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Putting potential environmental risk of Australia's trawl fisheries in landscape perspective: exposure of seabed assemblages to trawling and inclusion in closures and reserves

Roland Pitcher, Wayne Rochester, Malcolm Dunning, Tony Courtney, Matt Broadhurst, Craig Noell, Jason Tanner, Mervi Kangas, Stephen Newman, Jayson Semmens, Cassandra Rigby, Thor Saunders, Julie Martin and Bill Lussier

Final Report: June 2018

FRDC Project No 2016-039

A catalogue record for this book is available from the National Library of Australia

Pitcher, C. R. (Clifford Roland)
Putting potential environmental risk of Australia's trawl fisheries in landscape perspective: exposure of seabed assemblages to trawling, and inclusion in closures and reserves / FRDC project; no. 2016/039.
Pitcher, C.R., Rochester, W., Dunning, M., Courtney, T., Broadhurst, M., Noell, C., Tanner, J., Kangas, M., Newman, S., Semmens, J., Rigby, C., Saunders T., Martin, J., Lussier, W.

ISBN: 978-1-4863-0998-6 (ebook : pdf)
Subjects: Mathematics & Science. | Earth Sciences, Geography, Environment, Planning. | Australian.

CSIRO Oceans and Atmosphere, St. Lucia, Brisbane, QLD
June 2018.

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This publication (and any information sourced from it) should be attributed to:

Pitcher, C.R., Rochester, W., Dunning, M., Courtney, T., Broadhurst, M., Noell, C., Tanner, J., Kangas, M., Newman, S., Semmens, J., Rigby, C., Saunders T., Martin, J., Lussier, W. (2018) *Putting potential environmental risk of Australia's trawl fisheries in landscape perspective: exposure of seabed assemblages to trawling, and inclusion in closures and reserves — FRDC Project No 2016-039*. CSIRO Oceans & Atmosphere, Brisbane, 71 pages.

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The Fisheries Research and Development Corporation plans, invests in and manages fisheries research and development throughout Australia. It is a statutory authority within the portfolio of the federal Minister for Agriculture, Fisheries and Forestry, jointly funded by the Australian Government and the fishing industry.

Researcher Contact Details

Name: Dr C. Roland Pitcher
Address: CSIRO Oceans & Atmosphere
Queensland Biosciences Precinct
306 Carmody Road, ST. LUCIA QLD 4067 Australia
Phone: +61 (7) 3833 5954; Fax: +61 (7) 3833 5501
Email: roland.pitcher@csiro.au

FRDC Contact Details

Address: 25 Geils Court
Deakin ACT 2600
Phone: 02 6285 0400
Fax: 02 6285 0499
Email: frdc@frdc.com.au
Web: www.frdc.com.au

In submitting this report, the researcher has agreed to FRDC publishing this material in its edited form.

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Acknowledgments

This project was supported by funding from the FRDC on behalf of the Australian Government, and from the collaborating research agencies including CSIRO, Qld DAF, NSW DPI, SARDI, WA DPIRD, IMAS, NT DPIR, and VFA.

Stakeholders, including trawl-fishery managers and industry from multiple jurisdictions provided valuable guidance and feedback to the project.

The CERF Marine Biodiversity Hub (2008-2010) supported the initial collation and mapping of many of the national environmental variables; collation of many of the regional scale demersal biological surveys; and development of the approach used to predict and map assemblages. The NERP Marine Biodiversity Hub Project 2.3.2 (2011-2015) originally developed the approach applied here for quantifying exposure of assemblages to trawling.

Updated ocean colour data were sourced from the Integrated Marine Observing System (IMOS), which is supported by the Australian Government through the National Collaborative Research Infrastructure Strategy and the Super Science Initiative.

The sources of biological survey datasets listed in Appendix 2 (7.2) and of other environmental variables listed in Appendix 3 (7.3) are acknowledged.

