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Evaluating impacts of fishing on benthic habitats: A risk assessment framework applied to Australian fisheries

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ABSTRACT

Ecosystem-based management (EBM), in the context of fishing, considers impacts on all parts of an exploited marine ecosystem. Understanding the impacts of fishing on habitats is a necessary part of adopting EBM, but multi-scale data that describe the types and distributions of habitats, and the interactions of fishing with them, are typically limited or entirely lacking. An approach developed to address habitat impacts, and applied to all offshore bottom contact fisheries in Australian waters, forms part of a hierarchical risk assessment framework – the Ecological Risk Assessment for the Effects of Fishing (ERAEF). Its progressively quantitative hierarchical approach enables higher-risk interactions to be identified and prioritised in the early and intermediate assessment stages by screening out lower-risk interactions. The approach makes the best use of all available data, but it can also be inferential where data are lacking. At the intermediate level of the ERAEF, a semi-quantitative approach uses a general conceptual model of how fishing impacts on ecological systems, with a focus at the level of regional sub-fisheries defined by fishing method (gear type). A set of quantifiable attributes for habitats are used to describe the 'susceptibility' of each habitat to damage that may be caused by specific fishing gears; resilience is generalised as a habitat's inherent 'productivity' (ability to recover from damage). In the ERAEF, photographic imagery was used effectively to provide a standardised method to classify habitats, to visualise the attributes assessed, and to communicate with stakeholders. The application of the ERAEF to habitats is illustrated using results from a multi-sector fishery off southern Australia that has five primary sub-fisheries: two bottom trawl ('otter trawler' or 'dragger'), bottom set auto-longline, bottom set gill net, and Danish seine. In the case of the otter trawl sub-fishery, a set of 158 habitat types was considered, of which 46, mostly on the outer continental shelf and slope, were identified as potentially higher risk and deserving management attention. Strengths of the ERAEF approach for benthic habitats include methodological flexibility and wide applicability, and in being interactive and inclusive – bringing stakeholders, scientists and managers together to 'put habitat on the radar' and to develop management solutions. Limitations include difficulties in construction and validation of scored attributes and scale dependence. In the context of ecological risk management, this method offers a way to assess risks to marine habitats in a rigorous, transparent, and repeatable manner.

1. Introduction

Principles of ecosystem-based fisheries management (EBFM) (Pikitch et al., 2004) are being applied to wild capture fisheries worldwide. This approach represents a shift away from single-species management towards also incorporating the direct effects of fishing on target and bycatch species and habitats, and the indirect impacts of widespread removals on the broader ecosystem. The broad and rapid adoption of EBFM at a policy level in Australia (within a decade) has relied on developing scientific and management tools to support implementation (Smith et al., 2007a). Environmental legislation, including the Environmental Protection and Biodiversity Conservation Act (EPBC) 1999, has made it mandatory for Australian Commonwealth Fisheries to implement reporting and assessment in accordance with ecologically sustainable development (ESD) guidelines. The approach developed to address this requirement within Australia's Commonwealth fisheries is the Ecological Risk Assessment for the Effects of Fishing (ERAEF) (Hobday et al., 2007, 2011; Smith et al., 2007b). It is being actively applied to federally managed fisheries as the primary scientific tool for evaluating the risks posed to marine environments in which fishing occurs (Smith et al., 2007a).

Many ecological risk assessments (e.g. Fletcher, 2005; Astles et al., 2006; Campbell and Gallagher, 2007; Martin-Smith, 2009), are based on a likelihood-consequence approach to estimating risk.

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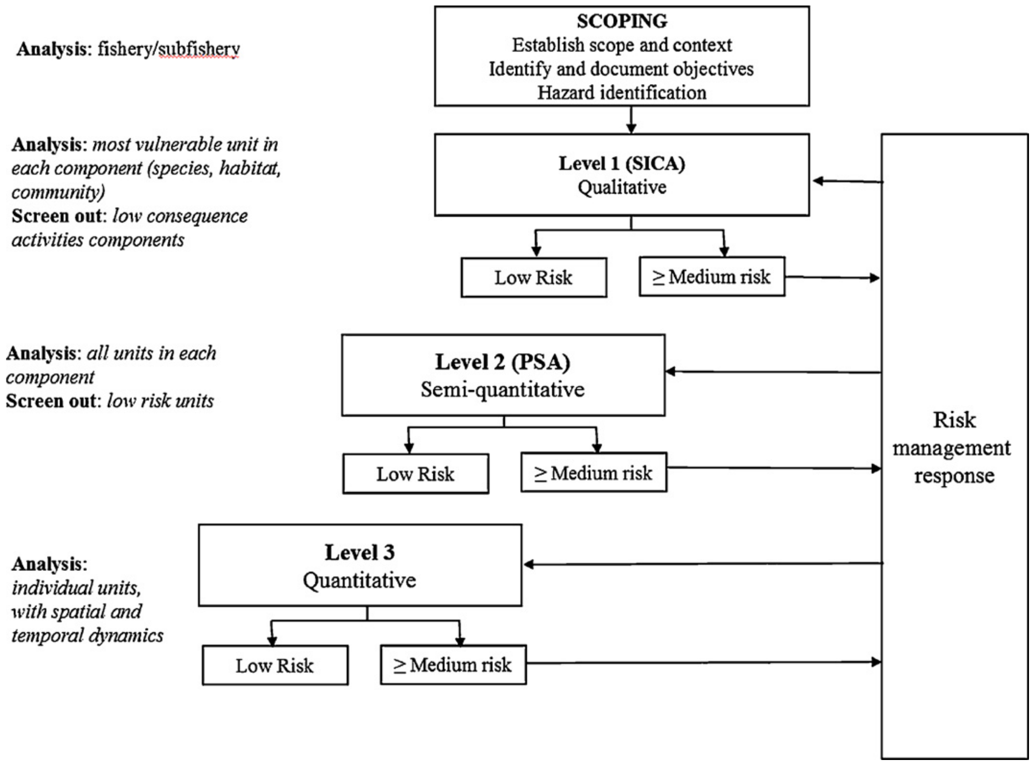

Fig. 1. Overview of the Ecological Risk Assessment for the Effects of Fishing (ERAEF) framework, showing the focus of analysis for each level (at left, in italics). At each level a risk management response is an alternative to proceeding to the next level in the hierarchy.

These assessment methods are suitable for a range of situations where data are limited, and have been applied in several Australian states. In contrast, the ERAEF is primarily an exposure-effects analysis (e.g. Boughton et al., 1999), which is more suited to assessing ongoing pressures such as fishing, rather than rare and unpredictable events or unintended 'accidents' (Smith et al., 2007a; Sharp et al., 2009). The ERAEF is a hierarchical framework (Fig. 1), with each level supported by a theoretical "impact" model (see Smith et al., 2007b; Hobday et al., 2007). Analysis at each level of the hierarchy increases in complexity, and acts to screen out low-risk impacts, so that resources can be directed to areas of relatively high risk or concern. It moves from a comprehensive but relatively imprecise assessment of all fishery–environment interactions at the first level, to a semi-quantitative assessment of highest-risk components at the second level. At the third level, only higher-risk interactions need to be considered in quantitative assessments. A precautionary approach to uncertainty is taken, and, at each level, there is the potential to introduce risk management responses, rather than to proceed to a more complex analysis (Hobday et al., 2011). At each level in the hierarchy, the approach also incorporates information derived during consultation with other risk assessment experts, industry stakeholders, and management bodies.

The ERAEF is designed around a set of criteria that are desirable in any general risk assessment process (Burgman, 2005). It is designed to be (i) comprehensive (identify and analyse all potential hazards); (ii) flexible (generically applicable to all types of fishery, irrespective of size, fishing method, species, etc.); (iii) transparent (clear about the methods, data and assumptions used in the analyses); and (iv) easily understood by stakeholders. Ultimately the approach also had to be (v) cost effective (making use of existing knowledge, information and data within realistic limits of time and resources); (vi) scientifically defensible (be able to withstand independent scientific peer review); and (vii) useful for management (inform appropriate risk management responses), which is perhaps the greatest challenge. These criteria are all met in the ERAEF (Smith et al., 2007b).

Potential impacts from fishing activities are assessed within the ERAEF against five ecological components representing the ecosystem: target species; by-product and bycatch species; threatened, endangered, and protected (TEP) species; habitats; and communities. The recent focus by management on habitats and communities represents the final extension of species-based fisheries management towards true EBFM. Recognition of the importance of habitats for fisheries has a long history, yet impacts on habitats are less commonly assessed in fisheries management. Assessing benthic habitats acknowledges the many essential roles habitats can have for fishery ecosystems (Rice, 2005; Thrush and Dayton, 2010), and also that habitat degradation from fishing activities may negatively affect these roles (Jennings and Kaiser, 1998; Auster, 2001; Thrush and Dayton, 2002). Documented examples from world fisheries illustrate impacts from a variety of different gears that vary in different habitats (e.g. Collie et al., 2000; Kaiser et al., 2006) and demonstrate the relatively high impacts of mobile bottom-contact gears (e.g. Watling and Norse, 1998; Kaiser et al., 2006). Impacts occur from the inter-tidal (e.g. Kaiser et al., 2006) to the deep sea – where there can be deleterious impacts on habitat features that support high fishery productivity, including seamounts (Koslow et al., 2001; Clark et al., 2010) and submarine canyons (Morais et al., 2007; Morell, 2009).

