Estimating the sustainability of towed fishing-gear impacts on seabed habitats: a simple quantitative risk assessment method applicable to datalimited fisheries.

Pitcher, Roland; Ellis, Nick; Jennings, Simon; Hiddink, Jan; Kaiser, Michel; Kangas, Mervi; McConnaughey, Robert; Parma, Ana; Rijnsdorp, Adriaan; Suuronen, Petri; Collie, Jeremy; Amoroso, Ricardo; Hughes, Kathryn; Hilborn, R.

Methods in Ecology and Evolution

DOI: 10.1111/2041-210X.1270

Published: 01/04/2017

Peer reviewed version

Cyswllt i'r cyhoeddiad / Link to publication

Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA): Pitcher, R., Ellis, N., Jennings, S., Hiddink, J., Kaiser, M., Kangas, M., McConnaughey, R., Parma, A., Rijnsdorp, A., Suuronen, P., Collie, J., Amoroso, R., Hughes, K., & Hilborn, R. (2017). Estimating the sustainability of towed fishing-gear impacts on seabed habitats: a simple quantitative risk assessment method applicable to data-limited fisheries. Methods in Ecology and Evolution, 8(4), 472-780. https://doi.org/10.1111/2041-210X.1270

Hawliau Cyffredinol / General rights Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

· Users may download and print one copy of any publication from the public portal for the purpose of private study or research.

- You may not further distribute the material or use it for any profit-making activity or commercial gain
 You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Estimating the sustainability of towed fishing-gear impacts on seabed habitats: a simple quantitative risk assessment method applicable to data-limited fisheries.

Journal:	Methods in Ecology and Evolution
Manuscript ID	MEE-16-07-540.R1
Manuscript Type:	Research Article
Date Submitted by the Author:	n/a
Complete List of Authors:	 Pitcher, C. Roland; CSIRO, Marine & Atmospheric Research Ellis, Nick; CSIRO, Marine and Atmospheric Research Jennings, Simon; CEFAS, ; Hiddink, Jan; University of Wales, Bangor, School of Ocean Sciences Mazor, Tessa; CSIRO, Oceans and Atmosphere Kaiser, Michel; University of Wales Bangor, School of Ocean Sciences Kangas, Mervi; Western Australian Fisheries and Marine Research Laboratories, Department of Fisheries Western Australia McConnaughey, Robert; NOAA Western Regional Center, Alaska Fisheries Science Center Parma, Ana; Centro Nacional Patagonico Rijnsdorp, Adriaan; National Institute for Fishery Research, Biology and Ecology Suuronen, Petri; Food and Agriculture Organization of the United Nations, Fishing Operations and Technology Branch (FIRO) Collie, Jeremy; University of Rhode Island, Amoroso, Ricardo; University of Wales, Bangor, School of Ocean Sciences Hilborn, Ray; University of Washington,
Keywords:	Modelling < Community Ecology, Habitats < Conservation, Applied Ecology
Abstract:	 Impacts of bottom fishing, particularly trawling and dredging, on seabed (benthic) habitats are commonly perceived to pose serious environmental risks. Quantitative ecological risk assessment can be used to evaluate actual risks and to help guide the choice of management measures needed to meet sustainability objectives. We develop and apply a quantitative method for assessing the risks to benthic habitats by towed bottom-fishing gears. The method is based on a simple equation for relative benthic status (RBS), derived by solving the logistic population growth equation for the equilibrium state. Estimating RBS requires only maps of fishing intensity and habitat type — and parameters for impact and recovery rates, which may be taken from meta- analyses of multiple experimental studies of towed-gear impacts. The aggregate status of habitats in an assessed region is indicated by the distribution of RBS values for the region. The application of RBS is illustrated for a tropical shrimp-trawl fishery.

3. The status of trawled habitats and their RBS value depend on impact rate (depletion per trawl), recovery rate and exposure to trawling. In the shrimp-trawl fishery region, gravel habitat was most sensitive, and though less exposed than sand or muddy-sand, was most affected overall (regional RBS=91% relative to un-trawled RBS=100%). Muddy-sand was less sensitive, and though relatively most exposed, was less affected overall (RBS=95%). Sand was most heavily trawled but least sensitive and least affected overall (RBS=98%). Region-wide, >94% of habitat area had >80% RBS because most trawling and impacts were confined to small areas. RBS was also applied to the region's benthic invertebrate communities with similar results.

4. Conclusions. Unlike qualitative or categorical trait-based risk assessments, the RBS method provides a quantitative estimate of status relative to an unimpacted baseline, with minimal requirements for input data. It could be applied to bottom-contact fisheries worldwide, including situations where detailed data on characteristics of seabed habitats, or the abundance of seabed fauna are not available. The approach supports assessment against sustainability criteria and evaluation of alternative management strategies (e.g. closed areas, effort management, gear modifications).

JLAK JLAK JUSCON

SCHOLARONE[™] Manuscripts

- 1 *Manuscript type*: Standard original research paper
- 2 Running title: A simple method for trawl risk assessment
- 3 Word count: title (20), authors (37), affiliations & addresses (97), summary (338), keywords (20), main text
- 4 (4256), acknowledgements (83), references (1343), tables (504), figure captions (227). TOTAL (6950).
- 5 Number of tables (4) and figures (6). Number of references: (39)
- 6 Estimating the sustainability of towed fishing-gear impacts on seabed habitats: a
- 7 simple quantitative risk assessment method applicable to data-limited fisheries.
- 8 C. Roland Pitcher^{1*}, Nick Ellis¹, Simon Jennings^{2,3}, Jan G. Hiddink⁴, Tessa Mazor¹, Michel J. Kaiser⁴, Mervi
- 9 Kangas⁵, Robert A. McConnaughey⁶, Ana M. Parma⁷, Adriaan D. Rijnsdorp⁸, Petri Suuronen⁹, Jeremy Collie¹⁰,
- 10 Ricardo Amoroso¹¹, Kathryn M. Hughes⁴, Ray Hilborn¹¹.
- 11 ¹CSIRO Oceans and Atmosphere, Brisbane, Australia
- 12 ²Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, UK
- 13 ³School of Environmental Sciences, University of East Anglia, Norwich, UK
- ⁴School of Ocean Sciences, Bangor University, Menai Bridge, Wales, UK
- 15 ⁵Western Australian Fisheries and Marine Research Laboratories, Hillarys, Western Australia
- 16 ⁶NOAA, Alaska Fisheries Science Center, Seattle, WA, USA
- 17 ⁷Centro Nacional Patagónico, Puerto Madryn Chubut, Argentina
- 18 ⁸IMARES Wageningen UR, Ijmuiden, Netherlands
- 19 ⁹FAO Fisheries and Aquaculture Department, Rome, Italy
- 20 ¹⁰University of Rhode Island, Narragansett, Rhode Island, USA
- 21 ¹¹University of Washington, Seattle, WA, USA
- 22 *Corresponding author: roland.pitcher@csiro.au
- 23 GPO Box 2583, Brisbane, QLD 4001
- 24 Ph:+61(7)38335954, Fax:+61(7)38335502