Abbreviations

AFMA	Australian Fisheries Management Authority
CARS	CSIRO Atlas of Regional Seas
CERF	Commonwealth Environment Research Facilities
CMRs	Commonwealth Marine Reserve system
CSIRO	Commonwealth Scientific and Industrial Research Organisation
db-RDA	distance-based Redundancy Analysis
DEM	Digital Elevation Model
EEZ	Exclusive Economic Zone
EKP	Eastern King Prawn fishery sector (Queensland)
EPBC	Environmental Protection and Biodiversity Conservation (Act)
ERA	Ecological Risk Assessment
ERM	Ecological Risk Management
FRDC	Fisheries Research and Development Corporation
GA	Geoscience Australia
GAB	Great Australian Bight trawl fishery (Commonwealth)
GAB	Great Australian Bight
GABIA	Great Australian Bight Industry Association
GBR	Great Barrier Reef
IMAS	Institute for Marine and Antarctic Studies
IMCRA	Integrated Marine and Coastal Regionalisation of Australia
IMOS	Integrated Marine Observing System
MPAs	Marine Protected Areas
MRT	Multivariate Regression Trees
NASA	National Aeronautical and Space Administration (USA)
NERP	National Environmental Research Program
NPF	Northern Prawn fishery (Commonwealth)
NSW DPI	New South Wales Department of Primary Industries
NT DPIR	Northern Territory Department of Primary Industry and Resources
NWS	North West Shelf
PIRSA	Primary Industries and Regions South Australia
QDAF	Queensland Department of Agriculture and Fisheries
SAFS	Status of Australian Fish Stocks Reports
SARDI	South Australian Research and Development Institute
SET	South East Trawl fishery (Commonwealth) = SESSF CTS
SETFIA	South East Trawl Fishing Industry Association
TSPF	Torres Strait Prawn fishery (Commonwealth)
VFA	Victorian Fisheries Authority
VMS	Vessel Monitoring System
WA DPIRD	Western Australian Department of Primary Industries and Regional Development
WAMSI	Western Australian Marine Science Institute

Executive Summary

This project implemented the first national spatial approach to quantifying the exposure of mapped seabed assemblages to the footprints of all demersal trawl fisheries that operate on the mainland continental shelf and slope of Australia, as well as their spatial protection in areas permanently closed to trawling. These outputs will assist understanding of the potential risk to demersal assemblages from exposure to trawling footprints and of the contributions of existing spatial management measures to environmental sustainability, and with identifying and prioritising future needs for addressing risks to habitats. The focus provided by this prioritization is intended to reduce the costs of environmental assessments, and ultimately facilitate outcomes including reduction of the ecological risks posed by trawling and improved environmental sustainability. Trawling footprints were mapped from fishery effort data for recent years. Protection provided by current spatial management included all permanent trawl-fishery closures, the Commonwealth Marine Reserve system (CMRs) and State Marine Protected Areas (MPAs). Seabed assemblages — as surrogates for broad habitats — were defined and mapped using a single consistent method that has been enabled by recent advances in analysis methods and the availability of new data and knowledge. The overlaps of each assemblage with trawl footprints, and with areas closed to trawling, were calculated to quantify trawl exposure and spatial protection.

Background

To date, ecological risk assessments (ERAs) for Australian trawl fisheries conducted in response to the requirements of environmental legislation, have largely focussed on bycatch and by-product species — and ecological risk management (ERM) responses have focused on species assessed as being at high risk. However, research has demonstrated that towed demersal fishing gears can also impact seabed habitats, which consequently may be at risk. Most fisheries currently lack adequate data for habitat ERAs, but in some fisheries, the identified nature & diversity of habitats indicate the potential for risks from different fishing gears. Due to the lack of consistent data across Commonwealth demersal trawl fisheries, CSIRO recently assisted AFMA to assess areas of potential risk and identify priorities for habitat ERAs. This project extends that consistent spatial approach to mapping demersal 'assemblages' and trawl footprints to all continental shelf demersal trawl fisheries to provide these outputs nationally. The project scope included both State and Commonwealth trawl and dredge fisheries, and where assemblages straddled jurisdictions, considered cumulative footprints of multiple fisheries where this occurred.

Aims

This project aimed to quantify the overlap of mapped seabed assemblages with trawl footprints, and with areas of spatial management that prohibit trawling, by building on previously collated data and assemblage mapping — as well as data for State and Commonwealth demersal trawling effort, fishery closures and marine reserves and protected areas. These trawl exposure and protection estimates provide information on the eco-regional extent of trawl footprints and potential risk of impacts that managers can use to focus priorities and gaps regarding the needs for future habitat ERAs, and the research that is required to support these assessments, in their progress towards ecosystem-based management.

Methods

Most fisheries lack data for seabed habitats, in the traditional or common-use sense of 'habitat'. Hence, as surrogates for habitats at meso-scales, assemblages were defined where each represented an area having a unique combination of environmental conditions and predicted to have a unique composition of demersal fish and/or seabed invertebrate species (benthos). This process built on the foundation provided by significant previous investment in a number of completed and other current projects, but also required collation of additional data including biological surveys and environmental layers, trawl effort distribution and intensity, permanent trawl-fishery closures, CMRs and State MPAs. The multiple biological survey datasets were analysed with the environmental layers to quantify the magnitude of change in demersal species composition along the environmental gradients (as predictors). This information was then used to predict and map the distribution of demersal assemblages on a 0.01° grid. Trawl footprints were estimated from logbook or vessel-monitoring-system (VMS) effort data, typically for a 5-year period post-2007 (a recent, relatively stable period of effort after prior declining trends in most fisheries), and mapped on the 0.01° grid. CMR and MPA zones that exclude trawling were identified from their current management plans; for CMRs in regions other than the southeast, the now approved post-review revised management plans (March 2018, with effect on 1 July 2018) were used. The overlap of each assemblage with trawling and with closed areas was then quantified by area and as a percentage. All Commonwealth and State demersal-trawl fisheries and scallop-dredge fisheries on the mainland continental shelf and slope, to a maximum depth of 1500 m, were included in the trawl footprint assessment.

