



Ecological risk assessment for the effects of fishing

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ABSTRACT

Management of fisheries around the world is challenged by fishing impacts on habitats, bycatch species, threatened and endangered species, and even associated ecological communities. One response to these other factors has been a call for ecosystem-based fisheries management (EBFM), which demands consideration of the above non-target interactions. A challenge with implementation of EBFM is the scale and range of issues to be considered, all of which cannot be addressed at the same level of detail as for target species, due to data or time constraints. We developed an approach to progress the EBFM mandate in Australia, using a new ecological risk assessment framework applied to fisheries, termed Ecological Risk Assessment for the Effects of Fishing (ERAEF). Novel features of this framework include its hierarchical structure and its precautionary approach to uncertainty. The amount of information required increases through the hierarchy, and allows application in data-limited situations. The ERAEF framework has been applied to over 30 fisheries in Australia and elsewhere. The efficiencies in application of the hierarchical approach are illustrated by the south-east otter trawl fishery, where following Level 1 assessment of all components, an initial set of 600 species and 158 habitats was reduced to a group of concern of 159 species and 46 habitats using the Level 2 analysis, with the number of species of concern further reduced to 25 following Level 3 analysis. As a result of the assessments in Australia, management actions have been enacted for a range of the high risk species. Overall, the ERAEF approach offers a realistic method to assess ecological risk in an EBFM context, and has applicability in a wide range of fisheries. The interactive and inclusive nature of the approach also has the advantage of bringing stakeholders, scientists and managers together to develop management solutions.

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1. Introduction

It is now widely recognized that fisheries have impacts on marine species, habitats and ecosystems that go well beyond the direct impacts of fishing on target species (see [Hollingworth, 2000](#)

and papers within; [Hall and Mainprize, 2004](#)). For example, hundreds of species are regularly caught and discarded in many trawl and longline fisheries, and global annual discards from fishing have been estimated at over 20 million tonnes ([FAO, 1999](#)). Interactions with threatened species can impact vulnerable populations, and are a concern in many fisheries (e.g. [Goldsworthy et al., 2001](#); [Kock, 2001](#)). Impacts on habitats and ecological communities have also been documented (e.g. [Thrush et al., 1995](#); [Freese et al., 1999](#); [Thrush and Dayton, 2002](#); [Althaus et al., 2009](#)).

To address these broader impacts of fishing, ecosystem-based fisheries management (EBFM), also called the ecosystem approach to fisheries, has emerged over the past decade as an alternative approach to single-species fishery management ([Link et al., 2002](#); [FAO, 2003](#); [Pikitch et al., 2004](#)). While policy has shifted towards

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EBFM in a number of countries, development of practical methods to implement EBFM has not been as rapid (Pitcher et al., 2009). For example, the EBFM approach has been broadly adopted at a policy level within Australia through a variety of instruments including fisheries legislation, environmental legislation, and a national policy on integrated oceans management (McLoughlin et al., 2008; Webb and Smith, 2008). These policy changes, occurring mainly in the late 1990s, required the rapid development of scientific and management tools to support practical implementation (Smith et al., 2007a; McLoughlin et al., 2008).

A key challenge in developing the scientific tools to support EBFM has been the paucity of data and understanding about the broader ecological impacts of fishing in particular fisheries (e.g. Leslie et al., 2008). One response to this has been the adoption of risk-based assessment methods, notably ecological risk assessment. In some cases, application of these tools to fisheries has adopted conventional likelihood-consequence approaches to risk assessment (Fletcher, 2005), while in other cases novel approaches have been developed (Stobutzki et al., 2002).

In this paper we describe a new ecological risk assessment framework applied to fisheries, termed ERAEF (Ecological Risk Assessment for the Effects of Fishing). Novel features of this framework include its hierarchical structure and its precautionary approach to ecological uncertainty. This method has been widely used within federally managed fisheries in Australia, and is now receiving international interest, having recently been adapted for use by the Marine Stewardship Council. Here we outline the rationale for risk assessments in fisheries and the desirable features of such approaches, before describing the ERAEF method in detail, and presenting some results from Australian fisheries. We conclude with some general observations about the challenge and future prospects of such methods in supporting the EBFM approach.

2. Risk assessment for fisheries

There are many definitions of risk and many approaches to risk assessment (Burgman, 2005). In the method we will describe, risk is defined as the probability that a (specified) fishery management objective is not achieved. By this definition, many tools currently used in fishery assessment, including conventional quantitative stock assessment, may be viewed as forms of risk assessment. Integration of social and economic aspects in risk assessments is less advanced (Webb and Smith, 2008, but see Pitcher and Preikshot, 2001), and so the focus here is on ecological risk assessments (ERA).

One way that ERA approaches can be distinguished is in the level of quantitative information required. Particularly for data-deficient fisheries and those with limited knowledge of ecological interactions, a qualitative risk assessment tool is needed (Fletcher, 2005; Astles et al., 2006; Walker, 2005; Campbell and Gallagher, 2007). Where more data are available, semi-quantitative or quantitative approaches may be useful (Stobutzki et al., 2002; Zhou and Griffiths, 2008). Most existing ERA methods operate at a single level of analysis (Scandol et al., 2009). The distinguishing feature of the ERAEF relative to other approaches is that it comprises a hierarchical set of methods or tools, representing different levels of “quantification”, that are linked within a single framework.

There are several desirable attributes of an ERA process (Burgman, 2005; Smith et al., 2007b; Scandol et al., 2009). An ERA that is used to assess the effects of fishing should ideally be:

- Comprehensive (identify and analyse all potential hazards).
- Flexible (applicable to all types of fishery, irrespective of size, fishing method, species).
- Transparent and repeatable (be clear about the methods, data and assumptions used in the analyses).

- Understandable (easy for stakeholders to grasp).
- Cost effective (make use of existing knowledge, information and data within realistic limits of time and resources).
- Scientifically defensible (be able to withstand independent scientific peer review).
- Useful for management (inform appropriate risk management responses), and
- Take a precautionary approach to uncertainty.

In reality, there are tradeoffs between these various criteria, and no single approach to ERA is likely to completely meet all criteria (Scandol et al., 2009). Nevertheless, the ERAEF method we describe here was designed with these criteria in mind. The individual methods used within ERAEF have evolved from several approaches, including Stobutzki et al. (2002), Fletcher (2005), Walker (2005), Griffiths et al. (2006) and Zhou and Griffiths (2008). Similar semi-quantitative approaches have also been developed over the last five years (e.g. Astles et al., 2006; Campbell and Gallagher, 2007). The ERAEF method described here is a framework rather than a single method, and is distinguished by its explicit hierarchical structure. Full details of the ERAEF methods, including a step-by-step user guide, are in Hobday et al. (2007) and an overview only is presented here.

3. Description of the ERAEF method

The ERAEF framework involves a hierarchical approach that moves from a comprehensive but largely qualitative analysis of risk at Level 1, through a more focused and semi-quantitative approach at Level 2, to a highly focused and fully quantitative “model-based” approach at Level 3 (Fig. 1). This approach is efficient because many potential activities/hazards are screened out at Level 1, so that the more intensive and quantitative analyses at Level 2, and ultimately at Level 3, are limited to a subset of the higher risk activities associated with fishing. It also leads to rapid identification of high-risk activities, which in turn can lead to immediate remedial action (risk management response) where it may be inappropriate to delay action pending further analysis. The ERAEF approach is also precautionary, in the sense that fishing activities are assumed to pose high risks in the absence of information, evidence or logical argument to the contrary (Hobday et al., 2007).

The approach makes use of a general conceptual model of how fishing impacts on ecological systems, which is used as the basis for the risk assessment evaluations at each level of analysis. Five general ecological components are evaluated, corresponding to five areas of focus in evaluating impacts of fishing for strategic assessment under Australian environmental legislation. The five components are:

- Target species.
- By-product and by-catch species.
- Threatened, endangered and protected species (TEP species).
- Habitats.
- Ecological communities.