The purpose of this paper is to illustrate the second level 'Productivity Susceptibility Analysis' (PSA) of the ERAEF in relation to benthic habitats. While pelagic habitats are included in the ERAEF, in practice this inclusion is for completeness, rather than because of direct impacts as a result of fishing. Hereafter, we focus on, and use the term habitat to refer to, benthic habitats. We first provide a contextual overview of the ERAEF methodology, and then focus on the detail of the habitat PSA in a case study. Summary results are given for five example sub-fisheries (gear types) from a multi-sector fishery off southern Australia, the Southern and Eastern Scalefish and

Shark Fishery (SESSF). These sub-fisheries are two bottom trawl (otter trawl or dragger), bottom set auto-longline, bottom set gill net, and Danish Seine. The results are used to illustrate the strengths and limitations of the ERAEF approach for benthic habitats, and are discussed in the context of management uptake.

2. Methods

The Ecological Risk Assessment for the Effects of Fishing (ERAEF) framework is based on a hierarchy with a scoping (review) stage and three analytical levels that are progressively more quantitative (Smith et al., 2007b; Hobday et al., 2007). The analytical levels are (1) a qualitative 'Scale, Intensity and Consequence Analysis' (SICA); (2) a semi-quantitative 'Productivity Susceptibility Analysis' (PSA); and (3) a highly focused and fully quantitative "model-based" risk assessment (Fig. 1). A full description of the ERAEF method is provided by Hobday et al. (2007) with further details in Hobday et al. (2011), and so the description here is restricted to the habitat component of the assessment. The approach makes use of a general conceptual model of the way in which fishing impacts ecological systems. The focus of analysis is a fishery, which may be further divided into sub-fisheries on the basis of fishing method (gear type) and/or spatial location.

The ERAEF method for assessing risk of fishing to habitats builds on a simple model of habitat vulnerability proposed by Bax and Williams (2001), and a conceptually similar approach for species developed around the same time (Stobutzki et al., 2001; Milton, 2001). The Bax and Williams (2001) model represented relative vulnerability in qualitative terms using two axes (i) a habitat's resistance (to physical modification) and (ii) its resilience (estimated as the time taken for the habitat to recover to its original state once modified). The ERAEF for habitats develops this model by using a set of quantifiable attributes to describe the resistance of a habitat to specific fishing gears as its potential 'susceptibility' (ability to avoid damage by the gear) and its resilience is generalised as its inherent 'productivity' (ability to recover from damage) (Hobday et al., 2007). This productivity-susceptibility language is consistent across the other four ecological components of the ERAEF. The calculated risk equates to the potential vulnerability of each particular habitat type to be impacted by different fishing gears.

2.1. Scoping (listing habitat types)

The aim of the scoping stage in the ERAEF is to develop a profile of the fishery being assessed, and is based on published and anecdotal information provided by a range of fishery stakeholders, including managers, fishers, sea-going observers, and scientists. A key aspect of scoping involves generating the list of "units of analysis": in this case, habitat types.

Assembling the list of benthic habitat types for assessment that occur within a fishery area may be difficult. In contrast to generating lists of species (e.g. fishes), for which descriptions and taxonomy are usually well established, habitats are less conventionally described. Extensive habitat lists based on standardised classifications are available for some regions, e.g. Europe (EUNIS: http://eunis.eea.europa.eu/introduction.jsp) and North America (CMECS: http://marinemetadata.org/references/cmecshabitat, and see Madden and Grossman, 2007), but in the absence of such data in Australia's diverse and geographically widespread federally managed ("Commonwealth") fisheries, the ERAEF methodology used the data type most widely available – seabed imagery. Defining habitat types required a classification approach to generate lists in a consistent and transparent manner for a range of levels of data availability. We used a definition of 'habitat' that included both physical seafloor structure and its attached invertebrate fauna, since both physical and biological elements of the habitat are at risk from fishing impacts and both contribute to the ecosystem values that habitats provide to the species impacted by the fishery, e.g. recruitment sites, shelters and refuges (Thrush and Dayton, 2002; Jennings and Kaiser, 1998).

Three characteristics were used to classify habitat type at the fine scales recorded by cameras: substrate type (S) – 7 categories; geomorphology (G) – 10 categories; and dominant fauna (F) – 10 categories (Kloser et al., 2007). Thus, an example of an SGF-based habitat type might be *fine sediment* substrate + *irregular* geomorphology + *bioturbating* fauna (Fig. 2). Libraries of benthic images representing all habitat types were compiled for each fishery.

Once the set of habitat types found in an area of interest (usually the range of the fishery) is established, the next step is to estimate where each habitat occurs. Again, in contrast to species (for which distribution maps are commonly available) habitat distributions are less well specified. At the scoping stage, distributions of habitat types were defined simply by their presence or absence in depth zones ('bathomes' sensu Last et al., 2010), and association with particular geomorphic seabed features. Bathomes are depth-related sub-divisions of the marine benthic realm defined by community structure (e.g. Last et al., 2010; Ponder et al., 2002). These coarse spatial-scale definitions are consistent with the multiscale and hierarchical 'seascape' classification adopted to define 'bioregions' for marine conservation planning in Australia (e.g. Williams et al., 2005; Last et al., 2010). Within bathomes, habitat types may be associated with geomorphic seabed features, which are now mapped at coarse scale in Australia's offshore waters (Heap and Harris, 2008). Two feature types – submarine canyons and seamounts – are common features of Australia's continental margin where they have special roles for fishery productivity and biodiversity (e.g. Schlacher et al., 2007; Althaus et al., 2009). The use of bathomes and geomorphic feature as surrogates to estimate habitat distributions is developed further at Level 2 (Section 2.3).

In summary, the scoping stage classifies every habitat type using its fine-scale characteristics (SGF-based), with distribution defined by bathome and feature type (Fig. 2). Thus, the above example could be further refined as (*fine sediments + irregular + bioturbators*)/*submarine canyon*/*upper slope* (200–700 m *depths*).

In some regions of Australia, seabed imagery is not available and so, to develop a list of habitats for the fishery, a second, inferential, method was used (Hobday et al., 2007). This approach relied on photographic data in adjacent or similar areas, biological data from survey, fishery observer and logbook (bycatch) information, GIS mapping of bathymetry, and coarse scale geomorphology (Heap and Harris, 2008). The resultant conservatively large lists of habitats are intentionally precautionary and contain habitat types that will be eliminated as additional data is included. Thus, even in the absence of image data, a set of possible habitats can be assembled for use in the ERAEF. Hereafter, only the primary method of generating habitat lists – the photographic method – is discussed.

For the SESSF fishery examined in this paper, the list of habitats was derived from underwater photographic data acquired during several surveys of the fishery (e.g. Bax and Williams, 2001; Williams et al., 2006). Within a fishery region, the units of analysis (habitat types) may vary between sub-fisheries, each subset being the types encountered within the jurisdictional boundary and depth range of the sub-fishery. Thus, a specific habitat list was generated for each of the five sub-fisheries considered here.

2.2. Level 1 – Scale, Intensity, and Consequence Analysis (SICA)

This comprehensive, but largely qualitative analysis of risk employs a "plausible worst case" approach to the evaluation of risk to ensure that elements screened out as lower-risk (either fishing activities or ecological components) are genuinely low risk (Hobday

