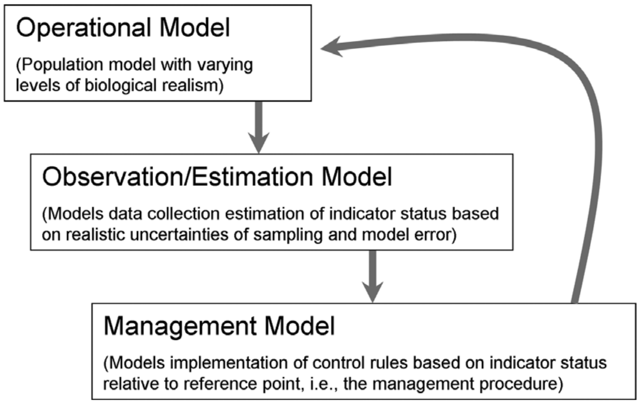

Figure 2 Management strategy evaluation components for a typical framework used to advise bycatch management.

a more ambitious population goal than prescribed under the MMPA.

Alternative approaches for incorporating risk into assessment and management

There are advantages to incorporating risk from uncertainty explicitly into reference point estimators. Once the estimator is tailored to population objectives and defined risk tolerances, calculating the reference point can be straightforward, and management action triggered (or at least guided) by whether the indicator exceeds the reference point. The management process is clearly defined and simplified, and explicitly takes a precautionary approach to uncertainty.

However, there are also disadvantages of this approach. While it is arguably desirable to agree upon manageable goals and acceptable risk levels prior to decision making, this can be politically difficult and poorly received by managers. The process may therefore not fit well within some management contexts, as when bycatch mitigation is a voluntary or consensus-based process (as is currently the case in many international RFMOs; Gilman 2011), or where 'allowable take' is an undesirable target for legal or political reasons. Moreover, estimators with built-in management goals and risk tolerance lose their generality and may thus be less applicable to other contexts where the goals or acceptable risk levels may differ or not be clearly defined (for example Williams *et al.* 2008). For example, although researchers have applied PBR to various systems and taxa to make inference about the sustainability of observed exploitation levels, conclusions from these studies must be qualified with the caveat that the PBR estimator only indicates a bycatch limit needed to reasonably assure that a population is maintained above its maximum net productivity level (Wade 1998 used a 5% risk level to tune PBR, specifically to address MMPA goals). Bycatch exceeding PBR by some degree could still correspond theoretically to a goal of maintaining populations above MNPL, but with less certainty (higher risk tolerance for management error), or it may be sustainable with respect to a less ambitious population goal.

Rather than build risk into the estimator itself, alternative approaches may explicitly summarize uncertainty in the reference point and indicator estimates as outputs, derived from inputting distributions rather than point estimates or particular quantiles for all biological parameters in the estimator. Then, risk tolerance can guide how these uncertainties are factored into decision-making. For example, Monte Carlo or other variance propagation methods may be used to evaluate the likelihood that various F_{lim} are exceeded (see Zhou *et al.* 2011; Richard *et al.* 2011; Fig. 3). Ranking these probabilities among species can help identify those most at risk in the case of multi-species assessments, and probability thresholds for action could correspond to risk tolerances that vary with species' conservation status. This has the added benefit of maintaining separation of the scientific process from the policy process (*sensu* Prager *et al.* 2003); the probability estimates strictly reflect biological uncertainty, while the probability thresholds for action reflect management goals and degree of risk aversion. Producing distributions of reference points and indicators corresponding to a range of risk tolerance also facilitates consideration of economic trade-offs in the form of fisheries losses at different buffer levels, where specific mitigation measures (whose cost per animal mitigated can be characterized) have been chosen (see Punt *et al.* 2012 for a similar analysis for a target species).

Suggestions in the previous paragraph provide more flexibility and in some sense more transparency in dealing with uncertainty and risk than incorporating risk directly into the reference point estimator. However, inference is susceptible to bias if the reference point estimators do not account for potential biases such as systematic bycatch mortality underestimation. Using distributions for parameters to estimate F_{lim}, abundance and bycatch deals with parameter uncertainty, but it does not address structural model uncertainty or bias (for example the form of the density-dependent response or other assumptions used to estimate various $F_{lim)}$. Structural uncertainty can be addressed by model-averaging (sampling from multiple plausible production models; for example Brodziak & Legault 2005) or using fixed precautionary assumptions (such as logistic density-dependent population growth), where the latter is advisable in the absence of contrary information. Robustness to bias can be achieved by the use of an extra multiplier (such as an uncertainty or recovery factor, or post-hoc decision rule that achieves the same result), but without simulation-based performance testing, it is difficult to know what the multiplier should be. Simulation analyses (Wade 1998; Curtis & Moore 2013) suggest that multiplying point estimates for bycatch mortality limits by 0.5 may be appropriate for addressing individual sources of bias, but these guidelines are conditional on context-specific sets of population goals, risk criteria and plausible biases. Dillingham & Fletcher (2008) proposed multipliers between 0.1 and 0.5 corresponding to IUCN Red List status, thus incorporating risk management and bias concerns into the estimator. In the USA, the Pacific Fishery Management Council (PFMC) uses a '40–10' rule that reduces