Because a single widely accepted operational definition of an ecosystem is lacking, we define these five components in such a way that “elements of an ecosystem” are covered. This compartmental approach allows all five components to be evaluated independently; a single component might be included in a risk assessment if a particular focus is required. Future expansion or contraction of the components is also possible within the ERAEF framework. Within each of these components, units of analysis are defined: in the three species components (target, bycatch, TEP) the units are species or stocks; for the habitat component the units

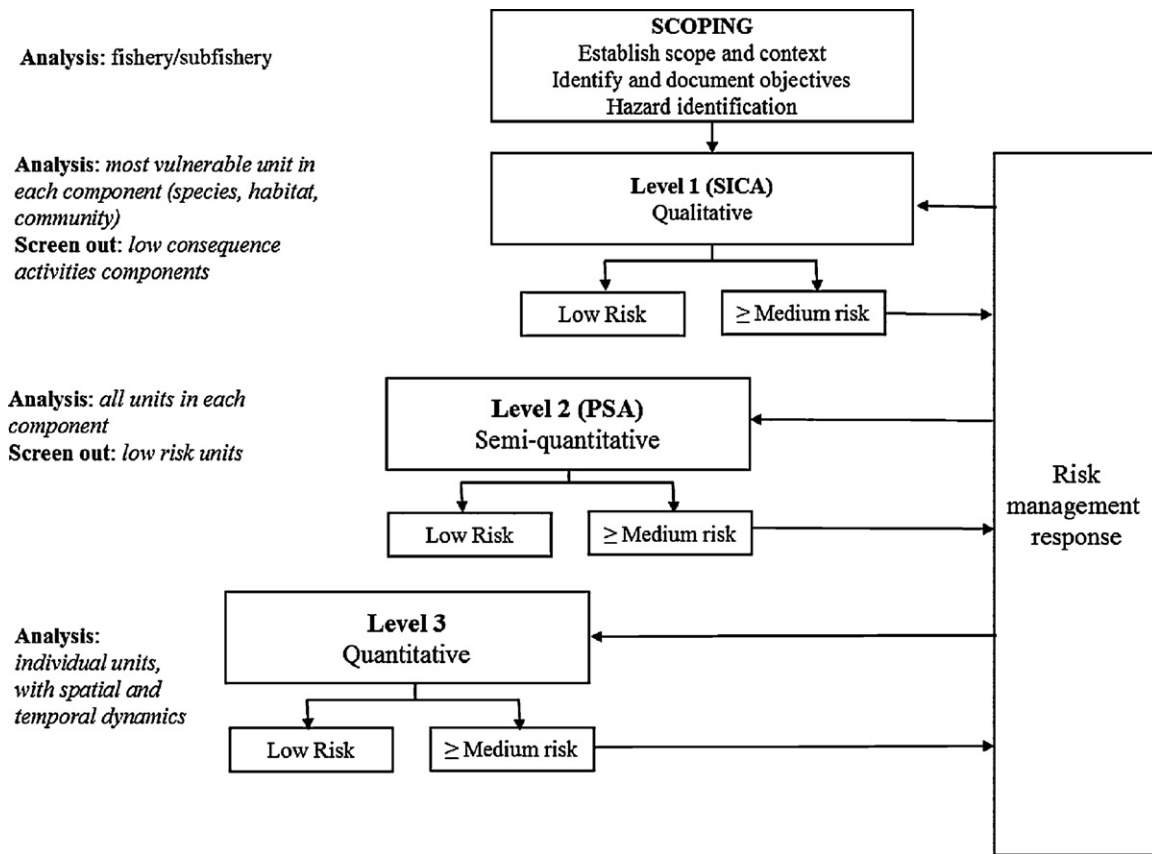


Fig. 1. Overview of the ERAEF framework showing focus of analysis for each level in the hierarchy at the left in italics. At each level a risk management response is an alternative to proceeding to the next level in the hierarchy.

are habitat types defined by abiotic and biotic elements; and for ecological communities, the units are assemblages.

A crucial process in any risk assessment framework is to document the rationale behind assessments and decisions at each step in the analysis (Burgman, 2005). The decision to analyse the risks at subsequent higher levels in the ERAEF depends on (i) estimated risk at the current level, (ii) availability of data to proceed to the next level, and (iii) management response to risks identified at the current level (e.g. if the risk is high but immediate changes to management regulations or fishing practices will reduce the risk, then analysis at the next level may be unnecessary).

In the hierarchy of the ERAEF, uncertainty decreases with increasing level (Fig. 2). Units that are clearly low risk can often be eliminated without analysis at higher levels of complexity. Units that cannot be clearly shown to be low risk are examined in more detail at the next level. The trade-offs in progressing to higher levels are increased data needs and costs to undertake the assessment. Thus, the ERAEF is able to screen out the low risk elements at each level, and focus attention on potential issues of higher and/or uncertain risk at subsequent levels. In the following sub-sections we outline the steps in the ERAEF approach, together with an explanation of the underlying model that unites the levels of the hierarchy.

3.1. Stakeholder participation in the ERAEF

Participation of stakeholders is an important feature of ERAEF, and is particularly important in the more qualitative levels in the hierarchy (scoping and Level 1), where a range of inputs requires a diverse group. Stakeholders in ERAEF are defined as those people who have a direct interest in a fishery, and can include for a commercial fishery: commercial fishers, managers, recreational

fishers, indigenous fishers, conservation focused non-government organizations, fishery scientists, and experts in particular taxa. Stakeholder participation in the process not only improves the assessments, but also increases the chance of uptake of results and helps in identifying suitable management responses. In many fisheries in Australia, a wide range of stakeholders are already involved in the management process, while for other jurisdictions, assembling representative stakeholders may pose a challenge. Without

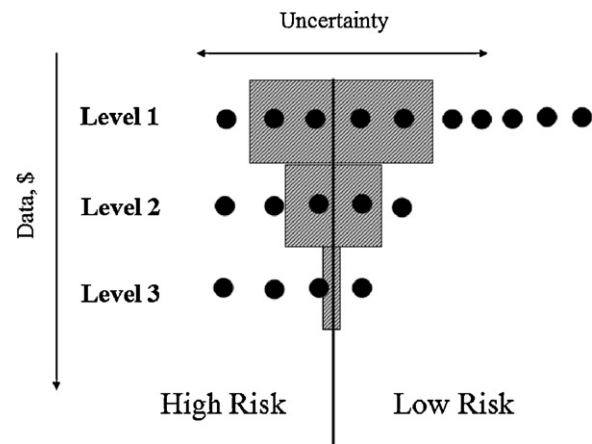


Fig. 2. Schematic representation of the successive screening of risk and reduction of uncertainty through the ERAEF hierarchy. The width of the grey bars at each level indicates the uncertainty in determining high or low risk. The activities, symbolized by black dots, can be more clearly distinguished as low or high risk (outside the grey bars) at higher levels in the hierarchy. Note that the reduction in uncertainty is accompanied by an increase in assessment costs (data and \$) in moving from Levels 1 to 3.

a good representation of stakeholders, issues may not be correctly identified or evaluated, particularly at Level 1 in the ERAEF. Most often, stakeholders are engaged through face-to-face meetings.

3.2. Precautionary elements in the ERAEF

The ERAEF approach has a number of features that result in a precautionary or conservative approach to identifying and ranking ecological risk. Principal among these is assuming high risk in the absence of data or information to the contrary. This feature provides an incentive to collect data to support future assessments. In general, the precautionary approach will result in more false positives (units identified at higher risk than would occur when assessed at a higher level with more data) than false negatives (units scored at a lower risk than would occur when assessed at a higher level with more data). This bias is important, as false positive results can be screened out at higher levels in the ERAEF hierarchy, while false negatives result in improper elimination of a hazard or unit, with no further opportunity to consider it at later stages in the ERAEF. While no bias would be preferable, the uncertainty associated with the qualitative and semi-quantitative risk assessments at Levels 1 and 2 argues in favour of maintaining a bias against false negative results.