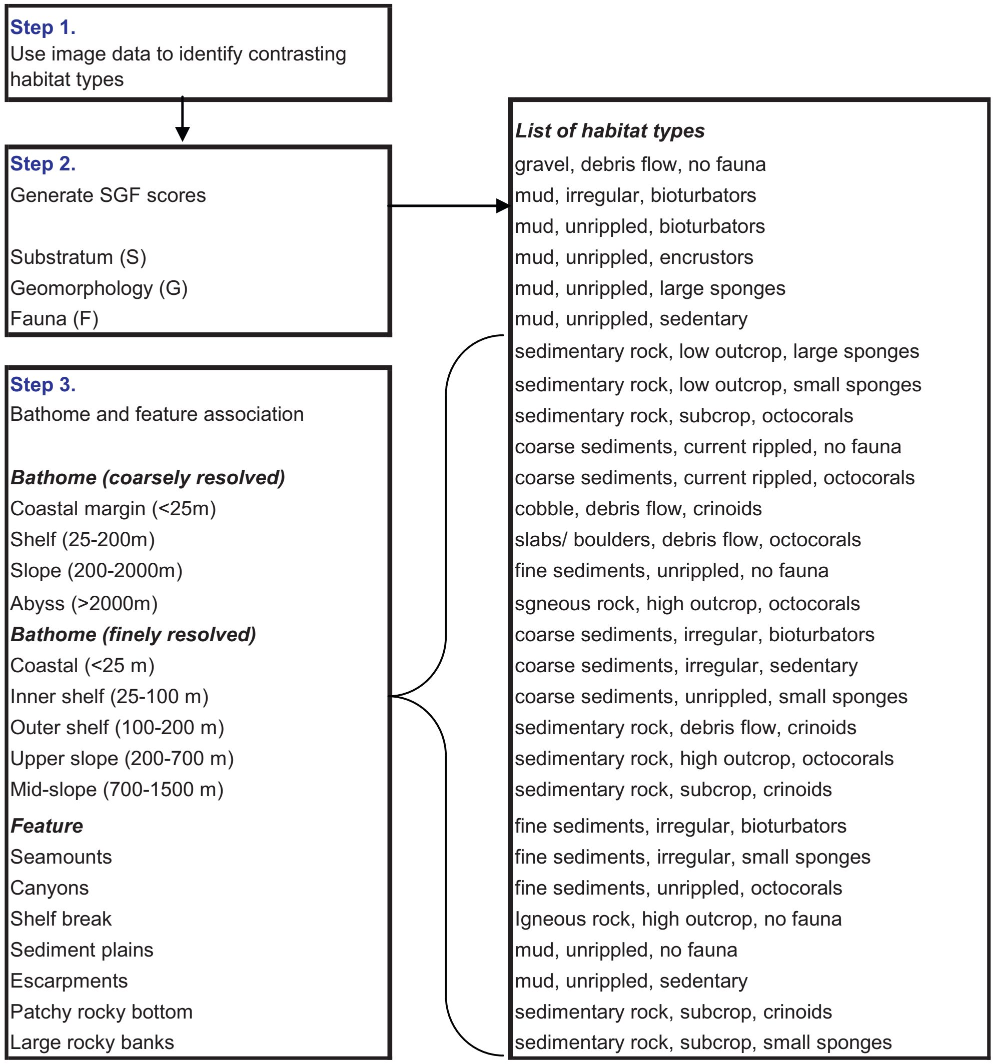

Fig. 2. The steps used to assemble lists of habitat types for each fishery area during the initial scoping stage of the Ecological Risk Assessment for the Effects of Fishing (ERAEF) framework. Habitats are classified using characteristics of substratum (S), geomorphology (G) and fauna (F) to provide an 'SGF' description and database code, and location recorded as presence within a depth defined bathome and association with features such as seamounts and canyons.

et al., 2007, 2011). For each fishing activity identified in the scoping stage, an impact scenario constructed from expert opinion, stakeholder input or reference to the literature is considered against a habitat (or set of habitats) deemed as the "worst case", in terms of impact due to the activity. The exposure (a combination of the spatial and temporal scale of the fishery and its intensity) and effect (the scenario) of each activity is estimated as a consequence score for this habitat type. When the "worst case" risk of an activity at Level 1 (SICA) is above the threshold score and no planned management interventions that would mitigate this risk are identified, an assessment is required at Level 2 (Fig. 1). All habitats are then assessed at the higher level. Level 1 is not described further in this paper.

2.3. Level 2 – Productivity Susceptibility Analysis (PSA)

The semi-quantitative PSA approach assumes that the risk to an ecological component depends on two characteristics of each unit in the component: (1) the extent of the impact due to the fishing activity, which will be determined by the susceptibility of the unit to the fishing activities (*susceptibility*) and (2) the productivity of the unit (*productivity*), which will determine the rate at which the unit can recover after depletion or degradation by fishing.

It is important to note that the PSA analysis measures *potential for risk* (hereafter referred to as 'risk'). A fully quantitative estimate of risk requires some direct measure of abundance or mortality rate for the unit in question, and this information is generally lacking for habitats. If that information were available, then an ERAEF Level 3 assessment could be conducted. The PSA for habitats examines attributes of each habitat type that contribute to, or reflect, its susceptibility or productivity. Collectively, these provide a relative measure of risk to each habitat type.

In the PSA, numerical values are ascribed to the interactions between fishing impacts and habitat types using a set of attributes representing the susceptibility and productivity axes of the model. Attributes must represent the potential risk of the fishing-habitat interactions, be relatively independent, and data must be available for all habitats in a national-scale application of the ERAEF.

Susceptibility of habitats is composed of three aspects – *Availability*, *Encounterability*, and *Selectivity* – while productivity is represented by a single aspect (Table 1). Each aspect in turn is represented by a set of *attributes*. Each attribute is scored either 1, 2 or 3 (reflecting relatively low, medium or high risk) based on the degree and type of interaction with fishing (susceptibility attributes) and the intrinsic properties of the habitat (productivity attributes) (Table 1). The assumption underlying this simple

Table 1
The attributes of benthic habitats used to assess the potential risks posed by fishing in the Ecological Risk Assessment for the Effects of Fishing framework. Attributes are nested within two primary characteristics of habitats: productivity and susceptibility (which has 3 aspects). The criteria for ranking each attribute are shown, with higher rank = higher risk. Each concept refers to a separate attribute 'reference table' (RT) which includes supporting information and decision rules; only two RT's are illustrated in this paper (Tables 2 and 3) with the remainder provided in Hobday et al. (2007).

	Aspect	Concept and rationale	Ranks		
	Attributes		1	2	3
	Productivity				
P1	Regeneration of fauna/flora	Accumulation/recovery of fauna/flora to pre-disturbance state. Based on intrinsic growth and reproductive rates that are variable in different temperatures, nutrients, productivity. See RT 1[a]	Annual	<Decadal	>Decadal
P2	Natural disturbance	Level of natural disturbance affects intrinsic ability to recover. See RT 2	Frequent, Regular or severe natural disturbance (0–60 m)	Irregular or moderate natural disturbance (60–200 m)	No natural disturbance (>200 m)
	Susceptability				
	Availability				
A1	General depth range (Bathome)	Spatial overlap of sub-fishery with habitat, defined at the scale of depth range (bathome) and based on the habitat's presence within it, within the managed area of the sub-fishery See RT 3[a]	Sub-fishery overlap with habitat distribution at bathomic scale is small (<10% habitat)	Sub-fishery overlap with habitat distribution at bathomic scale is 10–50% habitat	Sub-fishery overlaps majority of habitat at bathomic scale (>50% habitat)
	Encounterability				
E1	Depth zone and feature type	Habitat encountered at the depth and location at which fishing activity occurs: the overlap of the habitat's distribution, defined by an extrapolation to feature type (e.g. canyon, seamount), and bathome (depth zone) with the distribution of a sub-fishery's effort. See RT 4	Low overlap of fishing and habitat distribution (<10%)	Moderate overlap of fishing and habitat distribution (10–50%)	Majority of fishing overlaps habitat distribution (>50%)
E2	Ruggedness (fractal dimension of substratum and seabed slope)	Relief, rugosity, hardness and seabed slope influence accessibility to different sub-fisheries. Rugged substratum and steeply sloping seabed are less accessible to mobile gears. See RT 5[a]	High relief (>1.0 m), rugged surface structure (cracks, crevices, overhangs, large boulders, rock walls); >10° slope	Low relief (<1.0 m), rough surface structure (rubble, small boulders, rock edges); 1–10° slope	No relief, smooth simple surface structure (mounds, undulations, ripples); <1° slope
E3	Level of disturbance	Degree of impact is determined by the frequency and intensity of encounters, and gear footprint (the size, weight and mobility of individual gears). See RT 6[a]	Many encounters needed to cause impact	Several encounters needed to cause impact	Single encounter causes high impact
	Selectivity				
S1	Removability/mortality of fauna/flora	Erect, large, rugose, inflexible, delicate epifauna and flora, and large or delicate and shallow burrowing infauna (at depths impacted by mobile gears) are preferentially removed or damaged; mortality assumed. See RT 7[a]	Low, robust or small (<5 cm), smooth or flexible types, OR robust or deep burrowing types	Erect or medium sized (but <30 cm), moderately rugose or inflexible, OR moderately robust or shallow burrowing types	Tall, delicate or large (>30 cm high), rugose or inflexible, OR delicate or shallow burrowing types
S2	Areal extent	How much of each habitat is present. Effective degree of impact greater in rarer habitats: rarer habitats may maintain rarer species. See RT 8[a]	Common (> 10%) within sub-fishery depth zones	Moderately common (1–10%) within sub-fishery depth zones.	Rare (<1%) within sub-fishery depth zones.
S3	Removability of substratum	Intermediate sized clasts (~6 cm to 2 m) that form attachment sites for sessile fauna can be permanently removed. See RT 9[a]	Immovable (bedrock and boulders >2 m)	<6 cm (transferable)	6 cm to 2 m (removable)
S4	Substratum hardness	Composition of substrata: harder substratum is intrinsically more resistant. See RT 10[a]	Hard (igneous or indurated) lithotypes	Soft (sedimentary or weathered) lithotypes	Sediments
S5	Seabed slope	Mobility of substrata once dislodged; gravity or latent energy transfer assists movement of habitat structures, e.g. turbidity flows, larger clasts. Higher levels of structural fauna and densities of filter feeding animals found where currents move up and down slopes. See RT 11[a]	1°	1–10°	>10°

[a] The full set of Reference Tables (RT) are provided in Hobday et al. (2007).

scoring recognises a gradient of fishing impact between gear types and across habitats. Allocation of scores is based on predetermined thresholds or explicit decision rules for each attribute (Table 1). For example, the spatial extent of interaction (overlap) between a sub-fishery and a habitat type for the encounterability aspect (E1) uses thresholds of <10%, 10–50%, >50% to determine overlap. Threshold values are based on expert opinion and therefore do not represent a theoretically derived value, but rather a perceived consequence. The use of such heuristically derived methods are an accepted practice in risk assessment (Burgman, 2005), but in time they should be calibrated and validated using Level 3 (quantitative) assessments.