A simple method for assessing seabed trawl risk

Page 2

25 Summary

26 1. Impacts of bottom fishing, particularly trawling and dredging, on seabed (*benthic*) habitats are commonly 27 perceived to pose serious environmental risks. Quantitative ecological risk assessment can be used to evaluate 28 actual risks and to help guide the choice of management measures needed to meet sustainability objectives. 29 2. We develop and apply a quantitative method for assessing the risks to benthic habitats by towed bottom-30 fishing gears. The method is based on a simple equation for relative benthic status (RBS), derived by solving 31 the logistic population growth equation for the equilibrium state. Estimating RBS requires only maps of fishing 32 intensity and habitat type — and parameters for impact and recovery rates, which may be taken from meta-33 analyses of multiple experimental studies of towed-gear impacts. The aggregate status of habitats in an 34 assessed region is indicated by the distribution of RBS values for the region. The application of RBS is 35 illustrated for a tropical shrimp-trawl fishery. 36 3. The status of trawled habitats and their RBS value depend on impact rate (depletion per trawl), recovery 37 rate and exposure to trawling. In the shrimp-trawl fishery region, gravel habitat was most sensitive, and 38 though less exposed than sand or muddy-sand, was most affected overall (regional RBS=91% relative to un-39 trawled RBS=100%). Muddy-sand was less sensitive, and though relatively most exposed, was less affected 40 overall (RBS=95%). Sand was most heavily trawled but least sensitive and least affected overall (RBS=98%). 41 Region-wide, >94% of habitat area had >80% RBS because most trawling and impacts were confined to small 42 areas. RBS was also applied to the region's benthic invertebrate communities with similar results. 43 4. Conclusions. Unlike qualitative or categorical trait-based risk assessments, the RBS method provides a 44 quantitative estimate of status relative to an unimpacted baseline, with minimal requirements for input data. 45 It could be applied to bottom-contact fisheries worldwide, including situations where detailed data on 46 characteristics of seabed habitats, or the abundance of seabed fauna are not available. The approach supports 47 assessment against sustainability criteria and evaluation of alternative management strategies (e.g. closed 48 areas, effort management, gear modifications).

Key-words: ecosystem-based fishery management; ecological risk assessment; effects of trawling; trawl
 footprints; benthic fauna; vulnerability indicators; depletion; recovery; resilience; sensitivity

A simple method for assessing seabed trawl risk

Page 3

51 Introduction

52 Globally, bottom trawling and dredging interact directly with larger areas of seabed habitat than other human 53 activities (Kaiser et al. 2002) and are widely perceived to have significant direct and indirect impacts on these 54 habitats (Jennings & Kaiser 1998). Recognition of the collateral consequences of fishing, including habitat impacts by trawling, has led to the broader ecosystem being considered in managing fisheries ("ecosystem-55 56 based fishery management"; Pikitch et al. 2004) and to the emergence of policy commitments and 57 requirements from sustainable-seafood certification bodies to take account of ecosystem impacts of fishing in 58 management plans (e.g. Rice 2014). Increasingly, this is occurring as part of national and international 59 adoption and implementation of an "Ecosystem Approach to Fisheries" (FAO 2003; Sinclair & Valdimarsson 60 2003). These policies demand levels of evidence that often do not exist, or are too costly to obtain, at scales of 61 management regions. When resources are limited, a common approach for supporting management is risk 62 assessment, which seeks to describe the magnitude of fisheries impacts and requirements for measures to 63 meet management objectives. However, methods for risk assessment vary in their complexity and capacity to 64 support management (Smith et al. 2007).

65 Initially, environmental risk assessments for the effects of fishing (ERAEF) were based on a 'likelihoodconsequence' approach (e.g. Fletcher et al. 2002) and/or a qualitative 'susceptibility-resilience' approach (e.g. 66 67 Stobutzki, Miller & Brewer 2001) and often, expert judgment was used for scoring (e.g. Eno et al. 2013). These 68 non-quantitative, typically non-spatial, approaches provide estimates of relative levels of susceptibility or 69 potential risk, but have limited ability to assess sustainability. More recently, quantitative (Zhou & Griffiths 70 2008) and quantitative-spatial (Pitcher 2014) ERAEF approaches have been developed and applied. These 71 provide estimates of absolute status and thus support more refined advice about management measures 72 needed to meet sustainability objectives. These different levels of ERAEF were placed in a 3-tier 'triage' 73 framework by Hobday et al. (2011) where risk is assessed by more detailed level 2 or 3 methods (with greater 74 data demand and cost expected) if less detailed level 1 or 2 methods indicate that risk is non-negligible.

In trawl fisheries, ERAEF has largely focused on non-target or bycatch species at level-2 (e.g. Stobutzki Miller &
Brewer 2001; Astles et al. 2006), with recent level-3 assessments providing quantitative estimates of bycatch

	A simple method for assessing seabed trawl risk	Page 4
77	sustainability (e.g. Zhou & Griffiths 2008; Pitcher 2014). However, habitat ERAEF (e.g. Williams et al. 201	1) are
78	less commonly implemented and typically less developed, with only a few examples of level-3 quantitation	ve
79	spatial assessments (e.g. Pitcher et al. 2015a,b). The slower development of habitat ERAEF may be due to	o the
80	paucity of suitable data for habitats and the perception that habitats are intractable to model in a genera	alized
81	way, because they comprise or harbour many interacting species with complex dynamics. However, som	ie
82	studies indicate that aggregate properties of seabed habitats and communities do respond in predictable	e ways
83	to trawling impacts (Collie et al. 2000; Kaiser et al. 2006); thus their collective dynamics can be paramete	erised
84	and used in quantitative assessment models (e.g. Ellis, Pantus & Pitcher 2014). The reduced variation in	
85	aggregate parameters may be important from an ecological perspective, because some species in a	
86	community will be more sensitive to impacts, have slower recovery times or interact more strongly with	other
87	species. Nevertheless, assessment of trawl risk at the level of habitat has clear management relevance	
88	considering that management objectives and certification requirements often focus on habitats rather the	nan
89	species (MSC 2014; Rice, Lee & Tandstad 2015). Attribution of parameters to overall dynamics enables	
90	quantitative status assessment for habitats and communities. Such assessments require information on	their
91	sensitivity to impacts, recovery rates, distributions, and exposure to trawling,.	

Here, we develop a simple, widely applicable quantitative level-3 ERAEF method for assessing relative benthic
status (RBS) in areas fished with towed bottom-contact gears. As an example application, we assess RBS for
seabed habitats and benthic invertebrate taxa in a tropical trawl fishery.