3.3. Scoping

The first step in the ERAEF is the scoping stage, and it is here that a description of the fishery is completed, management objectives recorded, activities/hazards listed, and units of analyses identified. *Unit of analysis* is a generic term that applies to the species within the species components (target, bycatch, TEP), the habitats within the habitat component, and the ecological assemblages within the community component. The set of species to be considered can be assembled using catch data, observer records, expert opinion, and/or species distribution maps. The set of habitats is based on geo-morphology Williams et al. (in press). Substratum and faunistic characters and the community units are either qualitative or model-based foodweb descriptions (Hobday et al., 2007).

ERAEF requires the identification of management objectives for all five ecological components in the system. These are not always well defined *a priori*, and we have developed a generic set that can be modified by the stakeholders and assessment team (Hobday et al., 2007). For example, a generic objective for the habitat component is “Relative abundance of habitat types does not vary outside acceptable bounds”. While often quite general, these objectives serve to promote discussion and agreement among disparate stakeholders that a range of ecological values are important to the sustainability of the fishery. More specific “acceptable bounds” are then developed for use in Level 1.

The set of activities is selected from a comprehensive checklist. Formally, these activities are known as hazards (Burgman, 2005). In ERAEF, hazards are the activities undertaken in the process of fishing, together with any external activities, which have the potential to adversely impact on ecological components. The fishery-specific hazards are divided into the following categories based on the major effect of the activity:

- capture/removal;
- direct impact without capture;
- addition/movement of biological material;
- addition of non biological material;
- disturbance of physical processes;
- external hazards.

These categories are then subdivided into fishing activities (of the fishery being evaluated) and external activities (including other

fisheries) (Hobday et al., 2007). These fishing and external activities are scored on a presence/absence basis for each fishery. Only those activities that are scored as present in a fishery are then carried forward for analysis in subsequent levels.

Precautionary elements in the scoping stage are included in two ways. First, the identification of objectives allows an appropriate approach to precaution. The default objectives provided are generally of the form “impact is within acceptable bounds” and these bounds are selected to be precautionary (Hobday et al., 2007). The second precautionary element at this stage is in the identification of the activities. Use of a comprehensive activity checklist forces consideration of a broad range of potential hazards, which is precautionary in nature compared to considering only expert-selected subsets of activities. At the end of the scoping stage, the background characteristics and history of the fishery will have been documented, the objectives recorded, units of analysis identified, and the activities that may cause harm identified. The next stage in ERAEF is to proceed to the analytical levels of the hierarchy (Levels 1–3).

Levels in the ERAEF framework differ in the resolution at which risk is assessed, but the levels are linked by an underlying model. The underlying model is based on a theoretical relationship that describes the rate of change (in abundance, amount or extent) of the unit at risk (e.g. a species or habitat). The fishery under consideration has the potential to influence the rate of change of units in each component (e.g. target bycatch, TEP species, habitat types, and ecological communities) and the ecological risk is the expression of the influence of the fishery activities on the rate of change of the unit. Fishery activities that cause too much change in the dynamics of the ecological system are undesirable in terms of ecological risk. In general, the rate of change in a unit (dP/dt) can be expressed as a function of the intrinsic growth rate (r) and the total amount of the unit (P)

$$\frac{dP}{dt} = f(r, P) \quad (1)$$

Removal or enhancement (C , which can be positive or negative) due to anthropogenic factors can be subtracted from the relationship.

$$\frac{dP}{dt} = f(r, P) - C \quad (2)$$

This general form is suitable for all the components included in the ERAEF and can be modified to an appropriate model for each component (e.g. Williams et al., in press). The logistic equation is a well-known example from this general form (1) that describes the rate of change of a population biomass (unit measure for species) as a function of carrying capacity, intrinsic rate of population growth, and fishery removals that are related to effort, population biomass and catchability. The unit measures are specific to each component, expressed in terms of areal coverage for habitat components, or species richness for communities, for example. The exact formulation of the general model differs among components and sub-components, but the influence of fishing activities on the functional form (Eq. (2)) remains consistent. The relative magnitude of the impact on each of the parameters need not be considered prior to Level 3, although threshold levels for the acceptable rate of change may be identified, such as often occurs for TEP species.

3.4. Level 1 – scale intensity consequence analysis (SICA)

Level 1 analysis relies on expert judgment involving the stakeholders. The focus of analysis at this level (SICA) is the ecological component. In other ERA approaches that are equivalent to ERAEF's Level 1 (e.g. Fletcher et al., 2002; Fletcher, 2005), a likelihood-consequence framework has been employed in which likelihood

Table 1
Productivity cutoff scores for species attributes for the ERAEF Level 2 PSA method. These cutoffs have been determined from analysis of the distribution of attribute values for species in the ERAEF database, and are intended to divide the attribute values into low, medium and high productivity categories.

Attribute	Low productivity (high risk, score = 3)	Medium productivity medium risk, score = 2)	High productivity (low risk, score = 1)
Average age at maturity	>15 years	5–15 years	<5 years
Average maximum age	>25 years	10–25 years	<10 years
Fecundity	<100 eggs per year	100–20,000 eggs per year	>20,000 eggs per year
Average maximum size	>300 cm	100–300 cm	<100 cm
Average size at maturity	>200 cm	40–200 cm	<40 cm
Reproductive strategy	Live bearer (and birds)	Demersal egg layer	Broadcast spawner
Trophic level	>3.25	2.75–3.25	<2.75

and the consequence of the event is estimated for each unit in each of the components considered, which can be extremely time consuming (Scandol et al., 2009). In the ERAEF framework, an exposure-effects risk assessment approach is used at Level 1, and is only applied to the “worst case” unit (see below). The exposure-effects model is common in situations such as human drug testing, where an effect given an exposure to a drug is of interest. Similarly, in fisheries, the interest is the effect (e.g. impact on population size) resulting from a certain exposure (e.g. catch level). The approach used at Level 1 involves scoring each fishing activity (hazard) for impact on the core objective for the component. The scale and intensity of the activity are each scored (\approx exposure), and then the consequence score (\approx effect) is selected from a component-specific set of scoring guidelines (Hobday et al., 2007). These scoring tables, adapted from Fletcher et al. (2002), reflect a range of impact levels from negligible (score 1) to extreme (score 6). Scores of 3 or higher within a component result in that component being examined at Level 2.

The scale and intensity scoring reflects potential changes in the catch/removal term of the logistic model (q and E) due to the hazard, while the consequence scoring reflects the effect the hazard will have on the intrinsic rate of increase (r). For example, a high intensity score would indicate that “removal” is highly likely, while a high consequence score indicates that the rate of increase or carrying capacity would be greatly reduced by this activity. The effort term (E) is approximated by the spatial and temporal scale of the activity, which is an important consideration in evaluating the risk for particular activities.

3.4.1. Level 1 – uncertainty and precautionary elements

The SICA analysis employs a “plausible worst case” approach to evaluation of risk, rather than considering all possible interactions. In assigning a consequence score for each activity/component combination, the highest-scoring (worst case) plausible scenario is selected. For example, in scoring the direct impact of fishing on the bycatch component, the stakeholders would consider the relative vulnerability to the gear among the bycatch species, and select the most vulnerable species based on the combination of exposure to the gear and potential rate of recovery of the species to impact. The highest score consistent with a plausible scenario is reported in the case of dispute.

If the plausible worst case scenario is not assessed to be at significant risk, then all other hazards will be at even lower risk. This leads to considerable efficiency in screening out low risks. The level of consequence that is deemed “significant” can also be selected with precaution in mind. In Australian applications to date, any consequence level above “minor” (score of 2) either elicits a management response, or is analysed further at a higher level in the hierarchy.

3.5. Level 2 – productivity susceptibility analysis (PSA)

The analysis at Level 2 is based on scoring each unit of analysis within a component on a number of productivity and susceptibility

attributes, and follows from an approach developed by Stobutzki et al. (2002). The productivity attributes influence the “intrinsic rate of increase” (r) in the logistic model (Table 1), while the susceptibility attributes are reflected in the catch/removal portion, in particular the catchability term (q) (Table 2). Thus, the productivity and susceptibility concepts that are used at Level 2 are similar in approach to Level 1. A major difference is the amount of data required, but the underlying model is basically the same.