The overlap of fishing with habitats was estimated using fishery effort data mapped in a GIS and the distributions of habitat types interpolated to the scales of bathomes and geomorphic features (seamounts and submarine canyons). Availability (A1 – Table 1) is the spatial overlap of the sub-fishery with habitat, i.e. the area available to be fished, where bathomes are defined as the coastal margin (<25 m), continental shelf (25–200 m), continental slope (200–2000 m) and abyss (>2,000 m). Encounterability (E1) estimates the % of the habitat that is fished. Habitat distributions were refined to bathomes that delineate the coastal margin (<25 m), inner shelf (25–100 m), outer shelf (100–200 m), upper slope (200–700 m), and the mid slope (700–1500 m). Effort was mapped at the finest scale and the time period for which 'good' data (fishing positions recorded with latitude/longitude precision) were available. Habitat types with strong associations to geomorphic features such as seamounts or canyons that are target-fished were assessed at feature scale to avoid under-estimation of overlaps. Estimating areal extent of habitat types (S2 – Table 1) was difficult because finer scale distributions of habitats were usually not known. In some fishery areas the extent of individual habitat types were inferred from habitat mapping at 'terrain' resolution – hard,

Table 2
Attribute reference table (RT) to assist rank-scoring the productivity attribute 'regeneration of fauna/flora' for benthic habitats in the Ecological Risk Assessment for the Effects of Fishing framework. Supporting information and decision rules form part of several attribute reference tables.

Attribute reference table and decision rules for 'Regeneration of fauna/flora'

Assessment requires data on age/growth/recolonisation of fauna/flora. Data for Australian fishery regions will not be available in most cases, and so reference to comparative data from studies elsewhere is necessary. To some extent depth can be used as a general surrogate for accumulation and recovery time (deeper = longer) and this relationship is reflected in the data from other studies. Here, ranks aim to split fauna with regeneration times that are annual (1), <decadal (2) and >decadal (3). Decision rules: all fauna (other than encrusting) in continental slope depths (>200 m) = rank 3. A precautionary approach if no information is available for group/area in question is that large bodied, cold water (temperate) animals = rank 3. Score shelf break as for upper slope.

Productivity Ranks:
1 = Annual
2 = <Decadal
3 = >Decadal

Bathome	No fauna/Bio-turbators	Small sponges/ low encrusting taxa	Large sponges	Ascidians/ bryozoans	Crinoids/solitary/mixed commun-ities/hard and soft corals	Tropical mixed faunal communities/hard corals/ seagrass communities
Coastal margin	1	1	1	1	1	2
Inner shelf	1	1	2	2	2	2
Outer shelf	1	1	3	2	3	–
Upper slope	1	1	3	3	3	–
Mid-slope	1	2	3	3	3	–

soft and mixed substratum types – using data provided by the fishing industry (Williams et al., 2006) (and see Section 4.2.3).

Scoring of other attributes relies on a wide variety of published and unpublished information about habitats, and the impact of fishing on habitats. The attributes used for the habitat PSA are generic, but thresholds are unique to a sub-fishery to capture differences in fishing methods, regions and depths fished. Attribute reference tables are used to detail the relative effects and the differences in threshold values (e.g. Tables 2 and 3). Scores were recorded in Excel workbooks, with worksheets linked to calculate overall scores of susceptibility, productivity, risk value, risk ranks, and simple summary statistics. Use of spreadsheets makes the scoring accessible to a wide range of stakeholders, which is important in reviewing the risk assessment outcomes.

The attribute scores for productivity are averaged to provide a single estimate on the interval [1–3]. For susceptibility, the score for each aspect (availability, encounterability, selectivity) is averaged across the attributes contributing to that aspect so that each aspect scores in the interval [1–3]. However, the aspects operate multiplicatively rather than additively (a low score for just one aspect should ensure an overall low susceptibility) so the three aspect scores are multiplied rather than averaged to give a score on the interval [1–27]. The final susceptibility score is the cube root of the multiplicative score, ensuring a final score on the interval [1–3]. No weighting is applied to individual attributes. The ERAEF approach is deliberately precautionary with respect to uncertainty: attribute scores default to 3 (high risk) in the absence of information, evidence, or logical argument to the contrary (Hobday et al., 2011).

The overall risk score for each habitat type is the Euclidean distance from the origin (0 0) on a two-axes plot of susceptibility and productivity (Fig. 3), with high susceptibility and low productivity scores corresponding to high risk. For the overall PSA risk classification the PSA plot is divided into equal thirds, based on the distribution of Euclidean scores that result from the combination of the productivity and the susceptibility score. Habitat types that fall in the upper third of all possible scores (risk value >3.18) are classified as high risk, those in the middle third of possible scores (2.64 < risk value < 3.18) as medium risk while those in the lower third of possible scores (risk value < 2.64) are low risk (Hobday et al., 2007). Examples of attribute scoring, risk values, risk ranks and risk results are provided for the fishery considered here; the full documentation is provided in the ERAEF Methodology Report (Hobday

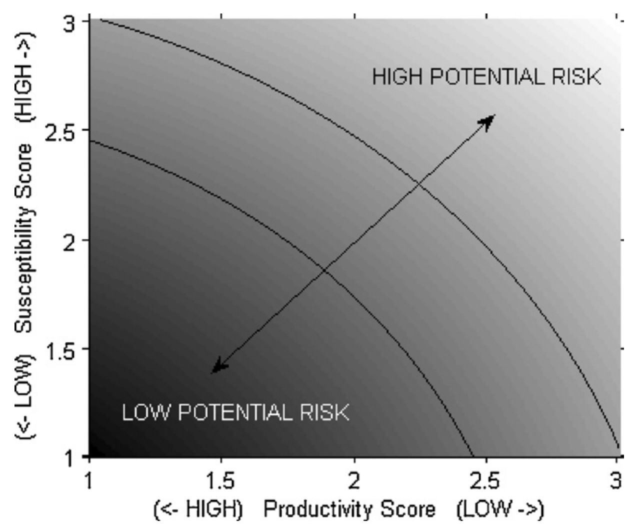

Fig. 3. The axes on which risk to each habitat type is plotted during the Level 2 Productivity-Susceptability Analysis (PSA) within the Ecological Risk Assessment for the Effects of Fishing (ERAEF) framework. The *x*-axis score is derived from attributes that influence the productivity of a unit, or 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; each third groups units with similar risk levels.

Table 3
Attribute reference table (RT) showing fixed rank scores for different sub-fisheries (gear types) applied to all benthic habitat types for the encounterability attribute 'level of disturbance' in the Ecological Risk Assessment for the Effects of Fishing framework.

Sub-fishery	Gear	Many encounters needed to cause impact	Several encounters needed to cause impact	Single encounter causes high impact	General characteristics of gear determining ranks			
					Size	Weight	Mobility	Footprint
GAB OT	Shelf and slope trawl			3	Large	Heavy	High	Large
SE OT	Otter trawl			3	Large	Heavy	High	Large
DS	Danish seine		2		Large	Intermediate	Intermediate	Intermediate
ALL	Auto-longline		2		Large	Intermediate	Low	Intermediate
GN	Shark gillnet		2		Intermediate	Intermediate	Low	Intermediate

et al., 2007). The concepts underlying the aspects, and their component attributes, are defined for each habitat type below, while the concepts, rationales and criteria for scoring are provided in Table 1.

2.4. *Case study: the SESSF fishery*

The Southern and Eastern Scalefish and Shark Fishery (SESSF) has a 100-year history (Smith and Smith, 2001). It is primarily a quota-managed fishery, and operates from inner shelf to mid slope depths (25–1300 m) over a broad geographical range spanning large areas of Australia's eastern, south-eastern and southern coastline. The fishery exploits numerous species with varied life histories in many demersal habitats (Smith and Smith, 2001). Five primary sub-fisheries exist and are distinguished by gear types and by the spatial and depth distribution of effort: south-east region otter trawl (SE OT); south region (Great Australian Bight) otter trawl (GAB OT); bottom set auto-longline (ALL); bottom set gill net (GN); and Danish Seine (DS). In this paper we focus on the south-east region otter trawl sub-fishery because it is the largest (many vessels taking the greatest tonnage), lands most species (>80), and operates over the broadest range of habitats and depth zones (~50–1300 m). The Level 1 SICA assessment identified that habitats within the SE OT sub-fishery had risk scores of 3 or greater which required a full PSA assessment of this component at Level 2 (Hobday et al., 2007). Here we focus on the Level 2 results for the SE otter trawl sub-fishery, and compare the summary results of PSA analyses for all five sub-fisheries to demonstrate various features of the ERAEF Level 2 habitat methodology.

3. Results

3.1. *Habitat types in the south-east otter trawl sub-fishery*

The broad range of depth and latitude used by this sub-fishery led to a large number of habitat types (158) being identified and assessed in the PSA (Wayte et al., 2007). All were identified using underwater photographic imagery and classified using the substratum-geomorphology-faunal (SGF) score in combination with feature type and bathome. Useful insights into fine-scale habitat distributions were provided by maps of 'terrains' – hard, soft and mixed bottom types derived from mapping fishers' knowledge (Williams et al., 2006). Many habitat types were assessed to fall in each of the high-, medium-, and low-risk categories. But because many types are similar, differing in only one respect of substratum or geomorphology or dominant fauna, groups of similar types can be readily aggregated into a smaller number of general categories for interpretation. For example, one general type will group together the habitats of a depth zone characterised by similar substratum and geomorphology but different large structural fauna (sponges, crinoids, octocorals or mixed communities).