95 Methods

96 DEVELOPMENT OF THE RBS METHOD

- 97 The dynamics of the abundance of seabed communities are assumed to be described by a Schaefer (1954)-
- type logistic population growth equation, with an additional term to describe the direct impacts of trawling on
- the seabed, consistent with previous ERAEF approaches (e.g. Smith et al. 2007; Ellis, Pantus & Pitcher 2014),

$\delta B/\delta t = RB(1-B/K) - DFB$

Page 5

A simple method for assessing seabed trawl risk

100 where $\delta B/\delta t$ is the rate of change in abundance B in time t, R is recovery rate, K is carrying capacity, D is trawl 101 depletion rate (specific to different gear-types) and F is trawling effort as swept-area ratio (the total area 102 swept by trawl gear within a given area of seabed, divided by that seabed area). This model has been used for 103 dynamic assessments of benthos faunal status (e.g. Ellis, Pantus & Pitcher 2014) and to evaluate the effects of 104 management (e.g. Pitcher et al. 2015a,b). Typically, assessment regions are gridded and the model (eqn 1) 105 applied within every cell, assuming that the fauna in each grid cell respond independently to trawling. This 106 assumption is considered acceptable for relatively immobile benthos, but cell-connectivity parameters could 107 be added for mobile fauna (if available). At the scale of grid-cell sizes typically used (e.g. 0.01°, 1×1 nmi, 3×3 108 km, 0.1° — Pitcher et al. 2015a; Dichmont et al. 2013; Hiddink et al. 2006a; Ellis, Pantus & Pitcher 2014), other 109 studies have observed differences in benthos abundances related to patterns of trawling intensity defined on similar scales (e.g. McConnaughey et al. 2000; Piet et al. 2000; Pitcher et al. 2000; Lambert et al. 2011). 110 111 The usual implementation of the logistic equation is dynamic, with trawling-induced mortality input as a time-112 series and abundance output as a time-series. However, for data-limited situations, an approach that does not 113 rely on a time series of inputs is desirable. If the question about risk is framed as "will the current level of 114 fishing lead (or has it led) to habitat status that compromises a defined management objective?", then a

- simpler approach can be used to assess status. This involves solving the logistic equation for the equilibrium
- 116 state (i.e. $\delta B/\delta t=0$), in which case eqn 1 has the solution:
 - *B*/*K*=1–*FD*/R if *F*<*R*/*D*, otherwise *B*/*K*=0

eqn 2

where *B/K* represents relative benthic status (RBS). Thus the equation can be used when *K* is unknown, or
cannot be clearly defined. The method assumes that the current (or future) level of trawl effort *F* has been (or
will be) applied indefinitely. An analogous approach, based on this assumption, was used to project long-term
biomass of benthic species under constant *F* (Appendix C in Ellis, Pantus & Pitcher 2014).

121 Estimation of RBS (eqn 2) requires relatively few parameters: habitat type, trawl effort, depletion rates and

122 recovery rates. Regional application of RBS requires maps of habitats and trawl effort; both should be

determined for grid cells at a scale that adequately captures within-region heterogeneity of habitats and trawl

124 effort. Grid cells of areas ~1–5 km² typically are small enough that the distribution of fishing effort within those

A simple method for assessing seabed trawl risk

Page 6

125 cells is random (e.g. Rijnsdorp et al. 1998; Deng et al. 2005; Ellis, Pantus & Pitcher 2014). Maps of trawling

126 intensity may be derived from fishing vessel logbooks and/or vessel monitoring systems (VMS); typically as

127 hours of effort. These data need to be gridded at a suitable cell resolution, and converted to trawl swept-area

ratio (using information on gear swept-width, tow speeds, and grid-cell area).

129 Trawl impacts differ among gear types and habitats, and recovery rates differ among habitats. Typically,

130 habitats in stable environments are dominated by longer-lived and more sensitive biota that recover slowly,

131 while habitats exposed to high levels of natural disturbance (e.g. mobile sediments) tend to be dominated by

132 less susceptible biota that recover quickly (Jennings & Kaiser 1998). Parameters for depletion and recovery

rates, if not available for habitats in an assessment region, may be obtained from suitable representative

134 meta-analyses of multiple trawl-impact experiments (e.g. Collie et al. 2000; Kaiser et al. 2006). However,

experimental-scale depletion and recovery rate estimates (d, r) must be adjusted to grid scale parameters (D, R

in eqn 2). If the grid scale is chosen so that trawling is distributed randomly within each cell then D=d, but R=r

137 only when trawling is uniform. When trawling is random, the following adjustment is required:

R=rd/[-ln(1-*d*)] eqn 3

where *d* is proportional depletion rate per trawl pass (Ellis, Pantus & Pitcher 2014). In implementation, RBS is
estimated for each grid-cell based on trawl effort and appropriate depletion and recovery rates for the gear
and habitat. The average RBS and distribution of RBS values over grid cells, by habitat, indicate the landscape
scale status of habitats.

142 APPLICATION OF THE RBS METHOD

We applied RBS to assess the status of habitats in Exmouth Gulf, Western Australia, which is fished for shrimps
by otter-trawlers. The region has also been disturbed by cyclones (Loneragan et al. 2013) and extreme
heatwaves (Caputi et al. 2016). Gear- and habitat-specific parameters for *d* and *r* were extracted from a
published meta-analysis (Collie et al. 2000) and linked to maps of habitats and trawling effort in the Gulf. The
sediment-habitat categories used in the meta-analysis were also adopted for Exmouth Gulf.

A simple method for assessing seabed trawl risk

Page 7

148 Depletion and recovery rates

Impact effects (*i*), as log(response ratio), were taken from figure 2 of Collie et al. (2000) for gear type, habitat type, and benthos taxa. Estimates of *i* for gear-by-habitat and for taxa-by-habitat (for otter trawl) were inferred assuming additivity on the log scale and ignoring the possibility of interactions (Table 1). Impact values were assumed, conservatively, to represent the effect of a single trawl pass, although this may not have been the case in all studies included in the meta-analysis. The impact values (Table 1) for otter trawling in sedimentary habitats, and for three taxa (for which recovery rates could be estimated), were converted to proportional depletion rates *d* per trawl pass:

d=1-e^{*i*}

eqn 4

156 Recovery was estimated from figure 5 in Collie et al. (2000), where LOESS curves were presented for 4 habitat types and 3 taxa, based on fits to recovery data. Time taken to recover to reference state differed across 157 habitats (for all taxa pooled), with ~100 days on Sand, ~200 days on Mud and ~300 days on muddy-Sand. 158 159 Recovery of Gravel was not presented in Collie et al. (2000), but was assumed to be similar to their 'Biogenic' 160 category, at about 500 days given other evidence suggesting that gravel habitats recover more slowly than 161 other sedimentary habitats (e.g. Kaiser et al. 2006). Recovery times also differed among the three taxa 162 presented (for all habitats pooled), with about 200 days for Malacostraca (crustaceans), ~250 for Polychaeta 163 (worms) and ~450 for Bivalvia (2-shelled molluscs). 164 To estimate r, we solved the logistic equation for B_t (eqn 5; Figure 1) and fitted this model to the LOESS curves

in figure 5 of Collie et al. (2000), after first back-transforming the response and re-scaling time from days to
years:

$$B_t = B_0 \mathcal{K} / [B_0 + (\mathcal{K} - B_0) e^{-rt}]$$
eqn 5

167 where B_0 is the abundance immediately after experimental impact. B_0 is a function of depletion rate d per