The level of fishing impact a unit of analysis (e.g. species, habitat type, or species assemblage) can sustain, and the capacity to recover from impacts depends on its inherent productivity. For example, the productivity of a species or populations is determined by demographic attributes such as longevity, growth rate, fecundity, recruitment and natural mortality (Table 1). The productivity of a unit such as a “habitat type” is determined by habitat attributes such as regeneration rates (see Williams et al., in press). For community units, the productivity might be determined by the diversity or size of the members. While units have inherent productivity, fishing can also affect productivity of the unit depending on the size of reduction in the unit and the life stage of a species taken by a fishery. The productivity attributes were scored using a default set of scores developed for Australian fisheries (for a species example see Table 1); values for the cutoffs between risk categories may need to be tuned for other regions. For example, in tropical regions, faster demographic rates may lead to different productivity for the same values as in temperate regions, and hence the need to modify the cutoff scores.

Following Walker (2005), species susceptibility is estimated as the product of four independent aspects: availability, encounterability, selectivity and post-capture mortality (PCM). A multiplicative approach is considered more appropriate for susceptibility because low risk for any single aspect acts to reduce the overall risk to a low value. For example, if a species is available in a fishing area, encounters the fishing gear, is selected by the gear, but is returned to the water unharmed (post-capture mortality low), then the overall susceptibility should be recognized as low. The treatment of these aspects has been tailored to utilize available datasets (e.g. FishBase), and incorporate additional information, such as outputs from mapping of species range and distribution (Hobday et al., 2007). The level of fishing impact that a unit of analysis can sustain depends on its susceptibility to capture or damage by the sub-fishery activities. For example, the susceptibility of a unit such as a species is determined by species attributes such as habitat overlap with the fishery, depth in the water column, and feeding method (Table 2). The susceptibility of a unit such as “habitat type” is determined by abiotic habitat attributes such as substratum type and the fishing method (Hobday et al., 2007). The susceptibility of the community units is determined by functional group redundancy, or trophic level diversity.

The productivity and susceptibility attributes are scored as 1 (low), 2 (medium) or 3 (high). Missing attributes are scored as a 3. These scores are then plotted for visualization on a PSA plot (Fig. 3A). An overall risk score is the Euclidean distance from the origin, which allows a single risk ranking. It is important to note

Table 2

Susceptibility cutoff scores for species attributes for the ERAEF Level 2 PSA method. These example cutoffs have been determined from analysis of the distribution of attribute values for species in the ERAEF database, and are intended to divide the attribute values into low, medium and high susceptibility categories. A choice of attributes exists for some susceptibility aspects, such as availability; where if data are available, availability 1 is preferred over availability 2, while for encounterability, the maximum score of the two attribute choices (encounterability 1 and encounterability 2) is used.

Attribute	Low susceptibility (low risk, score = 1)	Medium susceptibility (medium risk, score = 2)	High susceptibility (high risk, score = 3)
Availability 1. Overlap of species range with fishery	<10% overlap	10–30% overlap	>30% overlap
Availability 2. Global distribution. Also need to consider stock proxies	Globally distributed	Restricted to same hemisphere/ocean basin as fishery	Restricted to same country as fishery
Encounterability 1 – Habitat (scores vary by fishery)	Low overlap with fishing gear	Medium overlap with fishing gear	High overlap with fishing gear
Encounterability 2 – depth check (scores vary by fishery)	Low overlap with fishing gear	Medium overlap with fishing gear	High overlap with fishing gear
Selectivity (scores vary by gear type, this example is for set gillnets)	Species < mesh size, or >5 m in length	Species 1–2 times mesh size, 4–5 m in length	Species >2 times mesh size, to say, 4 m in length
Post-capture mortality (scores vary by fishery)	Evidence of post-capture release and survival	Released alive	Retained species, or majority dead when released

that these risk values are mostly determined by “intrinsic” properties of the species (productivity), and while the relative fishery interactions are measured through the susceptibility attributes, assessment of the actual impact of the sub-fishery on the species is not made.

Species identified as high-risk from the PSA analysis are candidates for further quantitative assessment at Level 3. In some cases, examination at Level 3 may not be necessary if alternative information exists (e.g. a pre-existing quantitative stock assessment that shows that harvest levels are sustainable). The advantage of Level 2 is that it allows the rapid screening of low-risk species, reducing the time and cost of analyses at Level 3. Some species will

be identified as high risk from a Level 2 analysis due to missing attributes (which automatically score high risk). For such species, priority is given to collecting missing attribute information rather than moving immediately to Level 3 analysis.

3.5.1. Level 2 – uncertainty and precautionary elements

The PSA method is based on a limited number of attributes that are widely available; however, the risk estimates derived are subject to a range of uncertainties. Chief among these is that the PSA scores estimate relative rather than absolute levels of risk, by using proxies for productivity, rather than productivity estimates as derived from quantitative assessment models. Furthermore, the

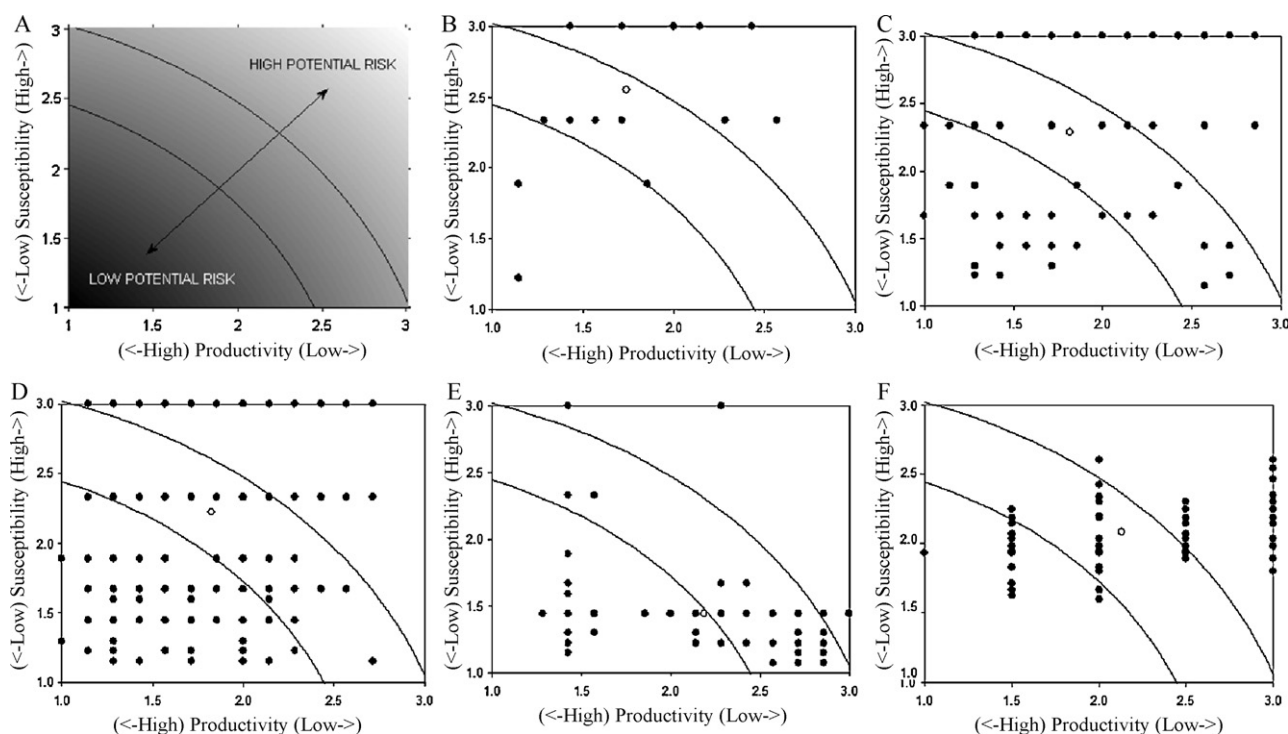


Fig. 3. Productivity Susceptibility Analysis (PSA). (A) The axes on which risk to the ecological units is plotted. The x-axis score derives from attributes that influence the productivity of a unit, or its ability to recover after impact from fishing. The y-axis score derives from attributes that influence the susceptibility of the unit to impacts from fishing. The combination of susceptibility and productivity determines the relative risk to a unit, i.e. units with high susceptibility and low productivity are at highest risk, while units with low susceptibility and high productivity are at lowest risk. The curved lines divide the PSA plot into thirds, representing low, medium and high risk, and group units of similar risk levels. (B–F) Results from the Level 2 PSA analysis of the SESSF otter trawl fishery. (B) Target species, (C) byproduct species, (D) bycatch species, (E) TEP species, and (F) habitat types. Note the species in the byproduct/bycatch component are plotted separately here due to the large number of species. The open circle on each plot shows the mean for the component. Multiple units can be plotted at the same point if the scores are the same.