Fifteen examples of habitat types (Fig. 4) demonstrate the habitat diversity in the SE OT fishery area. Their classification, rank score for each attribute, and risk scores for susceptibility and productivity and overall risk score for SE OT are shown in Table 4. Finally, the risk scores are plotted (Fig. 5) and summarised as the number of high-, medium- and low-risk habitat types by bathome (depth zone) (Table 5).

Two examples of attribute reference tables are also provided. The first shows the ranks assigned to the different sub-fisheries (gear types) for the 'level of disturbance' attribute – part of the encounterability aspect for scoring susceptibility (Table 3). The table demonstrates the way in which the three ranks are assigned to gears from the five sub-fisheries within the SESSF that impact benthic habitat, and shows how the differences between gears are justified by characteristics of gear relative size, weight, mobility

Table 4
Potential risk to benthic habitat types from trawling by the south-east otter trawl (SE OT) sub-fishery as assessed in the Ecological Risk Assessment for the Effects of Fishing framework. The method is illustrated using rank scores against each productivity and susceptibility attribute for the 15 example habitat types shown in Fig. 4 Habitats are classified using characteristics of substratum (S), geomorphology (G) and fauna (F); the corresponding descriptions and database codes are shown for each habitat. Attribute codes (A1, E1, etc.) are explained in Table 1.

Label (see Fig. 4)	Bathome	Feature	Habitat type (SGF description)	Habitat (SGF code)	Rank scores against attributes											Overall Scores and Risk Rankings			
					P1	P2	A1	E1	E2	E3	S1	S2	S3	S4	S5	Productivity score	Susceptibility score	Overall risk score	Overall risk category
a	Inner-shelf	Shelf	Sedimentary rock, low outcrop, large sponges	671	2	2	3	1	1	3	3	2	1	2	1	2	1.67	2.6	Low
b	Inner-shelf	Shelf	Coarse sediments, subcrop, large sponges	251	2	2	3	1	2	3	3	2	2	3	1	2	1.98	2.81	Med
c	Inner-shelf	Shelf	Sedimentary rock, high outcrop, large sponges	691	2	1	3	1	1	3	3	2	1	2	1	1.5	1.67	2.24	Low
d	Inner-shelf	Shelf	Coarse sediments, wave rippled, sedentary	227	2	1	3	1	3	3	2	1	2	3	1	1.5	1.93	2.45	Low
e	Outer-shelf	Shelf	Fine sediments, current rippled, bioturbators	119	1	2	3	2	3	3	1	1	2	3	1	1.5	1.95	2.46	Low
f	Outer-shelf	Shelf	Gravel, current rippled, bioturbators	319	1	2	3	2	3	3	1	2	2	3	1	1.5	2.07	2.55	Low
g	Outer-shelf	Shelf	Fine sediments, subcrop, large sponges	151	3	2	3	2	2	3	3	3	2	3	1	2.5	2.24	3.36	High
h	Outer-shelf	Canyon	Sedimentary rock, low outcrop, small sponges	672	1	2	3	2	1	3	2	3	1	2	3	1.5	1.98	2.48	Low
i	Outer-shelf	Shelf	Cobble, outcrop, crinoids	464	3	2	3	2	1	3	3	3	2	2	1	2.5	1.98	3.19	High
j	Upper-slope	Slope	Coarse sediments, irregular, small erect fauna	236	3	3	3	3	3	3	2	1	3	3	2	3	2.47	3.88	High
k	Upper-slope	Slope	Mud, irregular, mobile	038	1	3	3	3	3	3	1	1	2	3	2	2	2.2	2.97	Med
l	Upper-slope	Canyon	Sedimentary rock, subcrop, large sponges	651	3	3	3	3	2	3	3	3	2	2	3	3	2.54	3.93	High
m	Mid-slope	Slope	Sedimentary rock, subcrop, octocorals	657	3	3	3	2	1	3	3	2	1	1	2	3	1.8	3.5	High
n	Mid-slope	Slope	Sedimentary rock, low outcrop, octocorals	675	3	3	3	2	1	3	3	3	1	2	1	3	1.89	3.55	High
o	Mid-slope	Seamount	Sedimentary rock, high outcrop, octocorals	695	3	3	3	3	2	3	3	3	3	2	3	3	2.66	4.01	High

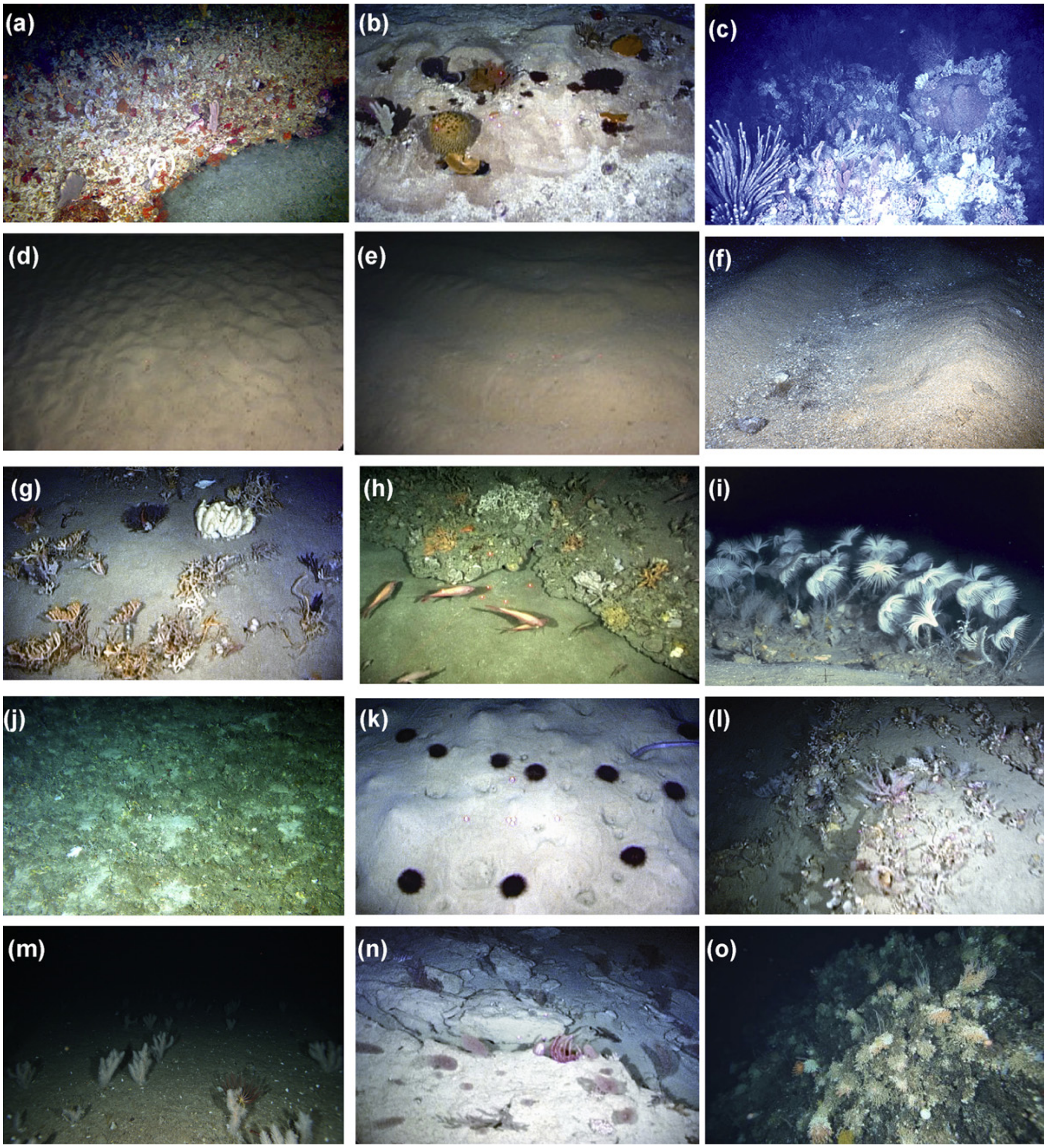

Fig. 4. A sub-set of 15 benthic habitat types (a–o) occurring off southeastern Australia as assessed by for the south-east otter trawl (SE OT) sub-fishery case study. The classification of each type is provided in Table 4.

and footprint. Heavy mobile gear (bottom trawl) score as relatively high risk (rank 3), static gears of varying sizes score as medium risk (rank 2), while a variety of small scale gears score low risk (rank 1). A second table shows the decision rule and ranks assigned to different benthic faunal types for the 'regeneration of fauna/flora' attribute for scoring productivity (Table 2). This table demonstrates the way in which the three ranks for regeneration time (annual, less or greater than decadal) are assigned to six broadly classified faunal groups on the basis of their composition, depth range and general locality (temperate versus tropical). The decision rule states the considerations necessary when defining the ranks (e.g. the need to refer to non-Australian data on recovery rates), and how rank scoring deals in a precautionary manner with particular faunal groups (e.g. deep water fauna).