Key findings

The majority of the 217 seabed assemblages defined and mapped had little or no exposure to trawling by the State and Commonwealth trawl fisheries included in the assessment. These assemblages with low trawl exposure also included a large number with little or no protection in any areas closed to trawling, in addition to those with higher levels of protection in closures. Across all fisheries, there were relatively few assemblages that had both high exposure to trawling and low protection by closed areas. Several more highly exposed assemblages also had substantive inclusion in closed areas. For example, 15 assemblages had >30% trawl footprint exposure (maximum footprint = 64.4%), of which 5 had >20% protection (max 37.5%) in areas closed to trawling. Assemblages with low exposure and high protection may warrant less focus for future habitat ERA. Assemblages with both high exposure and low protection are considered higher priority for future habitat ERA focus. These include assemblages along much of the Australian east coast from southern Queensland including deep areas of the southern GBR, through shelf areas of NSW, to eastern Victoria/Bass Strait — as well as western Tasmania to SE South Australia on the upper slope, inside Shark Bay, and near the shelf break in the Great Australian Bight. The identification of these trawl-exposed assemblages reflects potential rather than confirmed risk to habitat; information on the distribution of sensitive habitats, habitat-forming benthos or vulnerable species in higher priority assemblages is required to make such a risk assessment. However, such information is lacking in most priority assemblages — and in cases where some information is available, the presence of sensitive benthos and/or vulnerable species is indicated, thus raising the likelihood of actual risk, but currently the data are inadequate for comprehensive assessment of their status or risk. The current lack of adequate data needs to be addressed to achieve and demonstrate sustainability.

Implications for stakeholders

It is likely that the majority of demersal assemblages within Australian trawl fishery jurisdictions are not subject to substantive risk from these fisheries, due to their low exposure, and this is largely independent of whether assemblages have high or low protection. The relatively few assemblages within these jurisdictions that have higher exposures to trawling have high potential for risk to sensitive habitats and vulnerable species if they occur in these areas. Thus, the limited resources for future habitat ERAs can be focussed on the small number of more highly exposed assemblages, particularly those with lower levels of protection, that need further investigation to assess whether sensitive habitats and/or vulnerable species are present and whether they are at substantive risk from demersal trawl or dredge fishing. This focus will enable more efficient application of resources on ERAs for habitats. Ultimately, expected benefits include reduction in environmental risks due to trawling, management agencies meeting requirements of legislation regarding environmental sustainability, and hence improved social licence for fisheries. The recommended future research to assess actual habitat risks is essential to achieving these ultimate outcomes.

Recommendations

Decisions regarding the final priorities for future habitat risk assessments need to involve further discussions with management agencies and industry members, and consultative management and scientific committees that include other stakeholders — particularly for those fisheries that trawl the more exposed seabed assemblages in eastern and south-eastern Australia and elsewhere. The priorities for future habitat ERAs need to take precautionary account of the uncertainties inherent in mapping assemblages and trawl footprints. The discussions should address the research needed to determine whether sensitive habitats or habitat-forming benthos or vulnerable species (including e.g. elasmobranchs) are present in the priority assemblages and their distributions, and whether they are at substantive risk from trawling — as well as consider the potential methods that may be suitable. Where risk management may be required, a range of potential responses should be considered and evaluated objectively, including e.g. spatial management, move-on rules, effort management, and low-impact gear modifications.

Keywords

ERA; ecological risk assessment; bottom trawling; effects of trawling; trawl impacts; seafloor damage; trawl footprints; seabed assemblages mapping; ecoregions; marine protected areas; marine parks.

1 Introduction

Addressing and demonstrating the environmental sustainability of fishing — particularly trawling — remains a major challenge and priority in management plans for many demersal fisheries in Australia. The effects of trawling (EoT) are contentious, with often negative perceptions among the public and media, thus impeding social licence to operate. Australian fisheries must meet legislative requirements under the Environmental Protection and Biodiversity Conservation (EPBC) Act and regular environmental assessments by the Department of Environment.

Ecological risk assessment (ERA) approaches have been used for assessing EoT in response to EPBC Assessment requirements, primarily for bycatch at a qualitative or semi-quantitative level. However, EPBC Principle 2 / Objective 3 (minimise impacts on the ecosystem, including habitats and communities) has rarely been addressed and almost never quantitatively. These shortcomings limit the goal of ensuring no unacceptable impacts on ecosystems.

Further, linked to the legislative requirements, future reporting of the status of fisheries in Australia aims to be more holistic, including broader environmental status. In this respect, a range of indicators that may be suitable have been identified, such as the "habitat footprint" of fishing (i.e. the % of each habitat exposed to fishing, Hobday et al. 2016).