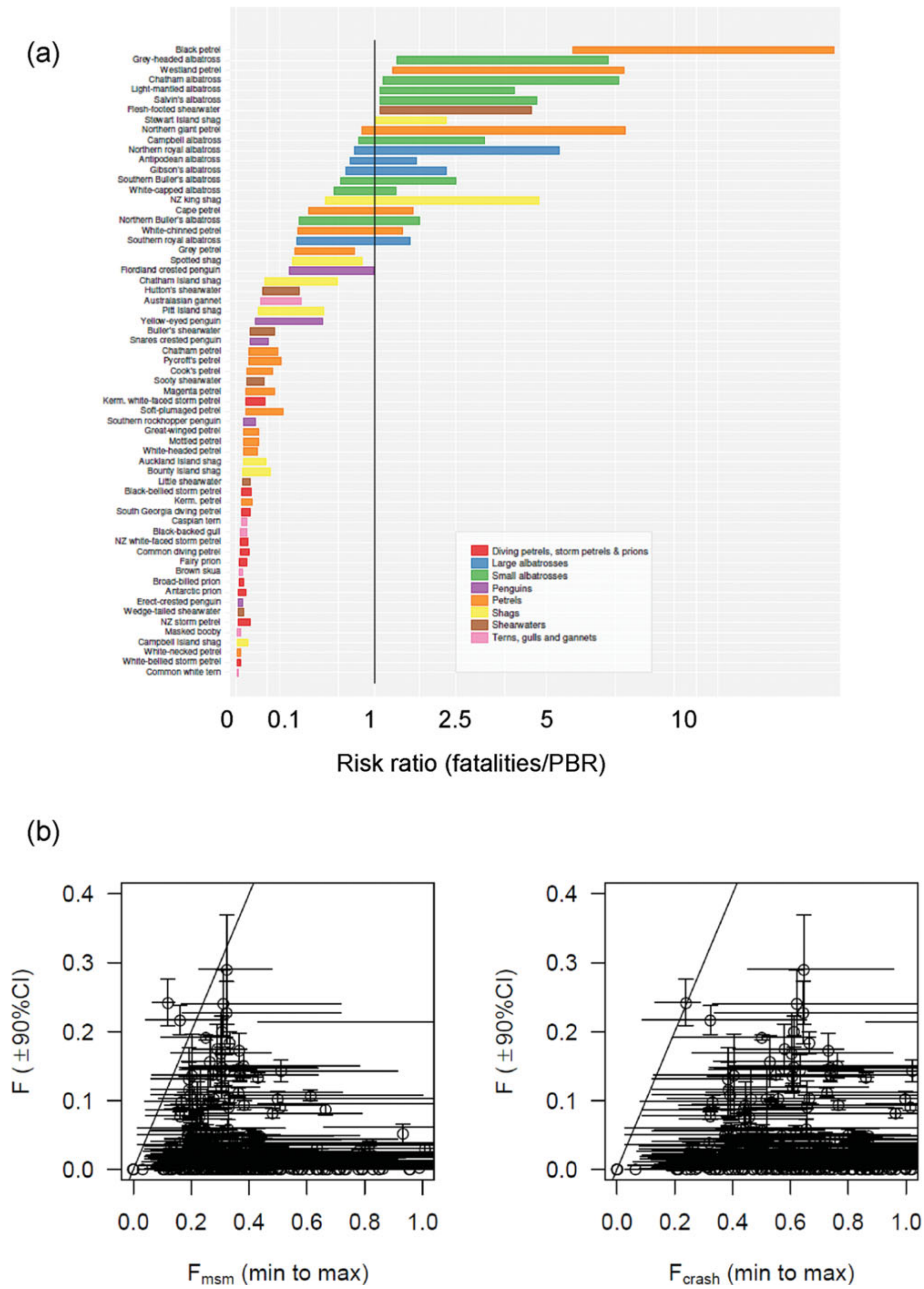

Figure 3 Examples of summarizing uncertainty in the likelihood that an indicator (bycatch mortality) exceeds a reference point (F_{lim}). (*a*) Richard *et al*. (2011) used Monte Carlo methods to estimate distributions for the 'risk ratio' (coloured bars), namely fishery-mortality divided by PBR (potential biological removal), for New Zealand seabirds. The proportion of the distribution exceeding 1 is the probability of exceeding PBR. (*b*) Uncertainty in estimates of two limit reference points (F_{msm} and F_{crash}) (*x*-axis; min–max is the range of estimates from multiple methods) and mortality (*y*-axis) in the Australian South East Scalefish and Shark Fishery, based on the SAFE (sustainability assessment for fishing effects) method of Zhou *et al*. (2008, 2011). The diagonal line is where $F = F_{lim}$. The length of error bars above and left of the diagonal reflect the probability of $F > F_{lim}$.

allowable target catch rate from the estimate corresponding to F_{MSY} when stock biomass is below a population reference point called $B_{40\%}$ (40% of unfished biomass) and disallows catch if biomass is below $B_{10\%}$ (10% of unfished biomass) (PFMC 2011).

Assessing management performance using management strategy evaluation

MSE (Smith 1994) involves simulating a whole management system, involving feedbacks between 'true' population dynamics, data collection and population assessment with observation and model error, and indicator-based management decisions and implementation, to evaluate the performance of a management process in terms of its ability to achieve desired outcomes (Butterworth & Punt 1999; Sainsbury *et al*. 2000; Punt *et al*. 2001; Punt 2006; Rademeyer *et al*. 2007; de Oliveira *et al*. 2009; see Rochet & Rice 2009 for criticism of the approach). Most MSEs are composed of multiple interacting models that can include economic and social processes (Dichmont *et al*. 2008; Bunnefeld *et al*. 2011). MSEs can act as a form of sensitivity analysis, revealing how data quality, assessment model structure, reference points and the management process itself affect the performance of a given management tool. Importantly, MSE can help identify the conditions under which a reference point estimator is likely to fail as a management tool, for example leading to severe over- or underestimation of a population's status or allowable bycatch mortality.

The MSE concept in fisheries originated in several forms; for example, it is often referred to as management procedure evaluation, with a substantial history of development by the International Whaling Commission (IWC) to manage commercial whaling (Cooke 1999; Butterworth & Punt 1999; Butterworth *et al.* 2010; Cooke *et al.* 2012). As relates to non-target or data-poor populations, MSE or MSE-like approaches have been used to develop PBR for marine mammals (Wade 1998) and RVLL for marine turtles (Curtis & Moore 2013; note Heppell 2011 also conducted an MSE of PBR applied to turtles), and to assess performance of catch strategies for data-poor fish stocks (Little *et al.* 2011; Wetzel & Punt 2011). Tuck (2011) used MSE to show that PBR was a more effective reference point for limiting seabird bycatch than simply limiting bycatch catch per unit effort (CPUE) below a fixed level. Despite these examples, the application of MSE to reference point models for management of bycatch species is still rarer than bycatch management based on reference points itself, and more work is needed to evaluate context-specific performance of proposed reference point estimators.

A typical MSE for bycatch management based on the use of reference points would have three primary components (Fig. 2). (1) An operating model represents the underlying 'true' population dynamics, with biological characteristics drawn from the literature. Uncertainty in vital rates and density-dependent responses can be included in the operating model, as well as uncertainty in spatial population structure (see Taylor 1997) and environmental stochasticity or cycles. (2) An observation model simulates the process by which data are collected and population indicators and reference points are estimated by managers given sampling error in the data, model assumptions and other uncertainties about the operating model. This component of the MSE is intended to generate realistic levels of error for determining the level of precaution needed to set removal rules based on available information. It also can be used to identify the potential value of improved monitoring efforts (Rosenberg & Restrepo 1994). (3) A management or removal model describes the implementation of rules (such as harvest control rules) in response to indicator status relative to reference points, to limit the level of population removal each year. Outcomes of the management procedure, including estimation and implementation error, feed back into the next time step of the operating model. Through many stochastic iterations of the MSE simulation, it is possible to estimate the probability that pre-defined management objectives are achieved given the specified uncertainties, although it is important to realize that inference from the MSE is conditional on the set of scenarios (such as types of bias or forms of stochasticity) explored.

The propensity for a management process based on reference points to be overly conservative can be tested, as well as its likelihood of failing to adequately protect a declining population (Snover & Heppell 2009; McElhany *et al.* 2010). Ideally, MSEs should be used to compare the risk probabilities and trade-offs in competing management goals (Sainsbury *et al.* 2000). For example, Maunder *et al.* (2000) used a Bayesian approach to assess the trade-off between risk of failing to adequately protect Hookers' sea lion *Phocarctos hookeri* and loss of squid catch associated with implementing a PBR-like management model in New Zealand. The extent to which trade-offs are considered in an MSE depend in part on the legal context of management; for example, the MSE conducted by Wade (1998) only considered risk of failing to achieve conservation objectives because of statutory mandates of the USA's MMPA. In the case of bycatch species, trade-offs also depend on mitigation methods, so the latter must be concretely identified *a priori* if trade-offs are to be evaluated through the MSE.

Value of reference points for multi-species risk assessments

Reference point estimators can also be used to facilitate and increase the value of multi-species risk assessments by permitting resource-efficient quantitative assessment of more populations than would be possible with more data-hungry assessment models. Reference points allow for rapid ranking of relative risk among many species and help focus research and mitigation priorities. Risk ranking is further improved if reference points or indicators can be described by posterior probability distributions (rather than point estimates), thus permitting probabilistic statements about the likelihood of an indicator exceeding a reference point (see for example Richard *et al.* 2011, Moore 2012). Taylor *et al.* (2000) clearly documented the value of the PBR management framework as a way of satisfying statutory mandates to assess status for large numbers of USA marine mammal stocks for which more data-hungry assessment methods were impossible. There are also more recent examples: the SAFE (sustainability assessment for fishing effects) tool applied in Australia within a hierarchical risk assessment framework called ERAEF (ecological risk assessment for the effects of fishing), and using PBR for seabirds to inform fishery policy in New Zealand.