168 trawl and the number of experimental trawls *T*; thus, $B_0 = K(1-d)^T$ and the complete model is:

$$B_{t} = K(1-d)^{T} / [(1-d)^{T} + (1-(1-d)^{T})e^{-rt}]$$
eqn 6

Page 8

A simple method for assessing seabed trawl risk 169 This model was fitted using iterative non-linear regression. K was set to unity since Collie et al. (2000) 170 presented their figure 5 on a log(response ratio) scale (i.e. relative to 1). T was assumed to be unity because, in 171 this instance, d was separately estimated by eqn 4 and to estimate r it was only necessary for the model to fit 172 abundance immediately after impact. If, in future, eqn 6 was used to simultaneously estimate both r and d, the 173 actual value of *T* would be important. 174 The recovery information in Collie et al. (2000) was for habitat and taxa main effects only. Habitat-by-taxa 175 recovery rates for 3 taxa in 4 habitats were inferred in the same manner as those for impact effects. The 176 experimental scale r estimates were adjusted, using eqn 3, to grid-scale R. 177 Regional habitats and trawl effort 178 Linking these estimates of depletion and recovery to the habitats of Exmouth Gulf requires that the region's 179 habitats are mapped according to the categories used in the meta-analysis. Mapped sediment data for the 180 Gulf were obtained from a global database (dbSeabed, http://instaar.colorado.edu/~jenkinsc/dbseabed/, 181 Jenkins 1997) as continuous fractions of mud, sand and gravel. These data are derived from any available 182 direct sediment sampling or observations (e.g. quantitative and textual descriptions of grab/core samples) and subsequently interpolated using an Inverse Distance Weighted method. For the study area ~630 source 183 184 samples were available, with their average separation of $\sim 2-3$ km comparable with the scale of the study grid. 185 The continuous sediment fractions were classified to habitat types matching those of Collie et al. (2000), using 186 a simplified Folk (1954) sediment ternary distribution (Gravel if %gravel>30%, else Sand if %mud<20%, else 187 Mud if %sand<20%, else=muddySand — Figure 2 inset), and mapped. 188 The distribution and intensity of trawl effort was mapped by interpolating and gridding position data of 189 trawling events recorded in confidential fishing vessel logbooks for a 5-year period (2008–2012). Each trawl 190 event included the associated hours of trawling effort. Gridding was done for 0.01° cells (~1.15 km²), because

- 191 trawling typically is distributed randomly at this scale (see previous section) and hence D=d in eqn 2. If trawling
- 192 at this scale was more uniform than random, then depletion would be greater; whereas if it was more
- 193 aggregated than random, then depletion would be less (Ellis, Pantus & Pitcher 2014). Effort in hours per grid-
- 194 cell was re-scaled to total swept area, based on gear swept-width (≤30 m sweep, for shrimp trawls comprising

Page 9

A simple method for assessing seabed trawl risk

- 195 4 nets of 5.5 or 6 fathom head-rope length without sweeps or bridles; Kangas et al. 2007) and tow speeds
- 196 (~3.5±0.3 knots). Total swept area per grid-cell was divided by grid-cell area to provide the swept-area ratio F.
- 197 Effort distributions were consistent among years, so the assumption of constant *F* was considered reasonable
- and the average annual effort was mapped and used in the assessment. The total trawl-footprint area,
- accounting for overlapping trawling, was estimated using both uniform and random assumptions for effort
- 200 distribution within cells.
- 201 Status assessment
- 202 The status of sedimentary habitats in Exmouth Gulf was assessed by setting the un-trawled status of each grid
- 203 cell to unity and using eqn 2 to estimate RBS for each cell (expressed as a proportion of un-trawled status)
- from the D, R and F values. By inference, the RBS of habitats represents an average over the mix of benthic
- taxa typically present in these sediment categories across the range of studies included in the meta-analysis.
- 206 The Gulf-wide status of habitats, accounting for their different sensitivity and exposure to trawling, was
- 207 quantified by plotting the distribution of RBS values against proportion of habitat area, by mapping their
- 208 spatial distribution and by the region-wide average RBS value.
- 209 RBS was also assessed for three benthos taxa. In addition, their absolute status was estimated using
- 210 information on their distributions (see Appendix S1).
- 211 Results

212 DEPLETION AND RECOVERY RATES

- 213 The status of trawled habitats, and hence their RBS score, depends on their depletion rate, recovery rate and
- exposure to trawling. Gravel and Malacostraca have the highest depletion rates in response to otter trawling,
- whereas Mud and Bivalvia have the lowest (Table 2). Sand and Polychaeta have the highest grid recovery rates
- 216 (*R*), whereas Gravel and Bivalvia have the lowest (Table 3). The sensitivity of habitats or taxa to trawling is
- given by the ratio D/R and the critical level of F that would drive their equilibrium status to 0 is R/D. Hence,
- 218 Gravel is the most sensitive habitat and has critical F=4.6, whereas Sand is least sensitive. Malacostraca are the
- 219 most sensitive taxa and have critical F=5.7 (pooled across habitats), whereas Bivalvia are least sensitive.

A simple method for assessing seabed trawl risk

Page 10

220 REGIONAL HABITATS AND TRAWL EFFORT

221 Most (51%) sediments of the ~3,500 km² Exmouth Gulf, between 1–50 m depth, were classified as Sand

followed by Gravel (27%, located mainly in the outer Gulf) and muddy-Sand (20%, mainly in the inner Gulf)

223 (Figure 2). There are a few small areas of Mud (2%) close to the coast.

224 Most trawling in the Gulf occurred in depths between 5–25 m and was aggregated in hotspots (Figure 3). No 225 trawling was recorded in half of the total grid cells (Table 4, Figure 4) including areas both closed to trawling 226 and open but not trawled. About 33% of cells were fractionally trawled (leaving ~75% area untrawled in total) 227 and ~17% were trawled more than once per year. The highest swept-area ratio at the 0.01° cell-scale was ~7.8 228 times per year. The trawl footprint calculated assuming random trawling (Table 4) estimates the area trawled 229 in a single year at ~740 km² (~21% of the Gulf). However, because within-cell trawling generally is not fixed in 230 space, the long-run expectation is that the area within each grid cell is trawled at the average swept-ratio 231 (Ellis, Pantus & Pitcher 2014); hence, the uniform assumption is most representative of the multi-year trawl 232 footprint (~892 km² or ~25% of the Gulf).

Most trawling footprint, by area, occurred on Sand, followed by muddy-Sand, Gravel and Mud (Table 4).
However, relatively, muddy-Sand was proportionally more exposed to trawling followed by Sand and Gravel
(Figure 4); there are few areas of Mud and these were least exposed. A similar proportion (~10%) of each
habitat, except Mud, was exposed to high effort (swept-ratio >~2).