CSIRO has been assisting AFMA to meet EPBC Assessment requirements, recently taking into account new data and methods — and recent management — to implement a consistent spatial approach to mapping demersal 'assemblages' and applying it to Commonwealth demersal trawl fisheries (Pitcher et al 2016c). However, there remained a need to extend this approach to all continental shelf demersal trawl fisheries to meet individual fishery and cumulative assessment and reporting requirements and deliver these benefits nationally. These needs were identified at a FRDC 'Key Projects Workshop' in February 2016 to develop a strategic plan for delivery of FRDC's National Priority 1: "Ensuring that Australian fishing and aquaculture products are sustainable and acknowledged to be so".

This project was developed, in collaboration with each state, to address the above needs. Most of the data required were already available and ready to use for the purpose, with some new data being collated (e.g. additional biological survey data in gap areas, state fishery closures, some effort data updates); the methods were established and successfully demonstrated (Pitcher et al 2016c); hence, the work could be completed cost effectively. Further, the eco-regional maps provided by mapping national assemblages can also be used as a spatial framework to underpin similar footprint assessments for other fisheries and marine uses.

The scope of the project is national, encompassing all Australian 'mainland' State and Commonwealth demersal fisheries that use towed bottom-contact trawls or dredges in shelf and upper-slope waters (<1500 m). These fisheries include fish trawl, prawn trawl and scallop trawl or dredge fisheries managed by AFMA and all States (Qld., NSW, SA, WA, NT, Vic. and Tas.). Each fishery is included within an eco-regional context that considers the extent of adjacent seabed assemblages and any overlapping and/or neighbouring fisheries, to a maximum depth of 1500 m.

2 Objectives

Build on previous research by collating additional data where required, analysing and mapping distributions of predicted seabed assemblages — and mapping state and Commonwealth demersal trawl effort, fishery closures and marine reserves — to:

- quantify the overlap of trawl effort and intensity with each mapped assemblage;
- quantify the overlap of each mapped assemblage with closures and reserves;
- identify mapped assemblages and fisheries that are priorities for habitat ERAs; and
- qualitatively describe the potential risk implications for any habitat-forming biota (if/where data are available) in assemblages with high exposure to fisheries, given current spatial management.

3 Methods

The project built on the foundations for characterising and assessing seabed assemblages that were provided by significant previous investment in a number of completed and current projects. These provided: the underpinning methods for high-resolution regional-scale quantitative risk assessments of assemblages and habitats (e.g. Pitcher et al 2007a); a comprehensive database of available demersal biodiversity survey datasets and environmental data layers with national coverage, new methods for predicting patterns of biodiversity composition at regional scale from multiple disparate inputs, and maps of predicted assemblages for each large marine planning region nationally (Pitcher et al 2011a); updated biological survey and environmental datasets and revised regional maps of predicted seabed assemblages, compilations of Commonwealth fishing effort and closures information, and development of the assemblages overlap approach to be used in this project (Pitcher et al 2015; Pitcher et al 2016c); and compilations of state trawl fishing effort for the international Trawl Best Practices Project (http://trawlingpractices.wordpress.com/). These existing data, including fishing effort, had already been mapped to a common 0.01° (~1.11 km) grid and were re-used by the current project, updated where required.

The previous predicted Australian marine region assemblage maps (e.g. Ellis & Pitcher 2009abc, 2010, 2011; Pitcher et al 2011b; Pitcher et al 2016c), fishing effort data and closures information from these projects provided the basis for the assessments reported here. However, the specific purposes of the current project — i.e. national scale assemblage maps that encompassed all fishery jurisdictions to ensure that assessments were appropriate — required a number of data updates, re-assembly of datasets and re-analyses. In addition, the entire national gridded coverage of environmental layers was re-generated to resolve issues identified by previous projects, including updating the CSIRO Atlas of Regional Seas (CARS) dataset and adding a longer time-series of the CSIRO national 'ribbon' circulation model. Further, 18 additional biological survey datasets were acquired and included in analyses. The assemblage maps provide meso-scale surrogates for seabed habitats, given the lack of data in most fisheries and nationally for habitats defined in a 'traditional' or common-use sense (e.g. seagrass meadows, temperate reef, sponge gardens, etc.). Each assemblage represents an area expected to have a similar mix of species that differs from neighbouring assemblages and increasingly to more distant assemblages.