Hierarchical management frameworks can provide evaluation of both status and potential impacts of bycatch that match levels of uncertainty with levels of precaution. ERAEF is a precautionary triage framework founded on principles of ecosystem-based fisheries management (EBFM) (Hobday *et al.* 2007, 2011; Smith *et al.* 2007*a*). Its hierarchical structure is designed to deal efficiently with assessing impacts for large numbers of species under data-poor circumstances. Designed initially in the context of the Australian Fisheries Management Authority (AFMA), the framework has been partially adopted by the Marine Stewardship Council (MSC) as part of their fisheries certification process (MSC 2009) and has been used in other international contexts, such as for assessing threats to seabirds by longline fisheries in the Atlantic (Tuck *et al*. 2011). Briefly, the framework consists of four stages of analysis ranging from mostly qualitative (scoping and level 1), where management objectives are defined and potential impacts described and scored using expert judgment, to semi-quantitative and quantitative (levels 2 and 3). The field of species considered is narrowed at each level. Level 2 is a productivity-susceptibility analysis (PSA), which can be semi- or fully-quantitative, used to rank relative risk for individual species evaluated within a fishery (see for example Stobutzki *et al*. 2001; Cortés *et al*. 2009; Patrick *et al*. 2010; Arrizabalaga *et al*. 2011; Cope *et al*. 2011; Tuck *et al*. 2011). Species ranked as medium or high risk in level 2 are assessed at the fully quantitative level 3 to provide a more absolute measure of risk. Precaution is handled by treating species with high uncertainty as higher risk in lower-level analyses. Using the SAFE tool in level 3, Zhou *et al*. (2011) evaluated hundreds of non-target fish species in Australian fisheries and identified unsustainable levels of catch for multiple elasmobranch species.

New Zealand's draft seabird policy (New Zealand Ministry of Fisheries 2011) is based on a two-level risk assessment framework, the second of which is quantitative and uses PBR (the same equation as applied to marine mammals) to identify populations with high probability of risk to unsustainable mortality (Fletcher *et al*. 2008; Richard *et al*. 2011). This framework was recently applied to rank the risk of dozens of seabird species, and several of the most at-risk species were identified as having a high probability of being impacted by unsustainable mortality levels (Richard *et al*. 2011). In both of the above examples, most species evaluated at the fully quantitative level could not have been assessed but for the use of simple reference point models. One potential advantage of hierarchical approaches like these is their incentive to improve data collection, so bycatch species that receive highly conservative reference points because of their data-poor status can be 'moved up' to higher tiers with less restrictive take allowances, when appropriate.

Challenges to using reference points for assessment and management of bycatch species

Implementation of reference points to inform and guide bycatch management of marine vertebrate megafauna remains rare. Several common technical, operational and political challenges continue to hamper their widespread application, but there is precedent for addressing many of these.

Technical challenges

The challenge of meeting even minimal data requirements is the primary technical hurdle to the proper development of robust reference points and measurable indicators for a given population. Basic population data on life history or abundance, necessary to calculate reference points, may be lacking. Insufficient information can be partially compensated for through theory-based prediction of life history parameters or meta-analyses of existing demographic information for related species (see Hoenig 1983; Frisk *et al*. 2001; Niel & Lebreton 2005; Le Quesne & Jennings 2012). Still, data gaps may limit many species assessments to a more qualitative level (for example Richard *et al*. 2011). Elasmobranch assessments are particularly prone to these limitations.

Quality bycatch data are often unavailable to use reference points. Many monitoring programmes do not mandate recording of species-specific data for discarded or even landed non-target species (for example ICCAT Standing Committee on Research and Statistics 2010), and where they do, identifying the source population for affected animals is a key challenge (see NRC 2010). At-sea observer programmes sample only a fraction of fisheries and often have insufficient coverage for reliable estimates of bycatch and uncertainty, especially for infrequently encountered species (for example NMFS [National Marine Fisheries Service] 2011). Moreover, estimates based on observer or self-reported data may be biased low by numerous factors (see for example Gales *et al* 1998; Haigh *et al*. 2002; Kelleher 2005; Brothers *et al*. 2010; Tuck 2011). Data access is also a major hurdle (Gilman 2011). Some of these issues may be addressed through data correction (Rago *et al*. 2005; Grinnell 2010), video monitoring (Ames *et al*. 2007; Mawani 2009), and strengthening at-sea and dockside monitoring programmes through increased coverage, standardized data collection, better training (for example Dietrich *et al*. 2007; Mawani 2009; WCPFC [Western and Central Pacific Fisheries Commission Secretariat] 2011) and by genetic sampling of landings (Shivji 2010). Accessible, global databases for demographic and catch information on non-target taxa can expedite data gathering and management.

Characterizing uncertainty and using simulation approaches such as MSE become particularly important when data are limited and likely biased, because they provide the means to evaluate whether application of reference point estimators for assessment and management is robust to the suite of known data problems. However, MSE outputs are only as robust as the range of biological and management scenarios considered, and under extreme data limitation, it may be difficult to reasonably define limits to uncertainty for specifying operating and observation models.

Apart from data limitations, fisheries sustainability assessments may be complicated by additional non-fisheries anthropogenic impacts, leading to elevated risk of an overall negative population outcome when fishing mortality alone is assessed as sustainable. To the extent that direct non-fisheries impacts can be quantified, they can be accounted for in sustainability assessments of fisheries. However, quantifying indirect impacts are more problematic. These include sublethal fisheries interactions, anthropogenic reductions in carrying capacity (see Moore 2012) or population vital rates not related to fishing, and negative repercussions of fisheries on fine-scale factors important to marine vertebrate demography, including social systems (Mills & Ryan 2005; Wade *et al*. 2012; Jacoby *et al*. 2012) and spatial complexity (Cardinale *et al*. 2011).

Operational challenges

At the operational level, a primary challenge to implementing management of megafauna bycatch based on reference points is the lack of clearly defined management objectives for non-target species in the majority of management contexts, both domestic and international (as identified by Smith *et al.* 1993 regarding target species). Vague language in the United Nations Fish Stocks Agreement of 1995 (see http://www.un.org/Depts/los/) refers to 'maintaining or restoring populations of such species above levels at which their reproduction may become seriously threatened' but provides no further guidance on defining the bounds of acceptable population status and risk as weighed against incentives or imperatives to maximize value (either economic, employment or protein) from fisheries. Domestic legislation and regulations are rarely more specific, with management plans rarely stating explicit goals for non-target species. The USA's Magnuson-Stevens Act (see URL http://www.nmfs.noaa.gov/msa2005/) is one exception, requiring use of reference points for all target and non-target species considered to be 'in the fishery', but guidelines for determining which non-target species are in the fishery are vague; non-target species may instead be considered 'ecosystem components' (NOAA [National Oceanic and Atmospheric Administration] 2009). Defining appropriate reference points is therefore difficult, ultimately requiring collaboration among decision-makers, scientists, managers and stakeholders to define population-relevant management objectives and acceptable risk levels for non-target species, as well as agreeing to management actions in response to assessment outcomes.

The process of pre-defining management objectives, establishing rules for action linked to the status of indicators relative to reference points, and performance testing a management procedure via MSE can be difficult, time consuming and frustrating (Smith *et al.* 1999; Kurota *et al.* 2010). However, well-developed management and assessment frameworks can streamline the assessment process, facilitate adaptive management by using monitoring programmes to update management procedures with new population information, build consensus among stakeholders and generate incentives to reduce uncertainty (see for example USEPA [United States Environmental Protection Agency] 1998; Taylor *et al.* 2000; Smith *et al.* 2009; Hobday *et al.* 2011). For example, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), which coordinates science and management for fisheries in the Southern Ocean, applies a framework for seabird bycatch management that incorporates elements of vessel-specific accountability, spatial management based on risk, and rigorous monitoring with up to 100% at-sea coverage; this programme continues to improve through annual monitoring, review and revision (Waugh *et al.* 2008).

Compliance is another major challenge to successful implementation of management procedures based on use of reference points. This may be addressed through requirements for data provision in exchange for fishing rights (for example ICCAT Recommendation 11–15; ICCAT 2012), increased at-sea observer coverage or video monitoring, and individual limits and accountability by vessel or license holder for impact on non-target species (see Waugh *et al.* 2008; Mawani 2009). Capacity to implement or augment cost-intensive programmes varies, however, among fishing nations. Management programmes should be no more expensive or complex than necessary to achieve management objectives, while negative impacts on fisheries (in terms of profit, landings or other prioritized values) should be minimized to the extent that sustainability objectives can still be achieved.