237 STATUS ASSESSMENT

The RBS (*B/K*) of each habitat type as a function of trawling effort shows that Gravel would be most affected
by trawling at all levels of effort (Figure 4), reflecting the higher depletion rates and slower recovery rates
(Table 2, Table 3). At swept-area ratios >4.6, the fauna of Gravel were estimated to be fully depleted, with
RBS=0 in 18 cells (~2.1%). Most Gravel was not exposed to trawling and ~93.4% of Gravel had RBS >50%. The
distribution of RBS values by habitat area (Figure 5) can be used to define other status thresholds; e.g. ~86% of
Gravel had RBS >80%. The Gulf-wide average RBS over all Gravel was 91%. Muddy-Sand was relatively more
exposed to effort but was less sensitive; the minimum RBS of muddy-Sand was 57% and ~93% had status >80%

Page 11

A simple method for assessing seabed trawl risk

(Figure 5). The Gulf-wide RBS of muddy-Sand was 95%. Sand had most exposure to high effort but was the
least sensitive habitat (Table 2, Table 3); its Gulf-wide RBS was >98% and >99% of Sand had status >80%. Mud
had limited exposure to effort and no exposure to high effort (Table 4); its Gulf-wide RBS was >99% and all
Mud cells had status >80%. The spatial distribution of habitat RBS (Figure 6) effectively matches that of trawl
effort but with differences in trawled areas due to differences in sensitivity among sediment types. For
example, the lowest RBS values were for Gravel in moderate-high effort areas, while neighbouring Sand
habitat exposed to similar or greater effort levels had higher RBS values.

The regional average RBS values of the three benthos taxa were similar to those for habitats, in the range ~91– 96%. Malacostraca were most affected and Bivalvia least. The absolute status results for taxa differed from their RBS, because they accounted for their distributions. Nevertheless, the Gulf-wide absolute status estimates were similar to average RBS because the abundance of each taxon was about average in trawled areas (Appendix S1).

257 Discussion

258 The development of the RBS method is timely because it addresses needs arising from national legislation that 259 incorporates the ecosystem approach to fisheries (FAO 2003) driven by international policy commitments (Rice 260 2014) and requirements from certification organisations (e.g. MSC 2014) to take account of the impacts of 261 towed bottom-fishing gears on seabed habitats in management plans and fishery assessments. RBS provides a 262 simple quantitative tool for assessing benthic impacts of bottom trawls and other towed fishing gears. The 263 method is widely applicable, including to fisheries where trawl impacts have not yet been assessed, because it 264 requires relatively few data inputs: 1) effort maps that can be derived from commonly collected VMS or tow 265 data; 2) habitat maps that may be available from local regional surveys, or alternatively national or global 266 geoscience databases of sediments provide first-order mapping of habitats (e.g. dbSeabed); 3) impact and 267 recovery parameters, ideally from local experiments linked to habitat classifications used for the seabed where available, but with meta-analyses (as used herein) providing a more widely applicable alternative. 268 269 Uncertainties in habitat classifications and depletion/recovery rate estimates could be quantified and their

270 implications assessed in future work.

A simple method for assessing seabed trawl risk

Page 12

271 RBS is a level-3 ERAEF method (sensu Hobday et al. 2011) that provides continuous quantitative estimates of 272 status with high-resolution at large spatial scales. Geographically, RBS can be applied most broadly for habitats 273 classified by sediment type, because sediment maps are more widely available than maps of other habitat 274 characteristics. RBS can enable assessments of risk framed as: will (or has) the current level of fishing lead to 275 habitat status that compromises a defined sustainability criteria (such as our example: proportion of habitat 276 with RBS>50%) or management objective (if set, such as our example: regional RBS>80%)? This flexibility of 277 application cannot be achieved with qualitative or categorical trait-based scoring type assessments and/or 278 non-spatial approaches, which only provide ranking of sensitivity or potential risk (e.g. low, medium, high). 279 Furthermore, there are intuitive relationships between the d and r parameters and traits used for resistance or 280 susceptibility (as measures related to d) and resilience or productivity (measures related to r). Thus, qualitative 281 trait scores might be used to infer likely ranges of d and r, enabling use of quantitative RBS. 282 Application of RBS to faunal and habitat-forming communities requires local mapping to describe their 283 distributions and, ideally also local information on impact and recovery. Here (Appendix S1), faunal 284 distributions were predicted, using simple linear models, from local data (Kangas et al. 2007) and a few readily 285 available physical variables. In practice, more sophisticated modelling methods could be applied and faunal 286 distributions could be predicted and assessed at species level if required to account for their differing 287 distributions (e.g. Pitcher 2014; Pitcher et al. 2015b). Faunal distribution data from recent surveys may be 288 influenced by past trawling, hence status assessments based on such data allow assessment of current and 289 future impacts but not necessarily past impact. Predicting status due to past impact may be possible (Appendix S1) where trawl effects can be quantified independently of environmental gradients that influence 290 291 distributions, enabling prediction of un-trawled states (e.g. Ellis et al. 2008; Lambert et al. 2011; Pitcher et al. 292 2015b). 293 For our application, we extracted d and r parameters from a published meta-analysis (Collie et al. 2000), which

included experimental studies up to the late 1990s. Another meta-analysis included a larger sample size of

studies up to the mid-2000s (Kaiser et al. 2006). Future meta-analyses could directly estimate d and r

296 parameters and their uncertainty, as well as quantify links between recovery and environmental variables

Page 13

A simple method for assessing seabed trawl risk

297 other than sediment type, such as temperature and/or primary production — which may enable recovery 298 parameters to account for regional variations in environment. One potential bias when applying RBS to mobile 299 fauna is the possibility that experimentally measured recovery rates reflect movement of individuals into the 300 impacted area, as well as population growth. This bias was accounted for, to an extent, by the adjustment of 301 experimental *r* to grid-scale *R*. In future, meta-analysis of faunal abundance across quantified gradients in 302 trawling intensity may be used to estimate grid-*R* directly.

303 In our assessment of Exmouth Gulf, habitat RBS and faunal absolute status were affected little at the regional 304 scale, with status \geq 90% for all habitats and faunal taxa assessed. This was because <2–7% of the region was 305 trawled sufficiently intensely to yield RBS values <50% and most of the area was either not trawled or trawled 306 lightly. Further, most high-intensity trawling occurred on Sand, which was relatively resilient. Nevertheless, in 307 regions where trawl effort is more intensive and more widely distributed, larger impacts may be expected. For 308 example, Hiddink et al. (2006b) estimated that bottom trawling in the North Sea had reduced benthic biomass 309 by 56% compared with an un-trawled state, albeit using a different method (size-based benthic community 310 model).

311 Our application focused on sedimentary habitats but many of the issues surrounding the sustainability and 312 management of bottom trawling relate to status and conservation of biogenic habitats (Rice, Lee & Tandstad, 313 2015). These habitats are more sensitive to trawling due to higher depletion rates and slower recovery than 314 sedimentary habitats or smaller discrete invertebrates. However, information on distributions of biogenic 315 habitats or habitat-forming benthos is often lacking or inadequate, and parameters for their depletion and 316 recovery rates are also scarce. Some examples where it has been possible to address these information needs 317 include a fish-trawl fishery in the SE of Australia where predicted 2015 regional status of habitat-forming 318 benthos ranged from ~82% to 94% of un-trawled (Pitcher et al. 2015a), and a shrimp-trawl fishery in NE 319 Australia where predicted 2015 regional status ranged from ~76%–98% (Pitcher et al. 2015b). In both cases, 320 status was predicted to be recovering in 2015 following a series of effort reductions and area closures.