3.1 Datasets

3.1.1 Biological survey datasets

Many existing biological datasets for large-scale surveys suitable for the project (geo-referenced sampling site by species abundance data) were available from previous projects (e.g. Pitcher et al 2011, among others. See Appendix 7.1). These were primarily from sampling with large fish trawls and comprised mostly larger species of fishes. For parts of Australia, there are also surveys that sampled with medium-sized trawls (prawn, scallop and scampi-trawls) that include smaller species of fishes and mobile invertebrates. In some regions, there are also epibenthic-sled datasets that include mobile and sessile invertebrates. A few regions also have sediment-grab data for infaunal species (e.g. Gulf of Carpentaria). Additional biological survey data were collated recently by Pitcher et al (2016c) including: the Museum of Victoria Bass Strait survey (epibenthic sleds and grabs); the NT demersal fish-trawl survey; WA prawn-trawl bycatch surveys; SARDI Great Australian Bight (GAB) grab and benthic-sled surveys; CSIRO NW slope voyage of discovery, and the Commonwealth South East Trawl (SET) and GAB fishery independent surveys (FIS) datasets (Appendix 7.2).

During the current project, additional biological survey datasets were contributed by QLD (DAF observer, Craigmin and Southern Intruder trawl surveys); NSW (DPI fish-trawl observer, prawn-trawl bycatch); SA (Spencer Gulf and Gulf St Vincent prawn-trawl bycatch surveys); WA (northern demersal finfish trawl and trap survey, southwest trawl survey); TAS (scallop-dredge bycatch survey, demersal fish-trawl surveys); CSIRO (Soela Coral Sea voyage 06/1985, NWS effects of trawl benthos photo survey, Southern Surveyor NPF voyage 03/2005, the Pilbara seabed biodiversity survey, WAMSI Kimberley benthic survey); and by others (Rigby deepwater EKP elasmobranch bycatch, Moreton Bay habitats video survey). These datasets have been checked, cleaned and re-formatted to be compatible with existing survey datasets and analysis procedures (Table 1, Figure 1, Appendix 7.2).

3.1.2 Mapped environmental predictors

The CERF Marine Biodiversity Hub initially collated and mapped 26 environmental variables at 0.01° resolution for the Australian EEZ, for the purpose of biodiversity distribution analysis and prediction (Pitcher et al 2011a; variables #1–27 Appendix 7.3). Subsequently, additional variables were collated as part of the CERF Hub Transition program (#28–35, McLeod & Pitcher 2011) and the NERP Marine Hub (#36–41, Pitcher et al 2015). The original GA GeoMACS 0.1° seabed stress layer was replaced by higher resolution layer from the CSIRO 'Ribbon Model' (#8). FRDC project 2014-204 (Pitcher et al 2016c) updated the Ocean Colour variables (#22–31) to higher resolution 0.01° products from IMOS and revised the derived variables BIR and EPOC (Appendix 7.4).

This project regenerated the entire national grid of environmental variables to resolve issues (e.g. cells missing due to elevation data errors; erroneous data for some CARS variables) found by previous projects, particularly in shallow coastal/inshore areas important for several state trawl fisheries in scope for the current project. This re-mapping included the bathymetry digital elevation model (DEM), sediment grain-size and terrain variables (see Appendix 7.5), as well as the IMOS/NASA ocean colour derived variables. The CSIRO CARS bottom water attributes (variables

#10–21) were updated from source, re-gridded and re-mapped (see Appendix 7.6). The CSIRO 'Ribbon' circulation model had continued to output several additional years of hourly seabed current stress values; these were also updated, re-processed and re-mapped from source with the addition of seasonal variation to the annual mean mapping (variables #8–9, Appendix 7.5).

Table 1 Summary of available collated biological survey datasets; and number of sites by sampling device type.

SURVEY DATASET	FISH TRAP	GRAB	FISH TRAWL	MEDIUM TRAWL	PHOTOS	SLED	VIDEO
Albatross Bay fish surveys			132				
FRV Courageous exploratory surveys			414				
FRV Courageous jack mackerel			51				
FV CraigMin trawl survey, Qld.*			25				
GAB fishery independent survey			225				
SET fishery independent survey			787				
GBR Seabed Biodiversity survey				458		1189	1210
Gulf of Carpentaria compilation		104	682	2054		308	
Gulf St Vincent bycatch survey*				38			
GBR Green Zone effects of trawling			145	120		158	
IMAS scallop bycatch survey*						179	
CSIRO mapping methods survey			18			41	
Moreton Bay habitats*							111
Museum Victoria Bass St survey		157				133	
NPF spatial management survey*		123		123		123	
NSW FRV Kapala trawl surveys			2258	1689			
NSW Ocean Trawl Fish observer*			2807				
NSW Ocean Trawl Prawn bycatch*				136			
NT demersal fish-trawl surveys			276				
NWS early exploratory surveys			502	119			
NWS effects of trawling project			1544		583*		
Orange Roughy exploratory surveys			321				
PCMP Pilbara biodiversity surveys*				43		111	125
Qld DAF East Coast Trawl observer*				116			
Qld DAF East Coast Trawl bycatch				387			
Rigby deep EKP elasmobranchs*				211			
SARDI GAB BPZ surveys		65				40	
SARDI GAB pilot survey						65	
CSIRO video compilation							856
SE Fishery project surveys			191			83	
Soela 06/85 Coral Sea survey*				82			
Soela exploratory fish-trawl surveys			273	1			
Southern Intruder trawl survey*				51			
Soviet fish trawl surveys			5006				
Spencer Gulf bycatch survey*				120			
TAFI fish-trawl surveys*			268				
Tasmanian seamounts surveys						78	
Torres Strait effects of trawling				53			
Torres Strait seabed biodiversity				147		163	170
WAF Northern Demersal Scale Fish*	421		58				
WA slope fish survey			64				
WA southwest trawl survey*				249			
WA Voyage of Discovery		136		119		73	
WA Shark Bay & Exmouth Gulf survey				52			
WAMSI Kimberley surveys*						122	83

* additional biological survey datasets collated by this project.