Political challenges

The incorporation of assessment tools and management of marine megafauna into fisheries governance regimes has been slow. Conservation and resource-use objectives are often conflicting and different stakeholders value them differently (Hilborn 2007). Non-target species sustainability is generally a lower priority than target species capture to fishing industry stakeholders who continue to generally hold the most influence with decision-makers, particularly outside the USA and Australia. In the case of some elasmobranchs, such as large sharks, their landed value provides a further barrier to reducing bycatch, but also potentially an economic incentive to sustainably manage the resource. Cumulative mortality across domestic and international fisheries and from non-fishing human impacts can derail discussions of limiting bycatch of highly migratory species, and uncertainty is also often used as an excuse for inaction. Consensus-based decision making in most international management forums further amplifies these challenges (Gilman 2011).

The FAO Code of Conduct for Responsible Fisheries (FAO 1995) calls for a precautionary approach to management of living marine resources based on best available information, which requires that uncertainty not be used to delay management action. Several sets of technical guidelines and plans of action agreed under the FAO Code of Conduct, other international and domestic instruments (for example the Convention on Migratory Species, http://www.cms.int/, and various regional agreements), as well as trade regulation and incentives provide means for progress toward management of fisheries impacts on non-target marine megafauna. Agencies or governments that champion these efforts, or partnerships among them and with non-governmental organizations, can shift fisheries debates toward broader ecosystem concerns and associated domestic and international policies (Andresen 2002; Betsill 2008) and thus hold promise for advancing the development of reference points as a basis for bycatch management for marine megafauna. However, unilateral management action should be taken with care so as to minimize unintended consequences, such as effort displacement to another area or fishery with potentially negative overall ecosystem consequences (Dinmore *et al.* 2003; Watson *et al.* 2009; Rausser *et al.* 2009).

CONCLUSIONS

There is a critical need to evaluate the potential impact of fisheries and other mortality sources on non-target marine populations, as fisheries bycatch is known or suspected to have serious population-level effects across a range of taxa. Despite their limitations, reference points are widely viewed as essential components of sound fisheries management frameworks for target fish stocks. Reference point estimators designed for non-target data-poor populations can likewise be applied to help manage ecoystem impacts of fisheries (Hall & Mainprize 2004: Daan 2005). The introduction of PBR for marine mammals in the USA following 1994 amendments to the MMPA was an early regulatory example of this (Taylor *et al*. 2000). Since then, there have been noteworthy changes in domestic fisheries policies to implement management procedures for assessing incidental impacts of fishing based on use of reference point estimators, including requirements under the U.S. Magnuson Stevens Act to use reference points for target and non-target species, New Zealand's draft seabird policy that employs a PBR-based reference point, and implementation by the Australian Fisheries Management Authority of ecological risk assessments using the SAFE model, with resulting management action.

Management strategy evaluation and other simulation approaches are an essential component of ensuring effective performance of a reference point estimator for use as part of a management procedure. MSE-type approaches have become relatively common practice in the management of target fish species. However, their use to date for evaluating management procedures for non-target populations based on data-poor reference point estimators is rare. The PBR management model (Taylor *et al*. 2000) remains the best example of policy implementation of an MSE-based management model for non-target species. Without such validation, there can be little assurance that the management approach will be sufficiently precautionary to achieve management objectives in the face of uncertainty.

There are numerous challenges to implementing simulation-tested reference point models for bycatch management. The most daunting include information limitations that can prevent use or evaluation of management models with even the simplest assumptions and minimal data needs, coupled with operational challenges such as defining management objectives and agreement on among managers. These problems are generally exacerbated in international fisheries by inconsistent levels of funding for and commitment to conservation objectives and agreements. Management is further complicated in the context of cumulative fishery and non-fishery population impacts.

Performance-tested management strategies based on reference points for data-poor species provide a powerful tool for identifying precautionary sustainable levels of mortality for many non-target populations and thus surmounting management challenges. Recently developed risk assessment frameworks also can help overcome management hurdles by establishing a template for building consensus around objectives, efficiently dealing with uncertainty, and providing a context for applying reference point models to large numbers of species. New examples are emerging that illustrate the utility of these complementary sets of tools to practically improve fisheries management (Smith *et al*. 2007*b*, 2009; Patrick *et al*. 2010; Hobday *et al*. 2011; Cope *et al*. 2011; Zhou *et al*. 2011). Increased uptake of these approaches by domestic and international fishery management institutions is needed to ensure the health of vulnerable populations of marine megafauna taken as bycatch in fisheries.

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References

Ames, R.T., Leaman, B.M. & Ames, K.L. (2007) Evaluation of video technology for monitoring of multispecies longline catches. *North American Journal of Fisheries Management* **27**: 955–964.

Andresen, S. (2002) The International Whaling Commission (IWC): more failure than success? In: *Environmental Regime Effectiveness: Confronting Theory With Evidence*, ed. E.L. Miles, A. Underdal, S. Andresen, J. Wettestad, J.B. Skjærseth & E.M. Carlin, pp. 379–404. Cambridge, Massachusetts, USA: MIT Press.

Arrizabalaga, H., de Bruyn, P., Diaz, G.A., Murua, H., Chavance, P., de Molina, A.D., Gaertner, D., Ariz, J., Ruiz, J. & Kell, L.T. (2011) Productivity and susceptibility analysis for species caught in Atlantic tuna fisheries. *Aquatic Living Resources* **24**: 1–12.

Berkson, J., Barbieri, L., Cadrin, S., Cass-Calay, S.L., Crone, P., Dorn, M., Friess, C., Kobayashi, D., Miller, T.J., Patrick, W.S., Pautzke, S., Ralston, S. & Trianni, M. (2011) Calculating acceptable biological catch for stocks that have reliable catch data only (only reliable catch stocks – ORCS). *NOAA Technical Memorandum* NMFS-SEFSC-616, National Marine Fisheries Service, Miami, FL, USA: 56 pp. [www document]. URL http://www.pifsc.noaa.gov/tech/NOAA_Tech_Memo_SEFSC_616.pdf

Betsill, M.M. (2008) Reflections on the analytical framework and NGO diplomacy. In: *NGO Diplomacy: The Influence of Nongovernmental Organizations in International Environmental*

Organizations, ed. M.M. Betsill & E. Corell, pp. 119–149. Cambridge, Massachusetts, USA: MIT Press.

Bisack, K.D. & Sutinen, J.G. (2006) Harbor porpoise bycatch: ITQs or time/area closures in the New England gillnet fishery. *Land Economics* **82**: 85–102.

Brodziak, J. & Legault, C.M. (2005) Model averaging to estimate rebuilding targets for overfished stocks. *Canadian Journal of Fisheries and Aquatic Sciences* **62**: 544–562.

Brooks, E.N., Powers, J.E. & Cortés, E. (2010) Analytical reference points for age-structured models: application to data-poor fisheries. *ICES Journal of Marine Science* **67**: 165–175.

Brothers, N., Duckworth, A.R., Safina, C. & Gilman, E.L. (2010) Seabird bycatch in pelagic longline fisheries is grossly underestimated when using only haul data. *PLoS ONE* **5**: e12491.

Bunnefeld, N., Hoshino, E. & Milner-Gulland, E.J. (2011) Management strategy evaluation: a powerful tool for conservation? *Trends in Ecology and Evolution* **26**: 441–447.

Butterworth, D.S., Bentley, N., De Oliveira, J.A.A., Donovan, G.P., Kell, L.T., Parma, A.M., Punt, A.E., Sainsbury, K.J., Smith, A.D.M. & Stokes, T.K. (2010) Purported flaws in management strategy evaluation: basic problems or misinterpretations? *ICES Journal of Marine Science* **67**: 567–574.