Table 5
Summary of risk categories for 158 benthic habitat types in 5 depth-defined bathomes encountered by the south-east otter trawl (SE OT) sub-fishery as assessed in the Ecological Risk Assessment for the Effects of Fishing framework.

Risk category	Coastal margin	Inner-shelf	Outer-shelf	Upper-slope	Mid-slope	Total habitats
High	0	0	18	12	16	46
Medium	0	5	5	28	20	58
Low	0	23	31	0	0	54
Total	Not in fishery	28	54	40	36	158

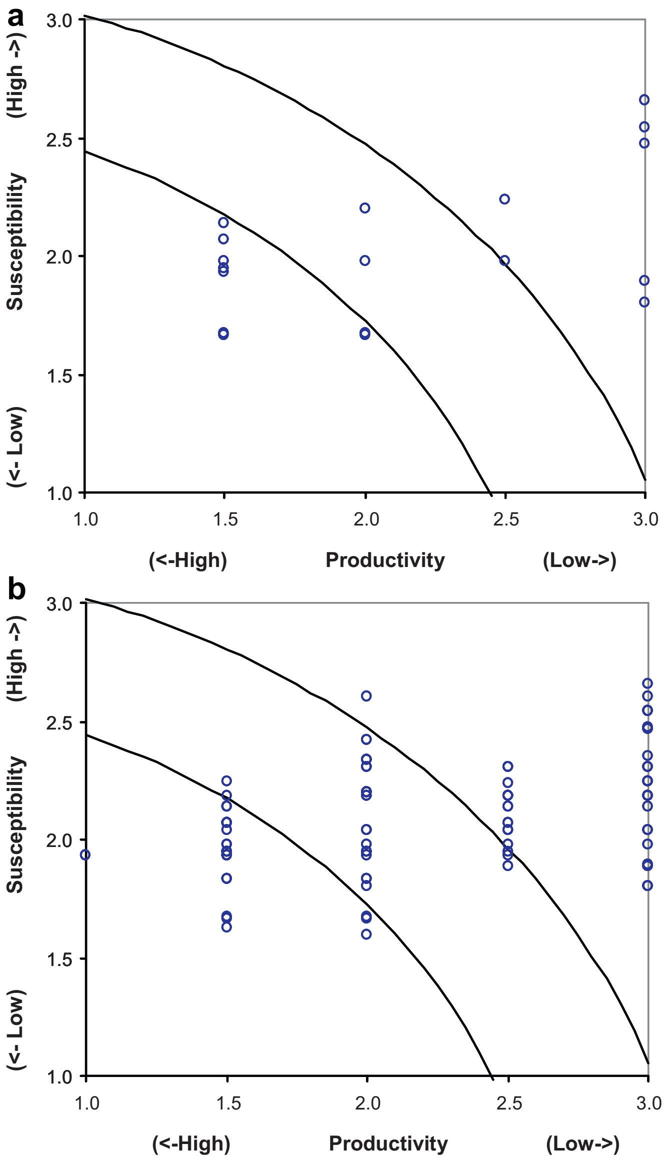

Fig. 5. Plots from the Productivity-Susceptibility Analysis (PSA) for habitats assessed for the south-east otter trawl (SE OT) sub-fishery (a) the distribution of risk scores for the 15 habitat types in the case study presented in this paper (see Fig. 4); (b) the distribution of risk scores for all 156 habitats assessed for the SE OT.

3.2. South-east region otter trawl PSA

An overview of results for the 158 habitat types is provided by a summary of relatively high, medium and low-risk types by bathome (Table 5). The distribution of risk values for south-east region otter trawl was approximately equal across the risk categories: 54 (34%) low, 58 (37%) medium and 46 (29%) high. No inner shelf habitats were classified as high risk, but five are medium risk, and 23 low risk. Eighteen outer shelf habitats produced high-risk scores, five medium risk and 31 low risk. On the upper slope 12 were scored as high risk, 28 at medium, while none score at low risk. Habitats at mid-slope depths were scored either at high risk (16) or at medium risk (20), while none were considered low risk. Coastal margin waters (<25 m depth) are not fished by the sub-fisheries considered here.

The high risk rating of 46 habitats reflects the relatively high level of disturbance by bottom trawling and the large number of continental slope habitats fished – where there has been a very high overlap of fishing effort with the upper slope bathome (>65% of area), extensive use of the mid-slope where productivity is lowest, and potential for large removals of epifauna that are large, erect, inflexible, or delicate, particularly where habitats have low ruggedness (low angle and high accessibility) and low resistance (e.g. sediments). On the mid-slope, 16 habitats scored at high potential risk included several categories of hard bottom, which are low-relief, mostly sub-cropping, friable sedimentary rocks or mud stones (present as slabs, boulders or cobbles), and also habitat types that are sediment veneers over hard bottom that supports large, erect or delicate epifauna consisting of octocorals, crinoids, small sponges and sedentary animals. Outcropping rocky habitat with low encounterability for bottom trawls eliminated many complex and diverse habitat types from the high-risk category. Several types of soft bottom habitats are also characterised by large, erect or delicate epifauna. Habitats of seamount and canyon features were included in this depth zone.

On the upper slope, 15 habitats also scored as high-risk; these included several low-relief hard bottom habitats, but featured epifauna dominated by large sponges not seen on the mid-slope. Several types of soft bottom habitats are characterised by large, erect or delicate epifauna. The most important upper slope soft seabed types were characterised by bryozoan communities, which are restricted to a narrow zone on the extreme outer shelf and upper reaches of the upper slope (~160–350 m depths). Habitats within canyon features are also included in this depth zone. On the outer shelf, 12 habitat scored as high-risk were mostly soft sediment seabed types, with some rock bottom, which is mostly low-relief, sub-cropping sedimentary rocks or cobble. Epifauna is characteristically dominated by large sponges, with sedentary and mixed epifauna dominant in some types.

Medium-risk scoring of 58 habitats was also influenced by the relatively high level of disturbance by bottom trawling and the large number of continental slope habitats fished. Inclusion of mid-slope habitats (18 types) was driven by the low productivity; they are mostly soft bottom types characterised by bioturbators and small encrusting species on low-relief, sub-cropping, friable sedimentary rocks. High outcrop habitats appear in this category because, despite low encounterability by bottom trawling, there is uncertainty about the degree of ruggedness that prevents trawl access using new technology. Such habitats are also rare features of the mid-slope, predominantly only associated with seamounts, canyons or large debris flows. On the upper slope, 28 habitats scored as medium-risk were an equal mix of soft bottom types characterised by small sponges, encrustors and bioturbators, and several types of rock bottom with epifauna consisting of small sponges and encrustors. On the outer shelf, five habitat types scored as medium-risk included outcropping and subcropping rock bottom, which are present as sedimentary rocks or cobble with epifauna dominated by large and small sponges and crinoids. On the inner shelf, five habitat types scored at medium-risk were soft sediment and characterised by large sponges and mixed epifaunal communities.

Fifty-four habitat types, all on the continental shelf, were scored at low risk. This result was driven partly by its relatively high productivity (compared to the slope) based on a faster regeneration time of fauna, and partly by adaptation of fauna to a greater degree of natural disturbance. There are several other driving factors for the inner shelf including its large overall area (151,000 km^2 or 60% of the SE OT sub-fishery area between 25 and 1500 m depth), low overlap by trawl effort (11%), large areas of relatively invulnerable habitat (dynamic, naturally disturbed sediment plains with little emergent fauna), and a relatively high proportion of hard, high relief rocky outcrop forming large (although incompletely quantified) areas, especially in the western half and NE of the fishery. On the outer shelf, 31 habitat types scored as low-risk were predominantly soft sediment without fauna or with small sponges, and/or encrusting or burrowing species; four hard bottom

Table 6
Risk categories for a subset of 21 habitats on the outer shelf encountered by all of the five main sub-fisheries of the SESSF fishery as assessed in the Ecological Risk Assessment for the Effects of Fishing framework. Habitat seq. is the sequence number in the ERAEF database; classification of habitat types by SGF code is explained in Table 4. Sub-fisheries are south-east otter trawl (SE OT), Great Australian Bight otter trawl (GAB OT), Auto-longline (ALL), Danish seine (DS), Shark gillnet (GN).. Shading highlights High and Medium risk categories.