RBS can be used to assess the cumulative effects of multiple bottom-contact fisheries (and potentially other
 human and environmental pressures causing seabed impacts, if these can be described by parameters

Page 14

323 analogous to *F* and *d*). Further, RBS also supports quantitative evaluation of the effects of alternative fisheries

A simple method for assessing seabed trawl risk

- 324 management options (e.g. effort reductions, closed areas and gear modifications) by simulating their
- 325 implementation and quantifying changes in estimated status. Such evaluations would assist decision-making
- regarding the choice of management measures to meet environmental targets (e.g. Dichmont et al. 2013) and
- 327 facilitate progress towards sustainable bottom-contact fishing.

328 Acknowledgements

- 329 The authors acknowledge their organizations for salary support; the Walton and Packard Foundations, FAO
- and fishing industry organizations for funding of workshops and travel; Chris Jenkins for dbSeabed sediment
- 331 data; Department of Fisheries Western Australia for trawl effort data from commercial fisher's logbooks and
- for biological survey data (FRDC 2002/038); Tony Smith and anonymous reviewers for constructive comments
- that improved the manuscript. SJ acknowledges the UK Department of Environment, Food and Rural Affairs
- 334 (MF1225); ADR and JGH acknowledge project BENTHIS (EU-FP7 312088).

20,74

335 References

Astles, K.L., Holloway, M.G., Steffe, A., Green, M., Ganassin, C. & Gibbs, P.J. (2006) An ecological method for
 qualitative risk assessment and its use in the management of fisheries in New South Wales, Australia.
 Fisheries Research, 82, 290–303.

A simple method for assessing seabed trawl risk

- 339 Caputi, N., Kangas, M., Denham, A., Feng, M., Pearce, A., Hetzel, Y. & Chandrapavan, A. (2016) Management
- adaptation of invertebrate fisheries to an extreme marine heat wave event at a global warming hot
 spot. *Ecology and Evolution*, doi:10.1002/ece3.2137.
- Collie, J.S., Hall, S.J., Kaiser, M.J. & Poiner, I.R. (2000) A quantitative analysis of fishing impacts on shelf-sea
 benthos. *Journal of Animal Ecology*, 69, 785–798.
- 344 Deng, R., Dichmont, C., Milton, D., Haywood, M., Vance, D., Hall, N. & Die, D. (2005) Can vessel monitoring
- 345 system data also be used to study trawling intensity and population depletion? The example of
- Australia's northern prawn fishery. *Canadian Journal of Fisheries & Aquatic Science*, 62, 611–622.
- 347 Dichmont, C.M., Ellis, N., Bustamante, R.H., Deng, R., Tickell, S., Pascual, R., Lozano-Montes, H. & Griffiths, S.
- 348 (2013) Evaluating marine spatial closures with conflicting fisheries and conservation objectives. *Journal*
- 349 *of Applied Ecology*, 50, 1060-1070.
- Ellis, N., Pantus, F.J. & Pitcher, C.R. (2014) Scaling up experimental trawl impact results to fishery management
 scales—a modeling approach for a 'hot time'. *Canadian Journal of Fisheries & Aquatic Science*, 71, 1-14
- Ellis, N., Pantus, F.J., Welna, A. & Butler, A. (2008) Evaluating ecosystem-based management options: effects of
 trawling in Torres Strait, Australia. *Continental Shelf Research*, 28, 2324–2338.
- Eno, N.C., Frid, C.L.J., Hall, K., Ramsay, K., Sharp, R.A.M., Brazier, D.P., Hearn, S., Dernie, K.M., Robinson, K.A.,
- 355 Paramor, O.A.L. & Robinson, L. A. (2013) Assessing the sensitivity of habitats to fishing: from seabed
- 356 maps to sensitivity maps. Journal of Fish Biology, 83, 826-846

- 357 FAO (2003) Fisheries management. 2. The Ecosystem Approach to Fisheries. Food and Agricultural
- 358 Organisation, Rome.
- 359 Fletcher, W.J., Chesson, J., Fisher, M., Sainsbury, K.J., Hundloe, T., Smith A.D.M. & Whitworth, B. (2002)
- 360 National ESD Reporting Framework for Australian Fisheries: The 'How To' Guide for Wild Capture
- 361 *Fisheries*. FRDC Project 2000/145, Canberra, Australia. <u>http://www.fisheries-</u>
- 362 <u>esd.com/a/pdf/WildCaptureFisheries V1_01.pdf</u>
- 363 Folk, R.L. (1954) The distinction between grain size and mineral composition in sedimentary rock
- 364 nomenclature. *Journal of Geology*, 62, 344-359.
- 365 Hiddink, J.G., Hutton, T., Jennings, S. & Kaiser, M.J. (2006a) Predicting the effects of area closures and fishing
- 366 effort restrictions on the production, biomass and species richness of North Sea benthic invertebrate
- 367 communities. *ICES Journal of Marine* Science, 63, 822–830.
- 368 Hiddink, J.G., Jennings S., Kaiser M.J., Queirós A.M., Duplisea D.E. & Piet G.J. (2006b) Cumulative impacts of
- 369 seabed trawl disturbance on benthic biomass, production and species richness in different habitats.

370 Canadian Journal of Fisheries and Aquatic Science, 63, 721-736.

- 371 Hobday, A.J., Smith, A.D.M., Stobutzki, I., Bulman, C., Daley, R., Dambacher, J., Deng, R., Dowdney, J., Fuller,
- 372 M., Furlani, D., Griffiths, S.P., Johnson, D., Kenyon, R., Knuckey, I.A., Ling, S.D., Pitcher, C.R., Sainsbury,
- 373 K.J., Sporcic, M., Smith, T., Walker, T., Wayte, S., Webb, H., Williams, A., Wise, B.S. & Zhou, S. (2011)
- Ecological Risk Assessment for the Effects of Fishing. *Fisheries Research*, 108, 372–384.
- Jenkins, C.J. (1997) Building Offshore Soils Databases. *Sea Technology*, 38, 25-28.
- Jennings, S. & Kaiser, M.J. (1998) The effects of fishing on marine ecosystems. *Advances in Marine Biology*, 34,
 201–352.
- 378 Kaiser, M.J., Clarke, K.R., Hinz, H., Austen, M.C.V., Somerfield, P.J. & Karakassis, I. (2006) Global analysis of
- 379 response and recovery of benthic biota to fishing. *Marine Ecology Progress Series*, 311, 1–14.

Page 17

A simple method for assessing seabed trawl risk

380 Kaiser, M.J., Collie, J.S., Hall, S.J., Jennings, S. & Poiner, I.R. (2002) Modification of marine habitats by trawling

381 activities: prognosis and solutions. *Fish & Fisheries*, 3, 114–136.