Butterworth, D.S. & Punt, A.E. (1999). Experiences in the evaluation and implementation of management procedures. *ICES Journal of Marine Science* **56**: 985–998.

Caddy, J.F. & Mahon, R. (1995) Reference points for fisheries management. *FAO Fisheries Technical Paper* No. 347. FAO, Rome, Italy: 83 pp.

Cardinale, M., Bartolino, V., Llope, M., Maiorano, L., Sköld, M. & Hagberg, J. (2011) Historical spatial baselines in conservation and management of marine resources. *Fish and Fisheries* **12**: 289–298.

Chen, S.B. & Watanbe, S. (1989) Age dependence of natural mortality coefficient in fish population dynamics. *Nippon Suisan Gakkaishi* **55**: 205–208.

Cooke, J.G. (1999) Improvement of fishery-management advice through simulation testing of harvest algorithms. *ICES Journal of Marine Science* **56**: 797–810.

Cooke, J., Leaper, R., Wade, P, Lavigne, D. & Taylor, B. (2012) Management rules for marine mammal populations: a response to Lonergan. *Marine Policy* **36**: 389–392.

Cope, J.M. (2013) Implementing a statistical catch-at-age model (Stock Synthesis) as a tool for deriving overfishing limits in data-limited situations. *Fisheries Research* **142**: 3–14.

Cope, J.M., DeVore, J., Dick, E.J., Ames, K., Budrick, J., Erickson, D., Grebel, J., Hanshew, G., Jones, R., Mattes, L., Niles, C. & Williams, S. (2011) An approach to defining species complexes for US west coast groundfishes using vulnerabilities and ecological distributions. *North American Journal of Fisheries Management* **31**: 589–604.

Cortés, E. (2002) Incorporating uncertainty into demographic modeling: application to shark populations and their conservation. *Conservation Biology* **16**: 1048–1062.

Cortés, E., Arocha, F., Beerkircher, L., Carvalho, F., Domingo, A., Heupel, M., Holtzhausen, H., Santos, M.N., Ribera, M. & Simpfendorder, C. (2009) Ecological risk assessments of pelagic sharks caught in Atlantic pelagic longline fisheries. *Aquatic Living Resources* **22**: 1–10.

Cortés, E., Brooks, E.N. & Gedamke, T. (2012) Population dynamics, demography, and stock assessment. In: *Biology of Sharks and Their Relatives*, Second edition, ed. J.C. Carrier, J.A. Musick & M.R. Heithaus, pp. 453–86. Boca Raton, FL, USA: CRC Press.

Cox, T.M., Lewison, R.L., Zydelis, R., Crowder, L.B., Safina, C. & Read, A.J. (2007) Comparing effectiveness of experimental and implemented bycatch reduction measures: the ideal and the real. *Conservation Biology* **21**: 1155–1164.

Curtis, K.A. & Moore, J.E. (2013) Calculating reference points for anthropogenic mortality of marine turtles. *Aquatic Conservation: Marine and Freshwater Ecosystems* doi 10.1802/aqc.2308 (in press).

Daan, N. (2005) An afterthought: ecosystem metrics and pressure indicators. *ICES Journal of Marine Science* **62**: 612–613.

de Oliveira, J.A.A., Kell, L.T., Punt, A.E., Roel, B.A. & Butterworth, D.S. (2009) Managing without best predictions: the Management Strategy Evaluation framework. In: *Advances in Fisheries Science: 50 Years on from Beverton and Holt*, ed. A. Payne, J. Cotter & T. Potter, pp. 104–34. Oxford, UK: Blackwell.

Dichmont, C.M., Deng, A., Punt, A.E., Ellis, N., Venables, W.N., Kompas, T., Ye, Y., Zhou, S. & Bishop, J. (2008) Beyond biological performance measures in management strategy evaluation: bringing in economics and the effects of trawling on the benthos. *Fisheries Research* **94**: 238–250.

Dick, E.J. & MacCall, A.D. (2011) Depletion-based stock reduction analysis: a catch-based method for determining sustainable yields for data-poor fish stocks. *Fisheries Research* **110**: 331–341.

Dietrich, K.S., Cornish, V.R., Rivera, K.S. & Conant, T.A. (2007) Best practices for the collection of longline data to facilitate research and analysis to reduce bycatch of protected species: report of a workshop held at the International Fisheries Observer Conference, Sydney, Australia, November 8, 2004. NOAA Technical Memorandum NMFS-OPR-35, 88 pp. [www document]. URL http://www.nmfs.noaa.gov/pr/pdfs/interactions/longline_bycatch.pdf

Dillingham, P.W. (2010) Generation time and the maximum growth rate for populations with age-specific fecundities and unknown juvenile survival. *Ecological Modelling* **221**: 895–899.

Dillingham, P.W. & Fletcher, D. (2008) Estimating the ability of birds to sustain additional human-caused mortalities using a simple decision rule and allometric relationships. *Biological Conservation* **141**: 1783–1792.

Dillingham, P.W. & Fletcher, D. (2011) Potential biological removal of albatrosses and petrels with minimal demographic information. *Biological Conservation* **144**: 1885–1894.

Dinmore, T.A., Duplisea, D.E., Rackham, B.D., Maxwell, D.L. & Jennings, S. (2003) Impact of a large-scale area closure on patterns of fishing disturbance and the consequences for benthic communities. *ICES Journal of Marine Science* **60**: 371–380.

Dunn, D.C., Boustany, A.M. & Halpin, P.N. (2011) Spatial-temporal management of fisheries to reduce by-catch and increase fishing selectivity. *Fish and Fisheries* **12**: 110–119.

FAO (1995) Code of Conduct for Responsible Fisheries. Food and Agriculture Organization of the United Nations, Rome, Italy [www document]. URL http://www.fao.org/docrep/005/v9878e/v9878e00.htm#table

FAO (2010) Report of the Technical Consultation to Develop International Guidelines on Bycatch Management and Reduction of Discards. Rome, 6–10 December 2010. FAO Fisheries and Aquaculture Report No. 957. Food and Agriculture Organization of the United Nations, Rome, Italy [www document]. URL http://www.fao.org/docrep/013/i2024e/i2024e00.pdf

Fletcher, D., MacKenzie, D. & Dillingham, P. (2008) Modelling of impacts of fishing-related mortality on New Zealand seabird populations. Report prepared for the New Zealand Ministry of Fisheries, Project ENV2004/05, December 2008. Ministry for Primary Industries, Government of New Zealand, Wellington, New Zealand.

Faunce, C.H. & Barbeaux, S.J. (2011) The frequency and quantity of Alaskan groundfish catcher-vessel landings made with and without an observer. *ICES Journal of Marine Science* **68**: 1757–1763.

Forrest, R.E. & Walters, C.J. (2009) Estimating thresholds to optimal harvest rate for long-live, low-fecundity sharks accounting for selectivity and density dependence in recruitment. *Canadian Journal of Fisheries and Aquatic Sciences* **66**: 2062–2080.

Fowler, C.W. (1981) Density dependence as related to life history strategy. *Ecology* **62**: 602–610.

Fowler, C.W. (1988) Population dynamics as related to rate of increase per generation. *Evolutionary Ecology* **2**: 197–204.

Frisk, M.G., Miller, T.J. & Fogarty, M.J. (2001) Estimation and analysis of biological parameters in elasmobranch fisheries: a comparative life history study. *Canadian Journal of Fisheries and Aquatic Sciences* **58**: 969–981.

Gales, R., Brothers, N., & Reid, T. (1998) Seabird mortality in the Japanese tuna longline fishery around Australia, 1988–1995. *Biological Conservation* **86**: 37–56.

Gallaway, B.J., Cole, J.G., Nance, J.M., Hart, R.A. & Graham, G. L. (2008) Shrimp loss associated with turtle excluder devices: are the historical estimates statistically biased. *North American Journal of Fisheries Management* **28**: 203–211.