Habitat seq.	SGF code	Bathome	Feature	Habitat type	Risk category				
					SET OT	GAB OT	ALL	GN	DS
017	151	Outer-shelf	Shelf	Fine sediments, subcrop, large sponges	High	High	High	High	Med
019	251	Outer-shelf	Shelf	Coarse sediments, subcrop, large sponges	High	High	High	High	Med
123	321	Outer-shelf	Shelf	Gravel, wave rippled, large sponges	High	High	Med	High	High
126	651	Outer-shelf	Shelf	Sedimentary rock, subcrop, large sponges	High	High	Med	High	Med
166	236	Outer-shelf	Shelf	Coarse sediments, irregular, small erect fauna	High	High	Med	Med	Med
101	252	Outer-shelf	Shelf	Coarse sediments, subcrop, small sponges	Med	Med	Low	Med	Low
125	052	Outer-shelf	Shelf	Mud, subcrop, small sponges	Med	Med	Low	Med	Low
109	152	Outer-shelf	Shelf	Fine sediments, subcrop, small sponges	Med	Med	Low	Med	Low
113	102	Outer-shelf	Shelf	Fine sediments, unrippled, small sponges	Med	Med	Low	Low	Low
120	319	Outer-shelf	Shelf	Gravel, current rippled, bioturbators	Med	Med	Low	Low	Low
121	329	Outer-shelf	Shelf	Gravel, wave rippled, bioturbators	Med	Med	Low	Low	Low
127	652	Outer-shelf	Shelf	Sedimentary rock, subcrop, small sponges	Med	Med	Low	Low	Low
107	132	Outer-shelf	Shelf	Fine sediments, irregular, small sponges	Med	Med	Low	Low	Low
124	320	Outer-shelf	Shelf	Gravel, wave rippled, no fauna	Low	Low	Low	Low	Low
025	220	Outer-shelf	Shelf	Coarse sediments, wave rippled, no fauna	Low	Low	Low	Low	Low
027	210	Outer-shelf	Shelf	Coarse sediments, current rippled, no fauna	Low	Low	Low	Low	Low
110	109	Outer-shelf	Shelf	Fine sediments, unrippled, bioturbators	Low	Low	Low	Low	Low
114	129	Outer-shelf	Shelf	Fine sediments, wave rippled, bioturbators	Low	Low	Low	Low	Low
117	120	Outer-shelf	Shelf	Fine sediments, wave rippled, no fauna	Low	Low	Low	Low	Low
112	100	Outer-shelf	Shelf	Fine sediments, unrippled, no fauna	Low	Low	Low	Low	Low
106	130	Outer-shelf	Shelf	Fine sediments, irregular, no fauna	Low	Low	Low	Low	Low

habitats are similar but exclude burrowing fauna. Twenty-three habitat types scored as low-risk on the inner shelf were similar to those of the outer shelf.

3.3. Comparison of sub-fisheries in the south-east region

Comparing the PSA results for the five primary sub-fisheries of the SESSF fishery illustrates their relative potential impacts on the benthic habitats encountered. Risk scores for 21 outer shelf habitat types encountered by all sub-fisheries showed that five habitat types were scored at high potential risk: all five from both otter trawl fisheries, two from auto-longline, four from GN, and one from Danish seine (Table 6). Three types at high risk to four sub-fisheries and one at high risk to three sub-fisheries were characterised by the presence of large sponges and differentiated by substratum and geomorphology as variously low relief gravel, subcropping rock or sediment veneer (Table 6).

The differences in scoring between sub-fisheries were based mainly on lower ranking of the encounterability attributes (Table 1). Auto-longline had a relatively low overlap with the shelf (attribute E1) and creates a lower level of disturbance (E3). Danish seine ranked lower on its access to rugged bottom where the sponge fauna is associated with sub-cropping rock (E2), and creates a lower level of disturbance (E3). The fifth habitat type rated as high risk was characterised by low erect fauna – a low relief 'thicket' composed predominantly of delicate bryozoans, small sponges, ascidians and ophiuroids that are vulnerable to damage or complete removal. The interaction with otter trawls rated as a higher risk than for the other sub-fisheries because trawling had a relatively high overlap (attribute E1) and created a higher level of disturbance (E3).

Importantly, the PSA analyses also showed that the majority of habitat types scored as medium or low risk to most sub-fisheries. Thirteen habitat types were scored at low risk to at least three sub-fisheries and no habitats scored at high risk across all five sub-fisheries (Table 6).

4. Discussion

4.1. The habitat PSA applied off south-east Australia

The aim of the intermediate (PSA) level in the hierarchical ERAEF framework is to identify the potentially high risk impacts of fishing using a semi-quantitative analysis. Our case study illustrates the ability of the generic framework to achieve this for benthic habitats by screening out lower-risk impacts, and identifying priorities for subsequent quantitative assessments. This is possible even where data on habitats at fishery scale are limited – the usual case (Astles et al., 2009) – because this intermediate level of risk assessment is not dependent on detailed mapping of habitats over entire fishery areas. The case study example – set in a complex multi-sector fishery that harvests a great variety of species from the coastal margin to the mid-continental slope (∼25 to 1300 m depths) across some 10° of latitude and 38° of longitude – identified large numbers of low-risk interactions across several sub-fisheries in addition to high-risk cases. The assessment made effective use of existing knowledge, information and data, and was comprehensive (all possible hazards were considered); the method was flexible and repeatable (applied to all sub-fisheries from which data are archived); and consultation was transparent (involved all stakeholders). Overall, the results captured the contrasts in risks from sub-fisheries (gear types) identified elsewhere, in heuristic assessments (Dorsey and Pederson, 1998) and in quantitative comparisons across habitats (Kaiser et al., 2006). Some of the high-risk fishery-habitat interactions have subsequently been verified by findings of long-lasting and potentially irreversible impacts (Althaus et al., 2009; Williams et al., 2010). The outputs have influenced the spatial management of fishing effort off temperate Australia, both in closed fishery areas (e.g. considerable restriction of bottom trawling in depths >700 m to protect species and habitats) and in conservation reserves (e.g. to fully protect particular seamounts habitats, and formulate zoning plans for multiple use areas of reserves).

4.2. Strengths, limitations and development of the habitat PSA

The broad application of the PSA method to habitats across Australia's federally managed fisheries, and the case study presented here, illustrated the strengths of the method but also identified several ways in which it can be refined and improved. These include opportunities to develop it for smaller or less complex fishery areas, individual sub-fisheries (gear types), or to focus the ERAEF at a particular management issue, e.g. regulation of fishing on individual features such as seamounts or submarine canyons.

4.2.1. Image-based methods to generate habitat lists for assessment

We showed that the use of imagery was effective in providing a standardised method to classify benthic habitats and to visualise the attributes assessed. Evaluating potential risks was helped by visualising habitats at the fine spatial scale at which direct impacts of fishing are recognisable. Conversely, we found little useful information on sessile invertebrates, substratum types or impacts in logbook catch records or scientific observer data from commercial fishery operations. The utility of high quality, geo-referenced and quantitative image data for risk assessment purposes is supported by its increasing availability as enabling technology has become simpler and more affordable. For example, photography is increasingly used for non-extractive sampling during observational fishery surveys (e.g. in Australia, Pitcher et al., 2007; Williams et al., 2009; Schlacher et al., 2010).

Notwithstanding the increasing availability of image data, a method based on image-derived data also has drawbacks. The large numbers of habitat types in each risk category generated by our classification – even with the biotic components defined at a coarse level – were not immediately intuitive to stakeholders. Fishers, for example, were familiar with more general definitions based primarily on physical features existing at larger spatial scales, e.g. sand plain, rocky bank, canyon. Multiple 'fine-scale' habitat types were, however, readily aggregated for interpretation and explanation at this intermediate step in the assessment. Finely resolved classifications are most appropriate at Level 3 (fully quantitative) analyses, or where there are concerns about particular species, habitat features or habitat types. Most obviously, quantitative analyses that incorporate physical sampling are needed to determine the impacts of fishing on sediment substrata where effects on small sized and sediment-dwelling biota are unrecognisable in imagery.

In data-poor situations where fisheries areas lack image data, qualitative or semi-quantitative risk assessment can employ an inferential process. This was the case for several areas in Australia's offshore waters where the inferential method was built on image data from adjacent or similar areas, but also incorporated other data from biological collections and bycatch information, GIS mapping of bathymetry, and coarse scale geomorphology ("Method 2" in Hobday et al., 2007). This inferential approach is less satisfactory, partly because some habitat types may remain unidentified, but it is feasible for data-poor situations and is precautionary since it contains habitat types that may be eliminated as additional data are incorporated.

4.2.2. Establishing an attribute set to evaluate fishing impacts

Selection of the attribute set was constrained both by the information available for benthic habitats, and by the timelines and scope of the risk assessment being undertaken, i.e. assessment of all Australian Commonwealth fisheries using a consistent methodology for species, habitats and communities. By using 11 individual habitat attributes that were neither reliant on complex analysis nor too specialised (focussed on specific fauna or habitats), we were able to generate data sets that represented the potential risk of the fishing-habitat interactions, were reasonably independent, were understood by stakeholders, and had no missing values.

Some individual attributes were well supported with data for some sub-fisheries, e.g. GIS mapping of the extent of fishing effort within the management area, where fishing position was recorded as latitude/longitude at a resolution of degrees and minutes (i.e. geolocation to 1 n.m.) for many consecutive years. Inevitably, given the variety of attributes and the range of fisheries assessed, other attributes were less well resolved and/or relied heavily on expert judgement. Thus, fishing effort distribution was resolved only at coarse grid scale (30 or 60 n.m.) in some sub-fisheries and in many historical data sets. There was some scope to address this kind of technical uncertainty with analytical procedures (e.g. further resolving effort distribution at finer scales using bathymetry and knowledge of the depth at which gear is deployed), but most evaluation of gear-habitat interactions and attribute scoring relied on expert judgement by the assessment team with oversight by stakeholders at consultative meetings during ERAEF implementation (Hobday et al., 2011).