method does not require or assume that levels of catch or effort are available for each ecological unit impacted (these are frequently not available for bycatch and TEP species). Nevertheless the method does allow the identification of species or habitats that are at greater potential risk due to characteristics of their biology or exposure to hazards from fishing, and this is useful in prioritizing remedial action or further analysis. Precautionary elements in the Level 2 PSA include:

- Attributes are set to default high risk values in the absence of information to the contrary.
- If independently verifiable information (such as independent observer data, scientific references or reports, expert knowledge from those with no vested interest in the fishery) can be clearly documented, scores can be modified (Hobday et al., 2007).
- Explicit assumptions in the detail of the methods – for example, the spatial overlap score for availability is based on overlap of effort with the species distribution only within the area of the fishery (implicitly assuming that there may be a stock that is local to the area of the fishery).

3.6. Level 3

Level 3 is the point in the ERAEF hierarchy where a fully quantitative assessment is first undertaken. A range of methods and approaches already exists at this level, but there remain challenges in finding methods that can work within the constraints of limited data and time for analysis.

One “rapid assessment” method that has been applied to species is the Sustainability Assessment for Fishing Effects (SAFE) method of Zhou and Griffiths (2008). This method provides an absolute measure of risk by directly estimating both a fishing mortality rate and a quantitative reference point associated with it, but is less demanding of data and much simpler to apply than a typical quantitative stock assessment – for example it requires information on levels of effort but not of catch. It has proven particularly valuable in assessing large numbers of bycatch species in multi-species trawl fisheries (Zhou et al., 2009). The SAFE relies fairly heavily on knowledge of the spatial overlap of fishing effort with the species distribution and the estimate of risk is sensitive to this quantity, but methods that do not account for this overlap can also miss important information. SAFE requires less “productivity” data than PSA.

With regard to habitat and community components, quantitative benthic species impact assessment models are starting to be used (Ellis et al., 2008; Dichmont et al., 2008) but have not to date been incorporated directly in ERAEF analyses (Williams et al., *in press*). Similar assessments of the impacts of trawling on benthic (sessile) species have also been conducted in the Great Barrier Reef (Pitcher et al., 2007a) and the Torres Strait (Pitcher et al., 2007b). Community and ecosystem level quantitative analyses have become more common over recent years with the advent of Ecopath with Ecosim (Christensen and Walters, 2004; Walters et al., 2005). The need for these tools is addressed in the final section.

3.6.1. Level 3 – uncertainty and precautionary elements

Being quantitative and generally model-based, Level 3 analyses can explicitly account for uncertainty. Although the SAFE analyses provide direct estimates of uncertainty in both the exploitation rate and the associated reference points, they are less explicit about uncertainties arising from key assumptions in the method, including spatial distribution and movement of stocks. SAFE analyses retain some of the key precautionary elements of the PSA method, including assumptions that fisheries are impacting local stocks (within the jurisdictional area of the fishery). Comparisons of PSA

and SAFE analyses for the same fisheries and species support the claim that the PSA method generally avoids false negatives but can result in many false positives. Limited testing of SAFE results against full quantitative stock assessments suggest that there is less “bias” in the method, but that both false negatives and false positives can and do arise (Hobday, unpublished data).

4. Application of the ERAEF

4.1. Summary across fisheries

The ERAEF method has been used in Australian federally managed fisheries over the period 2004–2007 to assess over 31 sub-fisheries (gear types within managed fisheries), ranging from demersal trawl to longline to purse-seine (Smith et al., 2007b). The scoping stage of the ERAEF identified five common activities (hazards) within these fisheries: (i) capture by fishing, (ii) direct impact without capture by fishing and general boat activity (e.g. steaming), (iii) addition of non-biological material by navigation and steaming, and from exhaust (iv) disturbance of physical processes by navigation and steaming, and by anchoring or mooring, and (v) activities in other fisheries affecting the fishery being assessed. The activities that were rarely occurring in these Australian fisheries included (i) stock enhancement, (ii) bait collection, and (iii) boat launching away from established harbours. Between 14 and 29 activities occurred in any one fishery (Smith et al., 2007b).

At Level 1, a comprehensive assessment of the risks associated with each of the identified fishing activities on all five ecological components was completed for the 31 sub-fisheries. The highest risk activities across all components were: (i) other fisheries, (ii) capture by fishing, (iii) direct impact of fishing without capture, and (iv) translocation of species. Although averaging scores can obscure the individual results, it does allow comparison of fishing impact at Level 1. The mean impact score across all fisheries for all activities (26 possible activities) was highest for the TEP component (1.15), followed by habitat (1.11), target species (1.01), communities (0.99) and the bycatch/byproduct component (0.92) (Fig. 4; Smith et al., 2007b).

There was often more than one activity-impact scenario for each component at Level 1 (score >2) that forced examination at Level 2 (Fig. 4). These multiple scenarios give greater confidence that the assessment should move to Level 2. The number of activities that led to a moderate or greater risk score varied between components and fisheries, with a maximum of six and a minimum of zero per fishery and component (Fig. 4). TEP species resulted in more activity-impact scenarios that scored >2. The mean number of scenarios scoring above this threshold (>2) per fishery was highest for both the target and TEP component (1.71), and lowest for the bycatch/byproduct and community components (1.41). The total number of cases across all fisheries that components progressed to examination at Level 2 ranged from 21 for habitats, to 29 for target species, out of a total of 31 fisheries assessed (Smith et al., 2007b). For individual fisheries, between 0 and 5 components per fishery progressed to examination at Level 2 assessment. A total of 12 fisheries had five components that were evaluated at Level 2, while only one fishery had no components moving to Level 2 (a squid jig fishery).

At Level 2, over 1200 unique species (68 target species, 857 byproduct and bycatch species, and 364 threatened, endangered and protected species) and over 200 habitats were assessed. Within each fishery, the number of species assessed ranged from 91 (dive fishery) to 788 (trawl fishery). The number of habitats assessed ranged from 4 (purse seine fishery) to 274 (wide ranging longline fishery), and the number of ecological communities from 3 (dive fishery) to 64 (long line fishery) (Smith et al., 2007b). Compar-