Gallucci, V.F., Taylor, I.G. & Erzini, K. (2006) Conservation and management of exploited shark populations based on reproductive value. *Canadian Journal of Fish and Aquatic Sciences* **63**: 931–942.

Garcia, S.M. & Staples, D.J. (2000) Sustainability reference systems and indicators for responsible marine capture fisheries: a review of concepts and elements for a set of guidelines. *Marine and Freshwater Research* **51**: 385–426.

Garcia, S.M. & Cochrane, K.L. (2005) Ecosystem approach to fisheries: a review of implementation guidelines. *ICES Journal of Marine Science* **62**: 311–318.

Gilman, E. (2011) Bycatch governance and best practice mitigation technology in global tuna fisheries. *Marine Policy* **35**: 590–609.

Grinnell, M.H. (2010) Evaluating the reliability and equitability of at-sea observer release reports in the BC offshore groundfish trawl fishery. Master of Resource Management Project No. 479, Simon Fraser University, Burnaby, British Columbia, Canada.

Haigh, R., Schnute, J., Lacko, L., Eros, C., Workman, G. & Ackerman, B. (2002) At-sea observer coverage for catch monitoring of the British Columbia hook and line fisheries. DFO Canadian Science Advisory Secretariat Research Document No. 2002/108. Fisheries and Oceans Canada, Nanaimo, BC, Canada [www document]. URL http://www.dfo-mpo.gc.ca/csas/Csas/DocREC/2002/RES2002_108e.pdf

Hall, S. J. & Mainprize, B. (2004) Towards ecosystem-based fisheries management. *Fish and Fisheries* **5**: 1–20.

Hall, M.A., Alverson, D.L. & Metuzals, K.I. (2000) By-catch: problems and solutions. *Marine Pollution Bulletin* **41**: 204–219.

Heppell, S.S. (2011) Development of quantitative methods to evaluate marine turtle management models. Unpublished report to the Southwest Fisheries Science Center, NOAA, USA.

Hilborn, R. (2007) Defining success in fisheries and conflicts in objectives. *Marine Policy* **31**: 153–158.

Hobday, A.J., Smith, A.D.M., Webb, H., Daley, R., Wayte, S., Bulman, C., Dowdney, J., Williams, A., Sporcic, M., Dambacher, J., Fuller, M. & Walker, T. (2007) Ecological risk assessment for the effects of fishing: methodology. Report R04/1072 for the Australian Fisheries Management Authority, Canberra, July 2007 [www document]. URL http://www.afma.gov.au/environment/eco_based/eras/docs/methodology.pdf

Hobday, A.J., Smith, A.D.M., Stobutzki, I.C., Bulman, C., Daley, R., Dambacher, J.M., Deng, R.A., Dowdney, J., Fuller, M., Furlani, D., Griffiths, S.P., Johnson, D., Kenyon, R., Knuckey, I.A., Ling, S. D., Pitcher, R., Sainsbury, K. J., Sporcic, M., Smith, T., Turnbull, C., Walker, T.I., Wayte, S.E., Webb, H., Williams, A., Wise, B.S. & Zhou, S. (2011) Ecological risk assessment for the effects of fishing. *Fisheries Research* **108**: 372–384.

Hoenig, J.M. (1983) Empirical use of longevity data to estimate mortality rates. *Fishery Bulletin* **82**: 898–903.

Huang, H. & Leung, P. (2007) Modeling protected species as an undesirable output: the case of sea turtle interactions in Hawaii's longline fishery. *Journal of Environmental Management* **84**: 523–533.

ICCAT (2011) Supplemental recommendation by ICCAT on reducing incidental bycatch of seabirds in ICCAT longline fisheries. Document No. PA4–813A / 2011, ICCAT, Madrid, Spain: 5 pp.

ICCAT Standing Committee on Research and Statistics (2010) Report of the 2009 Porbeagle Stock Assessments Meeting, Copenhagen, Denmark, June 22–27, 2009. Report SCRS/2009/014. *Collective Volume of Scientific Papers, ICCAT* **65**: 1909–2005.

ICCAT (2012) Compendium: management recommendations and resolutions adopted by ICCAT for the conservation of Atlantic tunas and tuna-like species. May 2012 [www document]. URL http://www.iccat.es/Documents/Recs/ACT_COMP_2012_ENG.pdf

Jacoby, D.M.P., Croft, D.P. & Sims, D.W. (2012) Social behaviour in sharks and rays: analysis, patterns and implications for conservation. *Fish and Fisheries* **13**: 399–417.

Jaramillo-Legorreta, A., Rojas-Bracho, L., Brownell, R.L., Read, A.J., Reeves, R.R., Ralls, K. & Taylor, B.L. (2007) Saving the vaquita: immediate action, not more data. *Conservation Biology* **21**: 1653–1655.

Kelleher, K. (2005) Discards in the world's marine fisheries: an update. FAO Fisheries Technical Paper No. 470. Food and Agriculture Organization of the United Nations, Rome, Italy.

Kurota, H., Hiramatsu, K., Takahashi, N., Hiroshi, S., Itoh, T. & Tsuji, S. (2010) Developing a management procedure robust to uncertainty for southern bluefin tuna: a somewhat frustrating struggle to bridge the gap between ideals and reality. *Population Ecology* **52**: 359–372.

Le Quesne, W.J.F. & Jennings, S. (2012) Predicting species vulnerability with minimal data to support rapid risk assessment of fishing impacts on biodiversity. *Journal of Applied Ecology* **49**: 20–28.

Lewison, R., Crowder, L., Read, A. & Freeman, S. (2004) Understanding impacts of fisheries bycatch on marine megafauna. *Trends in Ecology and Evolution* **19**: 598–604.

Little, L.R., Wayte, S.E., Tuck, G.N., Smith, A.D.M., Klaer, N., Haddon, M., Punt, A.E., Thomson, R., Day, J. & Fuller, M. (2011) Development and evaluation of a cpue-based harvest control rule for the southern and eastern scalefish and shark fishery of Australia. *ICES Journal of Marine Science* **68**: 1699–1705.

MacCall, A.D. (2009) Depletion-corrected average catch: a simple formula for estimating sustainable yields in data-poor situations. *ICES Journal of Marine Science* **66**: 2267–2271.

Martell, S. & Froese, R. (2012) A simple method for estimating MSY from catch and resilience. *Fish and Fisheries* doi: 10.1111/j.1467-2979.2012.00485.x (in press).

Maunder, M.N. (2003) Is it time to discard the Schaefer model from the stock assessment scientist's toolbox? *Fisheries Research* **61**: 145–149.

Maunder, M.N., Starr, P.J. & Hilborn, R. (2000) A Bayesian analysis to estimate loss in squid catch due to the implementation of a sea lion population management plan. *Marine Mammal Science* **16**: 413–426.

Mawani, T. (2009) Evaluation of the commercial groundfish integration pilot program in British Columbia. Thesis, Royal Roads University, Victoria, BC, Canada.

McElhany, P.E., Steel, A., Avery, K., Yoder, N., Busack, C. & Thompson, B. (2010) Dealing with uncertainty in ecosystem models: lessons from a complex salmon model. *Ecological Applications* **20**: 465–482.

Mills, M.S.L. & Ryan, P.G. (2005) Modelling impacts of long-line fishing: what are the effects of pair-bond disruption and sex-biased mortality on albatross fecundity? *Animal Conservation* **8**: 359–367.

Moore, J.E. (2012) Management reference points to account for direct and indirect impacts of fishing on marine mammals. *Marine Mammal Science* doi:10.1111/j.1748-7692.2012.00586.x (in press).

Moore, J.E., Wallace, B.P., Lewison, R.L., Zydelis, R., Cox, T.M. & Crowder, L.B. (2009) A review of marine mammal, sea turtle and seabird bycatch in USA fisheries and the role of policy in shaping management. *Marine Policy* **33**: 435–451.