Ideally, attribute scoring thresholds would be calibrated and validated before or during the assessment processes, but a paucity of information for some critical attributes cannot be easily remedied (Auster, 2001). For example, knowledge of productivity traits for many structural fauna – longevity, growth rate, fecundity, age at maturity, recruitment and dispersal – is limited or non-existent, or difficult to apply to aggregated faunal groups, even for species within genera for which expert opinions are provided (e.g. Williams et al., 2010).

An acknowledged weakness of our restricted set of relatively simple attributes was the inclusion of only two productivity attributes. These had a disproportionate effect on the overall risk score, and both strongly reflected an assumed relationship between increasing depth and lower productivity (based on great longevity and slow growth reported for deep fauna). While this relationship is supported by data for some taxa (e.g. Clark et al., 2010) and is consistent with patterns reported elsewhere (Kaiser et al., 2006), the use of only two productivity attributes did result in some over-estimates of risk, or 'false-positives'. One example was a score of high risk for bottom trawling interactions with deepwater high rocky outcrops despite a low encounterability score (many of these habitat types are untrawlable). Counter-intuitive outcomes were screened in the stakeholder consultative process where there was the opportunity to over-ride ('down-rank') such cases. Several additional productivity attributes were considered, but they were not easily quantified and/or were not supported by sufficient information in most fishery areas. They included *Habitat connectivity* (source-sink recruitment dynamics of structural fauna); *Chain of habitats* (habitat fragmentation); *Naturalness* (historical level of fishing impact); and *Export Production* (flux of organic material to benthos). These kinds of additional attributes, some identified at finer resolution, could be used during Level 3 (fully quantitative) analyses, or in a Level 2 framework where concerns are focussed on particular habitats, species or smaller fishery areas.

Arguably more important than identifying false positives, is the need to recognise and avoid 'false negatives' where potential risk is underestimated. False assessments of low-risk interactions that remain unidentified may prevent further assessment being undertaken. An example from our study, and a potential weakness in the results, was the low number of shallow (inner continental shelf) habitats in high-risk lists, especially sediment habitats. In most instances the finding of low fishing risk to inner shelf habitats was driven by a range of susceptibility attributes: relatively large habitat areas, low proportional overlap of fishing effort, large areas of relatively invulnerable habitat (dynamic, naturally disturbed sediment plains with little emergent fauna), and a relatively high proportion of inaccessible habitat (e.g. hard, high relief rocky outcrop to bottom trawl). However, false negatives could be generated by the two productivity attributes that assume higher productivity in shallow waters compared to deep, i.e. faster regeneration time of fauna, and adaptation of fauna to a greater degree of natural disturbance. Trawl impacts on shallow fauna vary greatly between major taxonomic groups (Kaiser et al., 2006), and may be long-lasting (years to decades) for large structural fauna (e.g. Pitcher et al., 2008) and those associated with biogenic habitat (Kaiser et al., 2006).

The overall result of the PSA for benthic habitat identified a degree of scale-dependence and relativity when applied to fisheries that operate over large areas, or in the Australian case, when applied at a national scale. As habitat heterogeneity increases as a result of increasing the geographical area of assessment, the scope of individual attributes also increases while the options for ranking remain static (3 categories of high, medium and low risk). This can have the effect of reducing the sensitivity of rank scores. Depth is the obvious example because several attributes are strongly influenced by or correlated with it. Thus, sensitivity may be increased if one or a few bathomes (depth ranges characterised by fauna or physical habitat structures) are included within a single assessment.

4.2.3. Habitat mapping at relevant scales

Maps of habitat distributions are required to move beyond purely qualitative assessments of fishing risks to benthic habitats (e.g. Astles et al., 2009), but this is problematic as detailed habitat maps are rarely available at the fishery scale. The distributions of finely detailed habitat types may be interpolated to larger spatial scales using surrogates (depth zones or features) as in the ERAEF, or simply be defined at a coarser surrogate scale in the first place (e.g. Auster and Shackell, 2000). Multibeam sonar (swath) mapping in conjunction with integrated environmental variables (Kostylev and Hannah, 2007) and/or with validation by physical or photographic sampling, has the potential to define and map habitats at finer spatial scales – but is expensive to collect over large areas and in shallow water (Kloser et al., 2007). In the absence of scientific mapping, quality-assured fishing industry data could possibly be used to produce useful fishery-scale maps. For example, the fishery area off south-east Australia (~141,000 km^2 in 25–1300 m depths) was segmented into 516 'fishing ground' polygons resolved at scales of 10 s to 100 s km^2. A variety of habitat attributes were recorded for each polygon, and confidence levels for habitat types and boundaries reflected the homogeneity of habitat, the distinctness of habitat boundaries, and the degree of validation and/or the corroboration of information (Williams et al., 2006). Fishers' knowledge also provided many insights into species-habitat associations and the ecological roles of habitats. There is incentive to provide such information because greater levels of understanding lead to reduced levels of precautionary management, and more predictability in commercial business planning (Auster, 2001).

4.3. Developing ecological risk management (ERM)

Ecological objectives are specified by a risk management process (e.g. NRC, 2002). Level 2 of the ERAEF considers risks to habitats from fishing by detailing the vulnerability of habitat types classified at fine scale, but with habitat areas and distributions quantified at relatively very coarse spatial scales. This alone may be sufficient for precautionary and pre-emptive management action within an EBM framework (Astles et al., 2009), or to regulate fishing within conservation reserves – as has been the case with deepwater benthic ecosystems off temperate Australia (see Section 4.1). In practice, we found that managers expressed a preference for quantitative analyses before implementing management actions. Such quantitative analyses (the equivalent of Level 3 in the ERAEF framework) can be focussed on particular issues or geographical areas, and the Level 2 analysis can help prioritise these analyses. Thus, sophisticated results such as large spatial scale mapping of impact (Sharp et al., 2009), predicted habitat distributions (Kostylev and Hannah, 2007; Clark and Tittensor, 2010), habitat sensitivity (Hiddink et al., 2007) or species and assemblage recovery rates (e.g. Hiddink et al., 2006; Pitcher et al., 2008), can be built into management frameworks, while models of benthic impact may form part of integrated management planning or management strategy evaluation (Sainsbury et al., 2000; Dichmont et al., 2008; Ellis et al., 2008; O'Boyle and Worcester, 2009). However, as proponents for EBM have noted, the more quantitative approaches require considerable time and money and may delay decision-making (Langton et al., 1996; Auster et al., 1997; Steneck et al., 1997). Avoiding the complexity trap in decision making ("let's wait till we know more") is critical for EBM given the high number of possible issues. Decision makers need to be provided with tools that allow precautionary decision-making, and that identify future needs for data (Auster, 2001).

The ERAEF provides a way of addressing the broad scale and range of issues that need to be considered when implementing EBM. Initially, there is the need to assess 'residual risk' for habitats – establishing whether current management measures already mitigate habitat interactions identified as high potential risk at Level 2. Assessments of residual risk, completed for species in some Australian fisheries (http://www.afma.gov.au/environment/eco_based/eras/default.htm; Hobday et al., 2011), formalise the continuing engagement of management agencies, stakeholders and risk assessment scientists. Assessing residual risk for habitats will need to consider the variety of existing management measures that may be effective for habitat protection: spatial closures, gear restrictions, changing fishing patterns including effort reduction, bycatch limits, move-on rules and restoration initiatives. Ideally this step incorporates more detailed data on habitat distributions, for example from scientific mapping with multibeam sonar or predictive modelling (e.g. Kostylev and Hannah, 2007; Clark and Tittensor, 2010). However, the 'data-poor' reality for most fisheries means that mapping habitats may be limited to estimating their associations with features and depth zones (bathomes). In data-poor cases, precautionary decisions need to be made about risks of localised extinctions of certain habitat types, and fragmentation leading to the associated loss of connectivity between types. For all areas, irrespective of data density, there is a need to account for cumulative impacts of different sub-fisheries (as well as other human pressures), and their combined impacts through time (Foden et al., 2010), because, at Level 2, the ERAEF method assesses sub-fisheries independently. In cases where extensive data exist, risk assessment will more ideally be based on understanding the roles of habitat for individual species and for broader ecosystem functions such as maintaining population connectivity and trophic relationships. Establishing habitat role and value requires integrating many ecologically relevant data sources, and then building the concept of ecological resilience into management planning (Thrush and Dayton, 2010).

Formalising the process to advance ERM for habitats in Australia lags behind the process for species. The options to be considered include establishing an expert group to evaluate strategies that include specific options and tools; this emulates the steps taken already in Australia to implement ERM for high-risk taxa, e.g. the formation of a Chondrichthyan Working Group to identify mitigation measures that might be effective for sharks and rays, and in what circumstances they should be used. An equivalent group focussed on mitigating risk to fishery habitats could progress at least three key areas: (1) identifying performance measures to determine acceptable levels of impact by establishing agreement on what constitutes an 'undesirable' consequence for habitat; (2) determining what monitoring is required to assess recovery from impact-related change and differentiate this from broader environmental change, e.g. climate related changes; and (3) defining ways to increase habitat-specific data collection to map spatial distribution of higher-risk habitat types. Data collection could be enhanced by improving habitat bycatch recording by fisheries observers, or capturing habitat classifications in a form that can be readily assimilated into existing frameworks. As an ERM process is developed, attention should be paid to the observations of Burgman (2005) who cautioned that results of risk assessments may not translate easily into policy and management decisions.

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