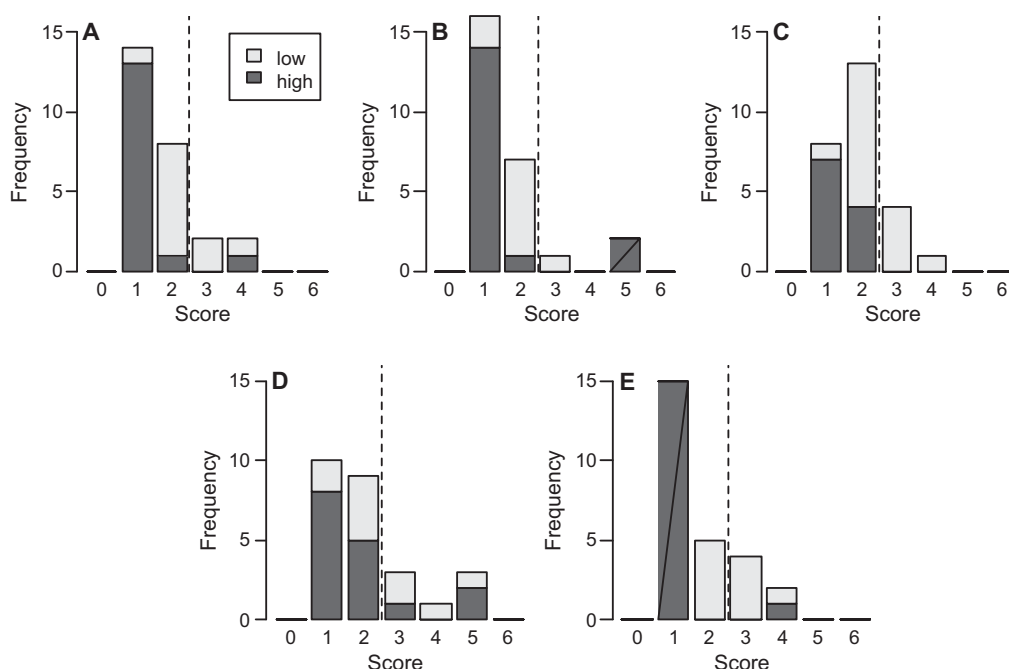


Fig. 4. Results from the Level 1 (SICA) analysis of the SESSF otter trawl fishery. In each of the five components there were some fishery-related activity-impact (consequence) scores >2, which moves each component to examination at Level 2. (A) Target species, (B) byproduct/bycatch species, (C) TEP species, (D) habitat types, and (E) community assemblages. Each consequence score can be assigned with high or low confidence, according to the consensus between the stakeholders.

isons between fisheries are more complex at Level 2, as the number of species/habitats/communities assessed varied across fisheries. However, as illustration only, the mean Level 2 risk score across fisheries differed between components, with the target species generally at highest overall risk (1.87) (possible range [1.41–4.24]), while the habitats that were assessed at Level 2 were overall at lower risk than bycatch and byproduct, and TEP respectively. Although risk profiles from PSA analyses are not strictly comparable across fisheries (because different species or habitat units are represented) several interesting trends emerged in our Australian application. For example the mean PSA score across species groups (target, bycatch, TEP) was notably higher for a pelagic long-line fishery than for a bottom trawl fishery. This appeared to reflect the higher mean trophic level of the catch in the longline fishery, with high selectivity for many high trophic level predators such as pelagic sharks.

4.2. Illustration of screening efficiency

Results from one fishery examined with the ERAEF approach in Australia are illustrative of the efficiency of the screening and the prioritization that is possible. The SESSF otter trawl fishery operates from Barrenjoey Point (Sydney) to Cape Jervis (Adelaide) in waters of depth 20–1300 m (Smith and Smith, 2001). At the time of the ERAEF assessment in 2005, the fleet size was approximately 100 vessels although only 76 were active. Total effort in the same year consisted of approximately 40,000 sets resulting in landings of 19,000 t. The discard rate of quota species was estimated at 8% and of non-quota species at 68% (2003 data). The main target species are tiger flathead (*Neoplatycephalus richardsoni*) on the shelf, pink ling (*Genypterus blacodes*) and blue grenadier (*Macruronus novaezelandiae*) on the upper slope, and orange roughy (*Hoplostethus atlanticus*) at mid-slope depths. There is a quota management system for 34 species/stocks and an observer program has been operating since the mid-1990s (Wayte et al., 2007).

The scoping analysis, which identified that 26 of 32 risk causing activities were present in this fishery (Wayte et al., 2007), did not

eliminate any ecological components. Risks rated as major or above (risk scores 4 or 5) were all related to direct or indirect impacts from primary fishing operations. Severe impacts (risk score 5) were confined to habitats and byproduct/bycatch species (Fig. 4). Significant external hazards included other fisheries in the region, coastal development, and other extractive activities. While these external activities are not examined beyond Level 1 in the ERAEF as they are outside the direct control of fisheries managers, their identification can lead to cross-sectoral consideration of these potentially neglected issues.

At Level 2, there were 600 species (28 target, 371 byproduct/bycatch, 201 TEP) assessed using the PSA analysis (Fig. 3B–E). Of these, 159 were assessed to be at potential high risk, including 15 target species, 39 byproduct species, 99 by-catch species, and 6 TEP species. By taxa, the high risk species comprised 58 chondrichthyans, 96 teleosts, 4 marine birds, and 1 marine mammal. Of the 159 species assessed to be at high risk, 4 had more than 3 missing attributes.

All the target species are managed through a quota system, and the introduction of harvest strategies for this group in 2006 has provided the foundation for ongoing sustainability of catches into the future (Smith et al., 2008). Of the 6 TEP species assessed to be at high risk, the four birds are at high risk due to lack of information. The single marine mammal at high risk (Australian fur seal, *Arctocephalus pusillus doriferus*) has low productivity and high susceptibility. It is captured in significant numbers by the fishery, but its overall population has increased rapidly in recent years (Goldsworthy et al., 2003), and so fishing is not considered a major risk to the population (though being a protected species, the fishery is expected to take active steps to avoid mortality on seals). The single TEP teleost at high risk is the spiny pipehorse (*Solegnathus spinosissimus*), which is occasionally found entangled in fishing gear (40 observations in 2004). The main ecological sustainability issue for species in this fishery is the number of non-target teleost and chondrichthyan species that are captured. In general, the chondrichthyan species are at high risk because of low productivity, and the teleost species because of high exposure

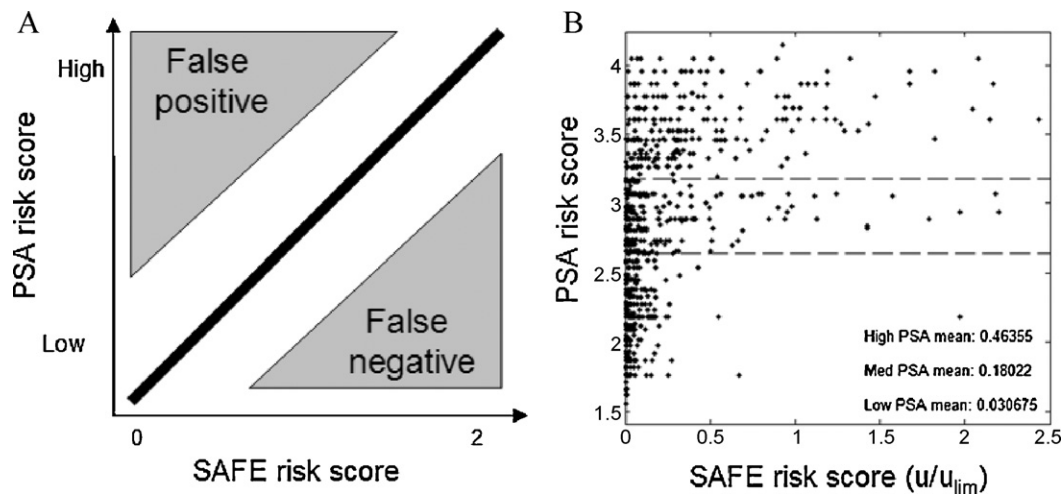


Fig. 5. (A) Schematic showing relationship between Level 3 (SAFE) and Level 2 (PSA) risk scores for 1164 species. Scores in the upper left and lower right represent false positives and false negatives respectively. (B) The observed relationship between the SAFE score and the PSA score. The average SAFE score in each of the high, medium and low PSA categories is also shown.

to fishing (high proportion of range within the fishery, live in habitats that are likely to encounter the gear, and are the right size to be selected by the fishery).