MSC (2009) MSC FAM default assessment tree. Marine Stewardship Council [www document]. URL http://www.msc.org/documents/get-certified/fisheries/MSC-FAM-default-assessment tree.pdf/view

NMFS (2011) US National Bycatch Report, ed. W.A. Karp, L.L. Desfosse, S.G. Brooke. NOAA Technical Memorandum NMFS-F/SPO-117C, National Marine Fisheries Service: 508 pp. [www document]. URL http://www.nmfs.noaa.gov/by_catch/BREP2011/Front%20Matter.pdf

NOAA (2009) 500 CFR Part 600; Magnuson-Stevens Act Provisions; Annual Catch Limits; National Standard Guidelines; Final Rule. *Federal Register* **74**: 3178–3213.

NRC (1990) *Decline of the Sea Turtles: Causes and Prevention*. Washington, DC, USA: National Academies Press.

NRC (2010) *Sea Turtle Status and Trends: Integrating Demography and Abundance*. Washington, DC, USA: National Academies Press.

New Zealand Ministry of Fisheries (2011) Draft policy for addressing the fishing-related mortality of seabirds in New Zealand fisheries waters. Ministry of Primary Industries, New Zealand [www document]. URL http://www.fish.govt.nz/en-nz/Consultations/Archive/2011/Draft+Seabird+Policy/default.htm

Niel, C. & Lebreton, J. (2005) Using demographic invariants to detect overharvested bird populations from incomplete data. *Conservation Biology* **19**: 826–835.

Patrick, W.S., Spencer, P., Link, J., Ormseth, O., Cope, J., Field, J., Kobayashi, D., Lawson, P., Gedamke, T., Cortés, E., Bigelow, K. & Overholtz, W. (2010) Assessing the vulnerability of US fisheries to becoming overfished or undergoing overfishing through the use of productivity and susceptibility indices. *Fishery Bulletin* **108**: 305–322.

PFMC (2011) Pacific coast groundfish fishery management plan for the California, Oregon and Washington groundfish fishery, as amended through December 2011 [www document]. URL http://www.pcouncil.org/wp-content/uploads/GF_FMP_FINAL_Dec2011.pdf

Peterson, I. & Wrobleski, J.S. (1984) Mortality rate of fishes in the pelagic ecosystem. *Canadian Journal of Fisheries and Aquatic Sciences* **41**: 1117–1120.

Pope, J.G., MacDonald, D.S., Daan, N., Reynolds, J.D. & Jennings, S. (2000) Gauging the impacts of fishing mortality on non-target species. *ICES Journal of Marine Science* **57**: 689–696.

Prager, M.H., Porch, C.E., Shertzer, K.W. & Caddy, J.F. (2003) Targets and limits for management of fisheries: a simple probability-based approach. *North American Journal of Fisheries Management* **23**: 349–361.

Punt, A.E. (2006) The FAO precautionary approach after almost 10 years: have we progressed toward implementing simulation-tested feedback-control management systems for fisheries management? *Natural Resource Modeling* **19**: 441–464.

Punt, A.E., Siddeek, M.S.M., Garber-Yonts, B., Dalton, M., Rugolo, L., Stram, D., Turnock, B.J. & Zheng, J. (2012) Evaluating the impact of buffers to account for scientific uncertainty when setting TACs: application to red king crab in Bristol Bay, Alaska. *ICES Journal of Marine Science* **69**: 624–634.

Punt, A.E., Smith, A.D.M. & Cui, G. (2001). Review of progress in the introduction of management strategy evaluation (MSE) approaches in Australia's South East Fishery. *Marine and Freshwater Research* **52**: 719–726.

Quinn, T.J. & Deriso, R.B. (1999) *Quantitative Fish Dynamics*. New York, NY, USA: Oxford University Press.

Rademeyer, R.A., Plagányi, É.E. & Butterworth, D.S. (2007) Tips and tricks in designing management procedures. *ICES Journal of Marine Science* **64**: 618–625.

Rago, P.J., Wigley, S.E. & Fogarty, L. (2005) NEFSC bycatch estimation methodology: allocation, precision, and accuracy. NOAA, Northeast Fisheries Science Center Reference Document 05–09: 44 pp. [www document]. URL http://noaa.ntis.gov/view.php?pid=NOAA:ocm65198714

Rausser, G., Hamilton, S., Kovach, M. & Stifter, R. (2009) Unintended consequences: the spillover effects of common property regulations. *Marine Policy* **33**: 24–39.

Read, A.J. (2008) The looming crisis: interactions between marine mammals and fisheries. *Journal of Mammalogy* **89**: 541–548.

Reilly, S.B. & Barlow, J. (1986) Rates of increase in dolphin population size. *Fishery Bulletin* **84**: 527–533.

Restrepo, V.R., Thompson, G.G., Mace, P.M., Gabriel, W.L., Low, L.L., MacCall, A.D., Methot, R.D., Powers, J.E., Taylor, B.L., Wade, P.R. & Witzig, J.F. (1998) Technical guidance on the use of precautionary approaches to implementing National Standard 1 of the Magnuson-Stevens Fishery Conservation and Management Act. NOAA Technical Memorandum NMFS-F/SPO-31, National Marine Fisheries Service.

Reuter, R.F., Conners, M.E., Dicosimo, J., Gaichas, S., Ormseth, O. & Tenbrink, T.T. (2010). Managing non-target, data-poor species using catch limits: lessons from the Alaskan groundfish fishery. *Fisheries Management and Ecology* **17**: 323–335.

Richard, Y., Abraham, E.R. & Filippi, D. (2011) Assessment of the risk to seabird populations from New Zealand commercial fisheries. Final Research Report prepared for Ministry of Fisheries projects IPA2009/19 and IPA2009/20. Unpublished report held by the Ministry of Fisheries, Wellington, New Zealand: 66 pp.

Richards, P.M., Epperly, S.P., Heppell, S.S., King, R.T., Sasso, C.R., Moncada, F., Nodarse, G., Shaver, D.J., Medina, Y. & Zurita, J. (2011) Sea turtle population estimates incorporating uncertainty: a new approach applied to western North Atlantic loggerheads *Caretta caretta*. *Endangered Species Research* **15**: 151–158.

Rochet, M.-J. & Rice, J. C. (2009) Simulation-based management strategy evaluation: ignorance disguised as mathematics? *ICES Journal of Marine Science* **66**: 754–762.

Rodríguez-Quiroz, G., Arragón-Noriega, A., Valenzuela-Quiñónez, W. & Esparza-Leal, H.M. (2010) Artisanal fisheries in the conservation zones of the Upper Gulf of California. *Revista de Biología Marina y Oceanografía* **45**: 89–98.

Rosenberg, A.A. & Restrepo, V.R. (1994) Uncertainty and risk evaluation in stock assessment advice for US marine fisheries. *Canadian Journal of Fisheries and Aquatic Sciences* **51**: 2715–2720.

Sainsbury, K.J., Punt, A.E. & Smith, A.D.M. (2000) Design of operational management strategies for achieving fishery ecosystem objectives. *ICES Journal of Marine Science* **57**: 731–741.

Shivji, M.S. (2010) DNA forensic applications in shark management and conservation. In: *Sharks and Their Relatives II: Biodiversity, Adaptive Physiology, and Conservation*, ed. J.C. Carrier, M.R. Heithaus & J.A. Musick, pp. 593–610. Boca Raton, FL, USA: CRC Press.

Smith, A.D.M. (1994) Management strategy evaluation - the light on the hill. In: *Population Dynamics for Fisheries Management: Australian Society for Fish Biology Workshop Proceedings, Perth, 24–25 August 1993*, ed. D.A. Hancock, pp. 249–253. Perth, Australia: Australian Society for Fish Biology.

Smith, S.J., Hunt, J.J. & Rivard, D. (1993) Risk evaluation and biological reference points for fisheries management. Canadian Special Publication of Fisheries and Aquatic Sciences 120: 442 pp.