- 382 Kangas, M.I., Morrison, S., Unsworth, P., Lai, E., Wright, I. & Thomson, A. (2007) Development of biodiversity
- 383 and habitat monitoring systems for key trawl fisheries in Western Australia. Final report to Fisheries
- 384 Research and Development Corporation on Project No. 2002/038. Fisheries Research Report No. 160,
- 385 Department of Fisheries, Western Australia, 334p
- Lambert, G.I., Jennings, S., Kaiser, M.J., Hinz, H. & Hiddink, J.G. (2011) Quantification and prediction of the
 impact of fishing on epifaunal communities. *Marine Ecology Progress Series*, 430, 71-86.
- 388 Loneragan, N.R., Kangas, M., Haywood, M.D.E., Kenyon, R.A., Caputi, N. & Sporer, E. (2013) Impact of cyclones
- and aquatic macrophytes on the recruitment and landings of tiger prawns *Penaeus esculentus* in

390 Exmouth Gulf, Western Australia. *Estuarine, Coastal and Shelf Science*, 127, 46-58.

- McConnaughey, R.A., Mier, K.L. & Dew, C.B. (2000) An examination of chronic trawling effects on soft-bottom
 benthos of the eastern Bering Sea. *ICES Journal of Marine Science*, 57, 1377–1388.
- MSC (2014) *MSC Fisheries Certification Requirements and Guidance Version 2.0* Marine Stewardship Council,
 London
- 395 Piet, G.J., Rijnsdorp, A.D., Bergman, M.J.N., Van Santbrink, J.W., Craeymeersch, J. & Buijs, J. (2000) A

quantitative evaluation of the impact of beam trawling on benthic fauna in the southern North Sea. *ICES Journal of Marine Science*, 57, 1332-1339.

- 398 Pikitch, E.E.K., Santora, C.C., Babcock, E.E.A., Bakun, A.A., Bonfil, R.R., Conover, D.O., Dayton, P., Doukakis, P.,
- 399 Fluharty, D., Heneman, B., Houde, E.D., Link, J., Livingston, P.A., Mangel, M., McAllister, M.K., Pope, J.
- 400 & Sainsbury, K.J. (2004) Ecosystem-based fishery management. *Science*, 305, 346–47
- 401 Pitcher C.R., Poiner I.R., Hill B.J. & Burridge C.Y. (2000) The implications of the effects of trawling on sessile
- 402 megazoo-benthos on a tropical shelf in northeastern Australia. ICES Journal of Marine Science, 57,
- 403 1359-1368

- 404 Pitcher, C.R. (2014) Quantitative Indicators of Environmental Sustainability Risk for a Tropical Shelf Trawl
- 405 Fishery. Fisheries Research, 151, 136–174 <u>http://dx.doi.org/10.1016/j.fishres.2013.10.024</u>
- 406 Pitcher, C.R., Burridge, C.Y., Wassenberg, T.J., Hill, B.J. & Poiner I.R. (2009) A large scale BACI experiment to
- 407 test the effects of prawn trawling on seabed biota in a closed area of the Great Barrier Reef Marine
- 408 Park, Australia. *Fisheries Research*, 99, 168–183.
- 409 Pitcher, C.R., Ellis, N., Althaus, F., Williams, A. & McLeod, I. (2015a) Predicting benthic impacts & recovery to
- 410 support biodiversity management in the South-east Marine Region. *Marine Biodiversity Hub, National*
- 411 Environmental Research Program, Final report 2011–2015 Report to Department of the Environment.
- 412 *Canberra, Australia*. (eds N.J. Bax & P. Hedge), pp. 24–25
- 413 http://nerpmarinebiodiversity2015.report/predicting-benthic-impacts-and-recovery-to-support-
- 414 biodiversity-management-in-the-south-east-marine-region/
- 415 Pitcher, C.R., Ellis, N., Venables, W., Wassenberg, T.J., Burridge, C.Y., Smith, G.P., Browne, M., Pantus, F.J.,
- 416 Poiner I.R., Doherty P.J., Hooper, J.N.A. & Gribble N. (2015b) Effects of trawling on sessile
- 417 megabenthos in the Great Barrier Reef, and evaluation of the efficacy of management strategies. *ICES*
- 418 *Journal of Marine Science*, 73, i115–i126. <u>http://icesjms.oxfordjournals.org/content/73/suppl_1/i115</u>
- 419 Rice, J., Lee, J. & Tandstad, M. (2015) Parallel initiatives: CBD's Ecologically or Biologically Significant Areas
- 420 (EBSAs) and FAO's Vulnerable Marine Ecosystems (VMEs) criteria and processes. *Governance of*
- 421 Marine Fisheries and Biodiversity Conservation: Interaction and Coevolution (eds S.M. Garcia, J. Rice &
- 422 A. Charles), pp. 195-208, John Wiley and Sons, New York.
- 423 Rice, J.C. 2014. Evolution of international commitments for fisheries sustainability. *ICES Journal of Marine*
- 424 *Science*, 71, 157–165.
- Rijnsdorp, A.D., Buys, A.M., Storbeck, F. & Visser, E.G. (1998) Micro-scale distribution of beam trawl effort in
 the southern North Sea between 1993 and 1996 in relation to the trawling frequency of the sea bed
 and the impact on benthic organisms. *ICES Journal of Marine Science* 55, 403–419.

Page 19

A SIMPLE MELIOU IOF ASSESSING SEADED LIAWI MSK	A simple me	thod for ass	essing seabe	ed trawl risk
--	-------------	--------------	--------------	---------------

- 428 Schaefer, M.B. (1954) Some aspects of the dynamics of populations important to the management of
- 429 commercial marine fisheries. *Bulletin of the Inter-American Tropical Tuna Commission* 1, 27–56.
- Sinclair, M. & Valdimarsson, G. (2003) *Responsible fisheries in the marine ecosystem*, Food and Agricultural
 Organisation, Rome.
- 432 Smith, A.D.M., Fulton, E.A., Hobday, A.J., Smith, D.C. & Shoulder, P. (2007) Scientific tools to support practical
- 433 implementation of ecosystem based fisheries management. *ICES Journal of Marine Science*, 64, 633–
- 434 639.
- 435 Stobutzki, I.C., Miller, M.J. & Brewer, D.T. (2001) Sustainability of fishery bycatch: a process for assessing highly
 436 diverse and numerous bycatch. *Environmental Conservation*, 28, 167–181.
- 437 Williams, A., Dowdney, J., Smith, A.D.M., Hobday, A.J. & Fuller, M. (2011) Evaluating impacts of fishing on
- 438 benthic habitats: a risk assessment framework applied to Australian fisheries. *Fisheries Research*, 112,
 439 154-167.
- 440 Zhou, S. & Griffiths, S.P. (2008) Sustainability Assessment for Fishing Effects (SAFE): A new quantitative
- 441 ecological risk assessment method and its application to elasmobranch bycatch in an Australian trawl
- 442 fishery. *Fisheries Research*, 91, 56–68.

445 **Tables**

446

447	Table 1. Impact (i) as log(response ratio) from figure 2 in Collie et al. (2000). All terms
448	include the overall mean log response (-0.79). (a) Gear-by-habitat effects were
449	inferred assuming main effects were additive and ignoring interactions (shaded); (b)
450	taxa-by-habitat effects for otter trawl (for three of 12 taxa).