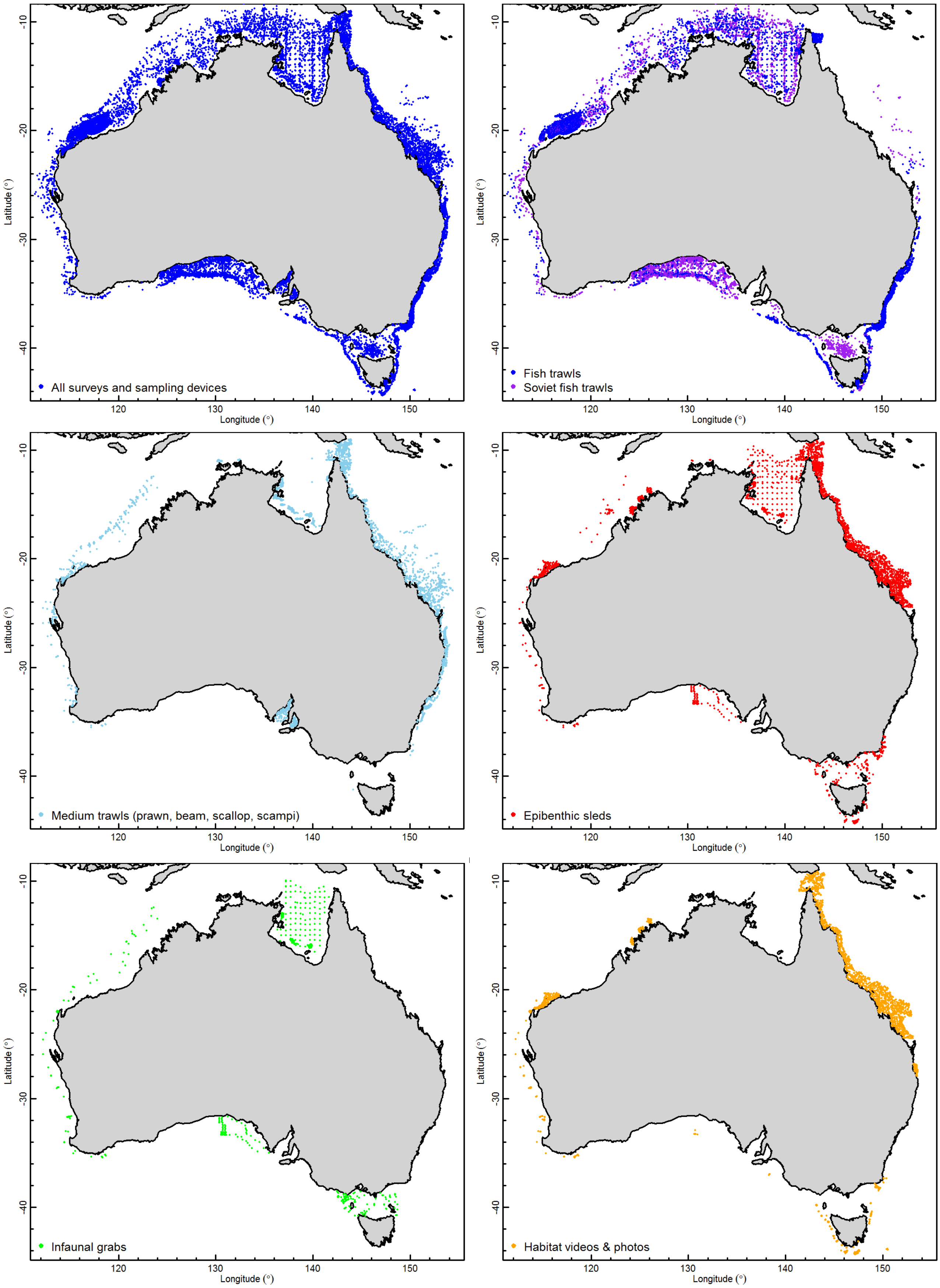

Figure 1 Maps of distributions of survey sites by sampling device type. Deepwater areas (>200 m depth) and the south west of Australia are relatively under-sampled.