Smith, A.D.M., Sainsbury, K.J. & Stevens, R.A. (1999) Implementing effective fisheries-management systems: management strategy evaluation and the Australian partnership approach. *ICES Journal of Marine Science* **56**: 967–979.

Smith, A.D.M., Fulton, E.J., Hobday, A.J., Smith, D.C. & Shoulder, P. (2007*b*) Scientific tools to support the practical implementation of ecosystem-based fisheries management. *ICES Journal of Marine Science* **64**: 633–639.

Smith, A.D.M., Hobday, A.J., Webb, H., Daley, R., Wayte, S., Bulman, C., Dowdney, J., Williams, A., Sporcic, M., Dambacher, J., Fuller, M., Furlani, D., Griffiths, S., Kenyon, R. & Walker, T. (2007*a*) Ecological Risk Assessment for the Effects of Fishing: Final Report R04/1072 for the Australian Fisheries Management Authority, Canberra, Australia.

Smith, D.C., Punt, A., Dowling, N., Smith, A.D.M., Tuck, G.N. & Knuckley, I. (2009) Reconciling approaches to the assessment and management of data-poor species and fisheries with Australia's harvest strategy policy. *Marine and Coastal Fisheries: Dynamics, Management and Ecosystem Science* **1**: 244–254.

Snover, M.L. & Heppell, S.S. (2009) Application of diffusion approximation for risk assessments of sea turtle populations. *Ecological Applications* **19**: 774–785.

Stevens, J.D., Bonfil, R., Dulvy, N.K. & Walker, P.A. (2000) The effects of fishing on sharks, rays, and chimaeras (chondrichthyans), and the implications for marine ecosystems. *ICES Journal of Marine Science* **57**: 476–494.

Stobutzki, I., Miller, M. & Brewer, D. (2001) Sustainability of fishery bycatch: a process for assessing highly diverse and numerous bycatch. *Environmental Conservation* **28**: 167–181.

Stobutzki, I.C., Miller, M.J., Heales, D.S. & Brewer, D.T. (2002) Sustainability of elasmobranchs caught as bycatch in a tropical prawn (shrimp) trawl fishery. *Fishery Bulletin* **100**: 800–821.

Tasker, M.L., Camphuysen, C.J., Cooper, J., Garthe, S., Montevecchi, W.A. & Blaber, S.J.M. (2000) The impacts of fishing on marine birds. *ICES Journal of Marine Science* **57**: 531–547.

Taylor, B.L. (1997) Defining 'population' to meet management objectives for marine mammals. In: *Molecular Genetics of Marine Mammals*, ed. A.E. Dizon, S.J. Chivers & W.J. Perrin, pp. 49–65. Society of Marine Mammalogy, Special Publication 3.

Taylor, B.L. & DeMaster, D.P. (1993) Implications of non-linear density dependence. *Marine Mammal Science* **9**: 360–371.

Taylor, B.L., Wade, P.R., de Master, D.P. & Barlow, J. (2000) Incorporating uncertainty into management models for marine mammals. *Conservation Biology* **14**: 1243–1252.

Taylor, I.G., Gertseva, V., Methot Jr, R.D. & Maunder, M.N. (2012) A stock–recruitment relationship based on pre-recruit survival, illustrated with application to spiny dogfish shark. *Fisheries Research* doi:10.1016/j.fishres.2012.04.018 (in press).

Tuck, G.N. (2011) Are bycatch rates sufficient as the principal fishery performance measure and method of assessment for seabirds? *Aquatic Conservation: Marine and Freshwater Ecosystems* **21**: 412–422.

Tuck, G.N., Phillips, R.A., Small, C., Thomson, R.B., Klaer, N.L., Taylor, F., Wanless, R.M. & Arrizabalaga, H. (2011) An assessment of seabird-fishery interactions in the Atlantic Ocean. *ICES Journal of Marine Science* **68**: 1628–1637.

USEPA (1998) Guidelines for ecological risk assessment. EPA/630/R-95/002F. *Federal Register* **63**: 26846–26924.

Wade, P.R. (1998) Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. *Marine Mammal Science* **14**: 1–37.

Wade, P.R., Reeves, R.R. & Mesnick, S.L. (2012) Social and behavioral factors in cetacean responses to overexploitation: are odontocetes less 'resilient' than mysticetes? *Journal of Marine Biology* doi: 10.1155/2012/567276 (in press).

Wallace, B.P., DiMatteo, A.D., Bolten, A.B., Chaloupka, M.Y., Hutchinson, B.J., Abreu-Grobois, F.A., Mortimer, J.A., Seminoff, J.A., Amorocho, D., Bjorndal, K.A., Bourjea, J., Bowen, B.W., Dueñas, R.B., Casale, P., Choudhury, B.C., Costa, A., Dutton, P.H., Fallabrino, A., Finkbeiner, E.M., Girard, A., Girondot, M., Hamann, M., Hurley, B.J., López-Mendilaharsu, M., Marcovaldi, M.A., Musick, J.A., Nel, R., Pilcher, N.J., Troëng, S., Witherington, B. & Mast, R.B. (2011) Global conservation priorities for marine turtles. *PLoS ONE* **6**: e24510.

Ward-Paige, C.A. & Lotze, H.K. (2011). Assessing the value of recreational divers for censusing elasmobranchs. *PLoS ONE* **6**: e25609.

Warden, M. L. & Murray, K.T. (2011) Reframing protected species interactions with commercial fishing gear: Moving toward estimating the unobservable. *Fisheries Research* **110**: 387–390.

Waugh, S.M., Baker, G.B., Gales, R. & Croxall, J.P. (2008) CCAMLR process of risk assessment to minimise the effects of longline fishing mortality on seabirds. *Marine Policy* **32**: 442–454.

Watson, J.T., Essington, T.E., Lennert-Cody, C.E. & Hall, M.A. (2009) Trade-offs in the design of fishery closures: management of silky shark bycatch in the Eastern Pacific Ocean tuna fishery. *Conservation Biology* **23**: 626–635.

WCPFC (2011) Report of the First Meeting of the Kobe Process Joint Technical Working Group on Bycatch, La Jolla, CA July 11, 2011. WCPFC-SC7–2011/EB-WP-14. Western and Central Pacific Fisheries Commission Secretariat.

Werner, T., Krauss, S., Read, A. & Zollett, E. (2006) Fishing techniques to reduce the bycatch of threatened marine animals. *Marine Technology Society Journal* **40**: 50–68.

Wetzel, C.R. & Punt, A.E. (2011) Model performance for the determination of appropriate harvest levels in the case of data-poor stocks. *Fisheries Research* **110**: 342–355.

Williams, R., Hall, A. & Winship, A. (2008) Potential limits to anthropogenic mortality of small cetaceans in coastal waters of British Columbia. *Canadian Journal of Fisheries and Aquatic Sciences* **65**: 1867–1878.

Zhou, S. & Griffiths, S.P. (2008) Sustainability assessment for fishing effects (SAFE): a new quantitative ecological risk assessment method and its application to elasmobranch bycatch in an Australian trawl fishery. *Fisheries Research* **91**: 56–68.

Zhou, S., Smith, A.D.M. & Fuller, M. (2011) Quantitative ecological risk assessment for fishing effects on diverse non-target species in a multi-sector and multi-gear fishery. *Fisheries Research* **112**: 168–178.

Zhou, S., Milton, D.A. & Fry, G.C. (2012*a*) Integrated risk analysis for rare marine species impacted by fishing: sustainability assessment and population trend modelling. *ICES Journal of Marine Science* **69**: 271–280

Zhou, S., Yin, S., Thorson, J.T., Smith, A.D.M. & Fuller, M. (2012*b*) Linking fishing mortality reference points to life history traits: an empirical study. *Canadian Journal of Fisheries and Aquatic Sciences* **69**: 1292–1301.