Malacostraca

Bivalvia

-1.36

-0.50

-0.88

-0.02

-1.09

-0.23

-1.04

-0.18

-1.23

-0.37

		Habitat main effect						
(a)		Mud	muddy-Sand	Sand	Gravel			
Gear main effect	i	-0.63	-0.84	-0.79	-0.98			
intertidal dredging	-1.91	-1.75	-1.96	-1.91	-2.10			
scallop dredging	-1.09	-0.93	-1.14	-1.09	-1.28			
intertidal raking	-1.07	-0.91	-1.12	-1.07	-1.26			
beam trawling	-0.56	-0.40	-0.61	-0.56	-0.75			
otter trawling	-0.47	-0.31	-0.52	-0.47	-0.66			
(b)		h	nferred effects f	or otter trawli	ng			
Taxa main effect	i	Mud	muddy-Sand	Sand	Gravel			
Polychaeta	-0.80	-0.32	-0.53	-0.48	-0.67			

A simple method for assessing seabed trawl risk

452

4

153	Table 2. Depletion rates (d) for habitats and taxa, by otter trawl. Taxa-by-habitat
154	estimates were inferred assuming main effects were additive and ignoring interactions
155	(shaded). The taxon rates for All habitats were derived by first adjusting the taxa main
156	effects in Table 1 for the otter trawl effect and subtracting the overall mean response
157	(i.e. adding –0.47 – (–0.79) = 0.32) then applying eqn 4.

	All habitats	Mud	muddy-Sand	Sand	Gravel
Taxon $↓$, All taxa $→$	d	0.27	0.41	0.37	0.48
Polychaeta	0.38	0.27	0.41	0.38	0.49
Malacostraca	0.65	0.59	0.66	0.65	0.71
Bivalvia	0.16	0.02	0.21	0.16	0.31

A simple method for assessing seabed trawl risk

459

460	Table 3. (a) Logistic recovery rates (r , year ⁻¹), for habitats and taxa, estimated by non-
461	linear regression fitted to recovery curves in figure 5 of Collie et al. (2000); taxa-by-
462	habitat recovery estimates were inferred assuming main effects were additive and
463	ignoring interactions (shaded). (b) Grid-scale <i>R</i> estimated by adjusting <i>r</i> , using eqn 3.

	All habitats	Mud	muddy-Sand	Sand	Gravel
(a) Taxon ↓, All taxa→	r	6.4	5.3	15.6	3.0
Polychaeta	5.8	4.9	4.0	11.9	2.3
Malacostraca	6.0	5.0	4.1	12.2	2.4
Bivalvia	3.6	3.0	2.5	7.4	1.4
(b) Taxon ↓, All taxa→	R	5.5	4.1	12.5	2.2
Polychaeta	4.6	4.2	3.1	9.5	1.7
Malacostraca	3.7	3.3	2.5	7.6	1.4
Bivalvia	3.3	3.0	2.2	6.8	1.2

A simple method for assessing seabed trawl risk

Page 24 of 31

465

466**Table 4.** Habitat areas and trawled areas (km²) by base 2 categories of trawl swept-area467ratio (area trawled/grid-cell area): total area; area of sediment habitat types; total swept468area; and estimates of trawl footprints (which account for overlapping trawls) assuming469trawling is uniform at 0.01° or randomly distributed within 0.01° grid cells.

Swept-area	Total		Habitat	area		Swept	Trawl fo	ootprint
ratio	area	Mud	muddy-Sand	Sand	Gravel	area	Uniform	Random
0	1760	34	244	892	590	0	0	0
>0-0.03125	454	9	94	234	117	9	9	8
0.0625	126	1	32	66	26	11	11	11
0.125	152	2	57	66	26	28	28	25
0.25	210	0	79	95	36	74	74	62
0.5	222	2	42	136	41	160	160	113
1	307	6	100	151	50	451	307	233
2	216	0	42	121	53	590	216	200
>4	88	0	8	53	28	481	88	88
Totals	3,535	55	698	1,815	967	1,803	892	740

A simple method for assessing seabed trawl risk

Page 24

471	
472	Figure captions
473	
474	Figure 1. Schematic representation of a trawl impact and recovery experiment, with changes in abundance (B)
475	as a proportion of carrying capacity (K) described with the logistic equation. Abundance is depleted from K to
476	B_0 by experimental trawling at time 0 depending on depletion rate d and number of trawls T, i.e. $B_0 = (1-d)^T$.
477	Recovery follows at rate r so that abundance is B_t after time t , eventually approaching K asymptotically.
478	
479	Figure 2. Map of sedimentary habitats in Exmouth Gulf, between 1–50 m depth (contours: 10 m intervals).
480	Inset: ternary (triangle) plot showing classification of mud, sand and gravel grain-size fractions (0–1) to
481	habitats.
482	
483	Figure 3. Map of trawl effort in Exmouth Gulf, as annual swept-area ratio per grid-cell, between 1–50 m depth
484	(contours: 10 m intervals).
485	
486	Figure 4. Proportion of total Exmouth Gulf area and cumulative total area by annual trawl swept-area ratio
487	(base 2); with cumulative distributions of area for each sediment-habitat type; and equilibrium status (B/K) of
488	habitats at each level of (constant) trawl intensity.
489	
490	Figure 5. Relative benthic status (RBS) of Exmouth Gulf total area and each sedimentary habitat against
491	cumulative proportion of habitat area, ordered by trawl effort, indicating the proportion of area above or
492	below any given status.
493	
494	Figure 6. Map of relative benthic status (RBS) of seabed in Exmouth Gulf, accounting for differing sensitivity of
495	sedimentary habitat types.
496	
497	

A simple method for assessing seabed trawl risk



499

500	Figure 1. Schematic representation of a trawl impact and recovery experiment, with
501	changes in abundance (B) as a proportion of carrying capacity (K) described with the
502	logistic equation. Abundance is depleted from K to BO by experimental trawling at time 0
503	depending on depletion rate d and number of trawls T, i.e. $BO=(1-d)^{T}$. Recovery follows
504	at rate <i>r</i> so that abundance is <i>Bt</i> after time <i>t</i> , eventually approaching <i>K</i> asymptotically.
505	

0,1





A simple method for assessing seabed trawl risk





518



- annual swept-area ratio per grid-cell, between 1–50
- m depth (contours: 10 m intervals).
- 520

521



524 t	rawl swept-area ratio	(base 2	2); with	cumulative of	distributions of	area for e	ach

- 525 sediment-habitat type; and equilibrium status (B/K) of habitats at each level of
- 526 (constant) trawl intensity.
- 527

522

1.0 – – Total area 0.9 Mud (2%) 0.8 Relative Benthic Status (B/K) mudSand (20%) 0.7 Sand (51%) 0.6 Gravel (27%) 0.5 0.4 0.3 0.2 0.1 0.0 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 Proportion of habitat area

529

Figure 5. Relative benthic status (RBS) of Exmouth Gulf total area and each
sedimentary habitat against cumulative proportion of habitat area, ordered by trawl

- 532 effort, indicating the proportion of area above or below any given status.
- 533

Page 30



seabed in Exmouth Gulf, accounting for differing

sensitivity of sedimentary habitat types.



Page 31

A simple method for assessing seabed trawl risk

540

541 Supporting Information

- 542 Additional Supporting Information may be found in the online version of this article:
- 543 **Appendix S1**. *Methods and results for benthic faunal status assessment.*

544

545 Author Contributions Statement

- 546 CRP and NE conceived and developed the model, MK provided fishery data, CRP implemented the model and
- 547 led writing of the manuscript. All authors contributed to review and integrity of the work, interpretation of
- results, drafting and revising the manuscript content and final approval for publication.