3.1.3 Closures and Marine reserves

Spatial data for Commonwealth fish-trawl fishery closures and Commonwealth Marine Reserves (CMRs) were largely available from recent projects (e.g. Pitcher et al 2015). Additional data for closures in Commonwealth prawn-trawl fisheries (NPF, TSPF) and for other marine protected areas (MPAs) were collated by FRDC project 2014-204. The current project, and related CSIRO projects (Mazor et al 2017), collated data for additional state MPAs and aquatic reserves, all state trawl-fishery closures, and for the revised CMRs. All were mapped to the 0.01° grid used by the project (Figure 2). Only fishery closures and reserves that permanently prohibit trawling were considered.

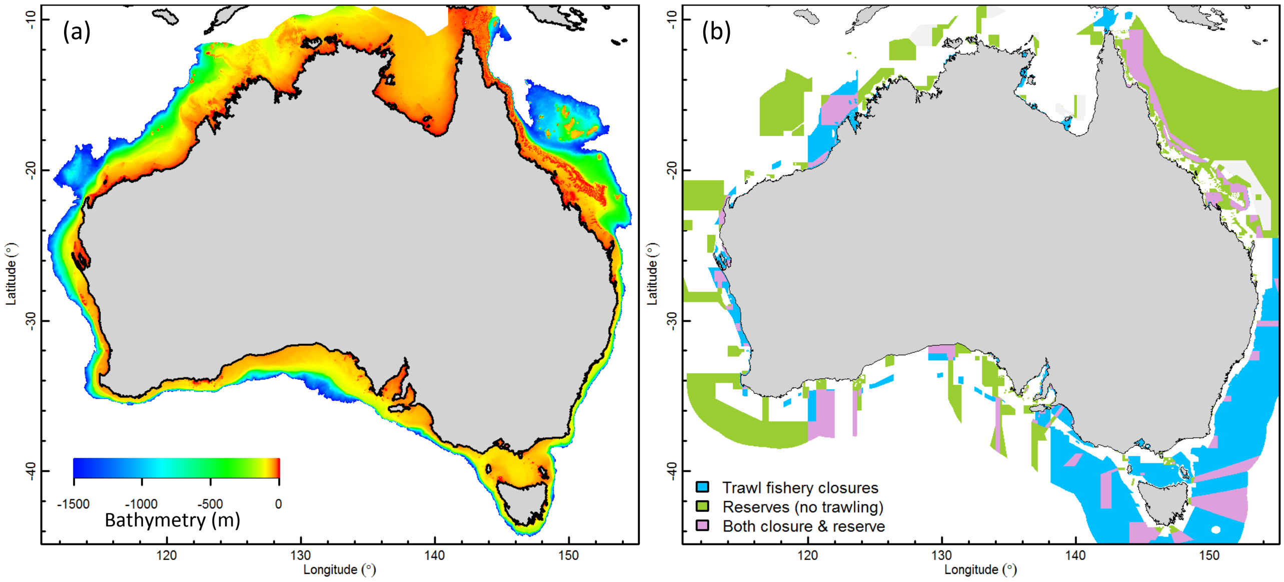

Figure 2 (a) Depth of continental shelf and continental slope areas in scope for the project (<1500 m). (b) Trawl-fishery closures (blue+purple) and marine reserve areas (green+purple) that permanently prohibit trawling. The revised Commonwealth Marine Reserves plans permit trawling in some special purpose zones (light grey).

All CMR zones that permanently prohibit trawling were identified as documented in their management plans. For the southeast region, these plans have been in force since 2013. For other regions, zones that prohibit trawling were identified using the revised CMR (now called "Australian Marine Parks") management plans (approved March 2018) — after extensive review and public comment — and in effect from 1 July 2018.

3.1.4 Trawl effort data

Data on annual trawl effort were largely available from previous recent or related projects, gridded at 0.01° from logbook records or vessel monitoring system (VMS) data as available for each fishery. For this project, effort data for a recent period, typically 5 years post-2007 and updated where required, were used to account for significant prior management changes in several fisheries. Effort data provided in various metrics (e.g. hours, metres, number of tows) were all converted to trawl swept-area per grid-area ratio, to standardise for different gear sizes, spread-ratios and tow speeds. The annual average for each grid cell, over the period, was taken to define the typical spatial distribution and intensity of trawling for recent years in each fishery. The swept-area ratio data were joined to the national gridded environmental layers and mapped (not shown, confidential). Note that source effort data are not free of errors and conversion to swept-area has uncertainties (see section 4.4.2 for details). The footprints for each fishery have been estimated (Table 2). These data show the total area of 0.01° grid cells with trawling recorded in recent years; the annual average total swept area of all trawls; the footprint area accounting for overlapping effort in grid cells with swept-area ratio >1, assuming trawling is conducted uniformly at 0.01° scale; and the footprint area accounting for overlapping effort *within* grid cells, assuming trawling is conducted randomly at sub-0.01° scale. The random <0.01° estimates the annual average footprint. However, among years the fine distribution of trawling at 10–1000 m scales is not exactly the same, and over multiple years the footprint tends to approximate the uniform footprint. Together, these estimated footprints range from almost 3 to 3.5% of the combined total area of shelf and slope (<1500 m) within the Australian EEZ.