With regard to the Habitat component, 158 habitats were assessed at Level 2 using the habitat PSA analysis. Habitat types were classified based on substratum, geomorphology, and dominant fauna, using photographic data (Williams et al., in press). Of the 158 habitat types, 46 were assessed to be at high risk, 58 medium, and 54 low (Wayte et al., 2007) (Fig. 3F). Of the high risk habitats, none were found on the inner shelf (0–100 m), 18 were on the outer shelf (100–200 m), 12 were on the upper slope (200–700 m), and 16 were on the mid-slope (700–1500 m). High risk mid-slope habitats include several categories of hard bottom (but still accessible to trawl gear) with delicate epifauna consisting of octocorals, crinoids, small sponges, and sedentary animals. There are also several types of soft bottom habitat that support large, erect or delicate epifauna. Habitats of seamount and canyon features occur at this depth zone. High risk habitats on the upper slope also include several hard bottom types, in this case dominated by large sponges not seen on the mid-slope. There are also several soft bottom habitats based on bryozoan communities which are restricted to a narrow zone near the shelf break. Habitats of canyon features occur at this depth zone. High risk habitats on the outer shelf include soft sediment seabed types interspersed with harder bottom supporting large sponges, mixed epifauna, and the bryozoan communities at the shelf break.

The community component was not assessed for this fishery, as the science-management decision taken at the conclusion of Level 1 (Fig. 1) was to gather more information to support the Level 2 assessment. Thus, the screening of communities at Level 2 is not illustrated in this paper.

Two key risks emerge from the Level 2 ERAEF analysis of the SESSF otter trawl fishery. Both risks are related to direct impacts from fishing, one on certain vulnerable benthic habitats, and the other on a suite of byproduct and bycatch species not currently managed directly through the quota management system. For both these components, there are species or habitats at risk across a broad range of depths, from the outer shelf to the lower slope. In addition, some inner shelf species are also at risk.

The Level 2 analysis suggested that 153 species from the target and bycatch/byproduct components were at high risk. A Level 3 SAFE analysis was undertaken for the majority of the 440 target, byproduct and bycatch species caught in the otter trawl (comprising 88 chondrichthyans and 352 teleosts) (Zhou et al., 2007). Of the 411 species examined, 25 were identified in a set of higher risk

categories, including 12 chondrichthyans. Two target species (both teleosts) were in the high risk category.

Overall, the ERAEF analysis for this trawl fishery shows the hierarchical screening process in operation. While in this case the Level 1 SICA analysis failed to eliminate any of the components from further consideration, the Level 2 species analysis focused attention on just over a quarter of the species examined (159 out of 600). Of the 153 non-TEP species in this list, the Level 3 SAFE analysis further focused attention on 25 of these. Of the 158 habitat types screened at Level 2, 48 were identified as a priority for further analysis or management response (Fig. 6).

The Australian Fisheries Management Authority (AFMA) is in the process of developing comprehensive environmental management strategies for each fishery in response to the ERAEF results to date (see also Fig. 7). For example in the case of the SESSF otter trawl fishery, extensive spatial closures have been implemented at mid-slope depths (>700 m), in part to aid in recovery of depleted orange roughy stocks, but also to protect high risk deepwater shark groups. On the upper slope, several closures have been implemented to protect threatened gulper shark species. These spatial management strategies also act to protect several of the benthic habitat groups identified to be at high potential risk from trawling.

At a more general level, the disproportionate representation of chondrichthyan species in the high risk groups at both Level 2 and Level 3 species analyses has led to the development of a practical guide for fishery managers to mitigate bycatch (Patterson and Tudman, 2009).

4.3. Comparison of methods used in the ERAEF

One of the claims made about the hierarchical approach adopted in ERAEF is that it is precautionary in the sense that less information or more uncertainty results in estimates of higher potential for risk. More specifically, it is claimed that the PSA analyses at Level 2 in the hierarchy are more likely to result in false positives (identifying high risk when it is low) than false negatives (identifying low risk when it is high). Comparison between the Level 2 results and the results obtained using the Level 3 SAFE method for 1164 species from six fisheries supports the claim that the Level 2 approach is biased to false positives and results in few false negatives (Fig. 5). The mean values for the SAFE score also increased within each PSA category, indicating correlation in the approaches. While this does not represent an independent validation of the methods as much of the same data is used in both the PSA and SAFE analyses, it does sug-

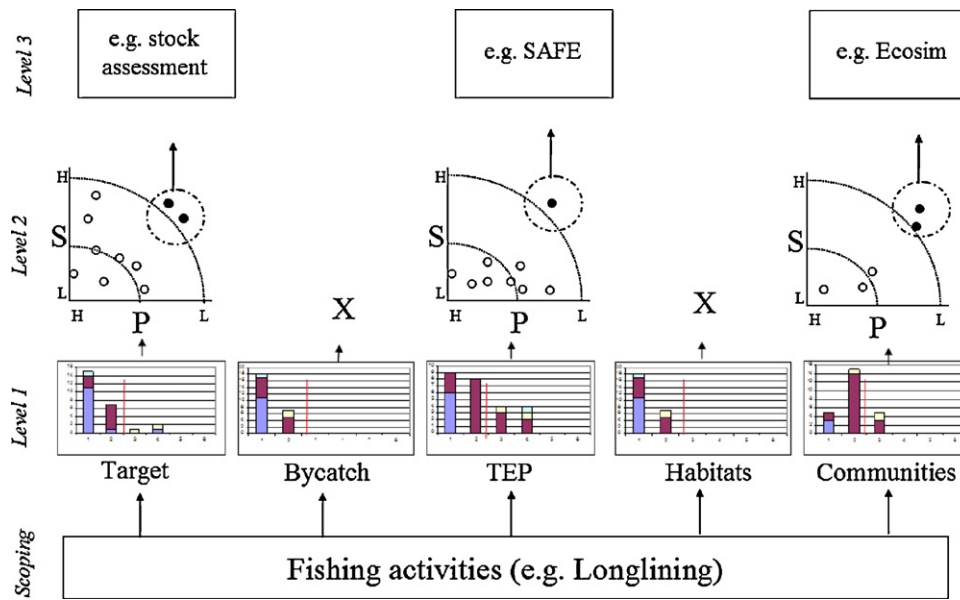


Fig. 6. Overall concept of the ERAEF. In the scoping stage, activities are defined and objectives set. At Level 1, the impacts of activities on each component are identified. Components with low scores are eliminated (e.g. bycatch and habitats), while those with some medium or greater risk scores are examined at Level 2. At Level 2, the risk to individual units (e.g. species) is evaluated. Individual units at high risk (solid circles) can be evaluated at Level 3.

gest that the overall hierarchy of methods is working as intended. Further unpublished comparisons of SAFE results for target species against full quantitative stock assessments for the same species suggest that the SAFE method is not biased towards either false positive or false negative results. Instances of both can occur, illustrating that further analysis will often be worthwhile to determine accurate estimates of risk from fishing.

5. Challenges and future development of the ERAEF

The hierarchical approach used in ERAEF helps meet one of the most important design criteria for assessment methods – cost effectiveness (Scandol et al., 2009). ERAEF makes use of existing knowledge, information and data within realistic limits of time and resources. In particular, the hierarchical approach moves from

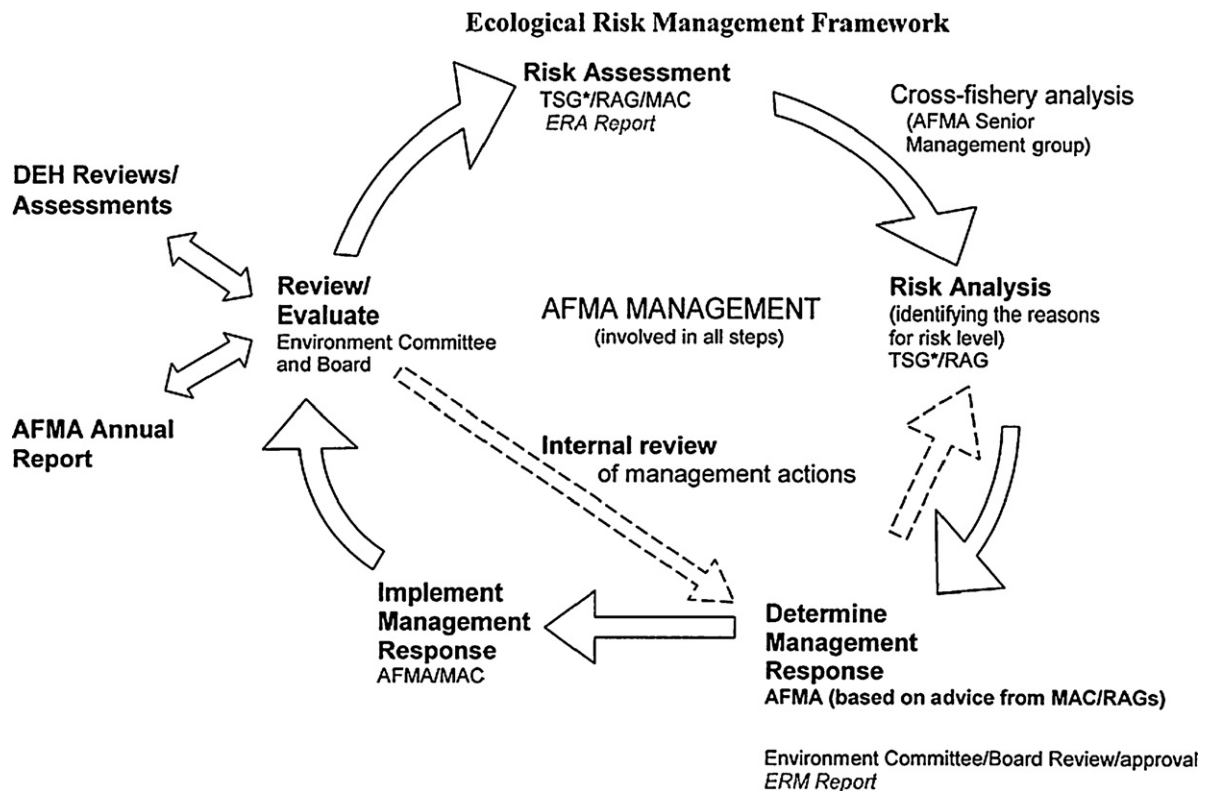


Fig. 7. Adaptive management cycle adopted by the Australian Fisheries Management Agency (AFMA), with the ERAEF noted here as the Risk Assessment at the top of the cycle. Within each fishery, the Management Advisory Committee (MAC), Technical Species Group (TSG) and Research Advisory Group (RAG) can contribute during decision making.

being comprehensive but relatively imprecise at Level 1, to focusing only on high risk components at Level 2. In moving from Level 2 to Level 3, only high risk units of analysis need to be considered in the more data and time intensive assessments. Thus ERAEF acts like a “triage” system, with low risk hazards successively eliminated at each level (Fig. 6).

Since completing development of the initial method described here, the ERAEF approach has been used and modified for specific purposes by a range of international groups, including the Marine Stewardship Council (2009), the ICCAT working group on ecosystems, the Western Central Pacific Fisheries Commission (WCPFC), the Caribbean Regional Fisheries Mechanism (CRFM), the National Marine Fisheries Service in the US (Patrick et al., 2009), and by scientists involved in assessing effects of fishing in the Galapagos Islands. Some groups have chosen to use only elements within the ERAEF, particularly the PSA approach (Patrick et al., 2009). The development of new tools that can be “plugged” into the hierarchy is also a feature of the ERAEF: each level is defined by the complexity and focus of the analysis and by the data requirements, rather than as a tool per-se. This flexibility has allowed application to all types of fishery, irrespective of size, method, or species. The ERAEF is, however, only an ecological risk assessment, and does not cover the economic, social and governance components of management that are important in many fisheries. A single level system used in Australia for state-based fisheries (Fletcher et al., 2002; Fletcher, 2005) does allow this holistic treatment, but at a more qualitative level (Scandol et al., 2009).

5.1. Lessons learned from implementation

The ERAEF is appealing as an approach that can cover a range of ecological issues within a fishery; however, there are a number of challenges in undertaking an assessment, some of which are linked to the design features of the method. The ERAEF is comprehensive, particularly during Level 1, when all potential activities and hazards are identified and treated. Some well-informed stakeholders are initially frustrated at this stage, as they often feel that time is spent on issues that “we already know are not a problem”. This comprehensive feature is appealing to other stakeholders, for example, with a conservation focus, as it allows all issues to be put on the table. The assembled information can allow more strategic responses over a period of time and within a planned management process, rather than the typical reactionary responses to the new “issue-of-the-day” that dominates much of fishery management.

The ERAEF approach is transparent and repeatable as the methods, terminology, data and assumptions used in the analyses are clearly documented. We contend that it is easy to understand, but due to the scope and multiple levels, as well as the novel terminology, it may take repeated exposure before all stakeholders are comfortable with the approach. Up to three workshops for a particular fishery assessment have been needed in Australia to develop this understanding. On the positive side, this effort does result in consensus building and a shared sense of ownership with the results, which we have seen translated into cooperatively developed management responses. The precautionary approach to uncertainty is also well received by some stakeholders, as the absence of information does not allow an issue to be dismissed and thereby induces an incentive to reduce the uncertainty.

In testing the ERAEF on a range of fisheries, a number of limitations have become apparent and need to be resolved in ongoing development (Smith et al., 2007b). Level 1 is qualitative and while scoring tables have been developed, it is possible that small groups of stakeholders might arrive at different risk scores. Initial guidance from one of our research team with experience in the method

and using a representative group of stakeholders has reduced this issue. In addition, the need for clear documentation of the rationale for the scoring allows decisions to be understood, debated, and reconsidered in future.

At Level 1, a range of potential risk-causing activities is considered, both direct and indirect. The activity with the greatest risk has typically been the “direct impact of fishing” on the species or habitat of concern. This has led to the Level 2 analysis being focused on the direct impact of the fishing activity, in terms of calculating the susceptibility axis. The structure of the PSA and the underlying equations do not limit analysis to this activity, and a PSA examining susceptibility to other activities could be developed, using different attributes and scoring tables. Because of the precautionary aspect to the scoring of attributes in the PSA, there is a bias to false positives. This sometimes raises a credibility issue with knowledgeable stakeholders, and discussion of the results is important to determine if some of the likely false positive risk scores can be corrected with additional information.

The Level 2 PSA also ignores some current management measures that may be in place to reduce risk, so operationally in Australian fisheries we have defined the outcome of the Level 2 as “potential risk”. Thus, a species can be at high potential risk, yet the management of that risk can be used to justify “no management action needed”. Explicit inclusion of management actions in the PSA is possible, and is under development.

One outstanding challenge in EBFM is to develop assessment tools that integrate across a range of fisheries or components (Smith et al., 2007a). For example, a species that is captured in several fisheries, each with different risk levels, may be better managed by a single set of arrangements, rather than fishery-specific rules. Integration and assessment of cumulative risk are easiest at the higher levels in the ERAEF framework, for example using the SAFE method. In traditional stock assessment, the estimates of fishing mortality can be combined across a range of fleets. Developments in ecosystem modelling and its application to issues in fisheries management are providing an important integrative approach to community and ecosystem level risk assessment (Smith and Fulton, 2009).

5.2. Operational uptake of the ERAEF

The ERAEF can be used as part of an iterative process, as at each level there is opportunity to improve the data used in the assessment, or to implement a management response. With regard to updating, the Australian ERAEF assessments for each federally managed fishery will be revisited every 3–5 years, or when certain conditions related to effort expansion or significant changes in the management of the fishery are encountered. ERAEF assessments have now been formally linked to an Ecological Risk Management framework within AFMA, and are seen as integral to ongoing management (Fig. 7). Linking the assessment to a management response is critical in leading to improved outcomes with regard to ecological risk (Burgman, 2005). To aid this, CSIRO and AFMA are in the process of extending the ERAEF to include two further stages: (i) risk categorisation for species that provides more information about the reasons why certain species have been identified as high risk; and (ii) an assessment of residual risk, which is the level of risk remaining after current management arrangements are fully taken into account (Smith et al., 2007b).

In conclusion, development and application of hierarchical methods like the ERAEF presented here may offer a practical way to realistically tackle one of the challenges that arise in implementing an EBFM approach – how to assess ecological risk for the hundreds of species, habitats and ecological communities that may be impacted by fishing.

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