Table 2 Estimates of trawl footprints (km²) of State and Commonwealth demersal trawl fisheries in 0.01° grid cells.

FISHERY	YEARS INCLUDED	TOTAL WITH TRAWL	TOTAL SWEPT AREA	UNIFORM @ 0.01°	RANDOM <0.01°
Queensland: Gulf Developmental Fish Trawl	2011–2013	6,934	546	546	507
Queensland: East Coast Otter Trawl (prawn!)*	2008–2012	97,799	58,741	29,024	23,961
New South Wales: Ocean Trawl Fish	2009/10–13/14	14,116	7,304	4,514	3,630
New South Wales: Ocean Trawl Prawn*	2009/10–13/14	20,918	7,941	2,904	2,465
Victoria: fish trawl	2002–2012	6,546	91	65	54
Victoria: prawn trawl	2002–2012	5,397	502	477	358
Victoria: scallop dredge	2002–2012	7,748	17	12	10
Tasmania: scallop dredge:	2003–08, 12–13	1,679	61	61	58
South Australia: Gulf St Vincent Prawn	2007–2011	3,144	296	296	257
South Australia: Spencer Gulf Prawn	2008–2012	10,851	2,257	1,655	1,347
South Australia: West Coast Prawn	2008–2012	831	235	175	138
Western Australia: Pilbara Fish Trawl*	2008–2012	21,645	6,061	6,012	4,916
WA: combined prawn trawl fisheries	2008–2012	12,356	8,373	3,999	3,375
WA: combined scallop trawl fisheries	2008–2012	5,902	1,028	960	772
Northern Territory Finfish Trawl	2010–2012	42,736	3,873	3,873	3,573
Commonwealth: South East Trawl*	2008–2012	77,763	33,843	22,344	17,965
Com'wealth: Great Australian Bight Trawl*	2008–2012	20,383	10,087	7,676	5,951
Commonwealth: Western Deepwater Trawl*	2008–2012	3,296	267	260	219
Commonwealth: North West Slope Trawl*	2008–2012	8,877	904	890	776
Commonwealth: Torres Strait Prawn*	2010–2012	4,771	2,949	1,848	1,487
Commonwealth: Northern Prawn*	2008–2012	79,195	14,863	12,563	10,238
Commonwealth: Bass Strait Scallop*	2009–2012	706	32	32	29
TOTALS		**453,593**	**160,270**	**100,185**	**82,085**
Percentage of shelf & slope (0-1500 m)	**2,923,734 km²**	**15.51%**	**5.48%**	**3.43%**	**2.81%**

* trawl effort datasets updated by this project, regarding either years included and/or details of calculation of trawl swept areas.

! note, QECOT is primarily a prawn-trawl fishery but includes scallop-trawl and stout-whiting trawl.

3.2 Analyses

3.2.1 Statistical details

The approach used for characterising and mapping seabed assemblages is now established; it involves quantifying the magnitude of change in species composition along environmental gradients (predictors) and using this information to predict distribution patterns of demersal biodiversity. The method, "Gradient Forest" (Ellis et al 2012), is described in this section and is illustrated for the Gulf of Carpentaria region at the beginning of the results.

The R package gradientForest is an extension of Random Forest (Breiman 2001), which fits an ensemble of bootstrapped regression tree models (a 'forest' — of 500 trees in our case) between each individual species abundance and environmental variables. The many branches (or 'splits') in the tree models are fitted recursively along the environmental gradients at locations on variables where the most deviance in species response is explained (fit 'improvement'). Each tree is fitted to a different random sample of ~⅔ of the data (in-bag) and fit performance is tested on the ~⅓ of data held out-of-bag (OOB). The influence of each variable is assessed by randomly permuting each variable in turn and quantifying the degradation in prediction performance on the OOB data ('predictor importance'). Models were fitted for every species with adequate occurrence in every available biological survey dataset.

From the Random Forest models, Gradient Forest extracts each split value and deviance improvement. The split-improvements were aggregated and standardised by data density to quantify where species composition changes occurred along the gradients. Cumulative distributions of the splits on each predictor represent overall changes in the whole community, or compositional turnover, in standardised units of R^2 along the gradient of each predictor. These turnover curves are accumulated for the fishery region to provide empirical functions for transforming the multi-dimensional environmental gradients to common biologically-scaled axes that can be used to estimate the spatial pattern of species composition — or *assemblages* — associated with the environment, and mapping in geographic space. Because these functions integrate biological information, they provide improved use of environmental variables as surrogates for predicting and mapping patterns of biodiversity. The method has been used to produce biodiversity and bioregional maps in Australia and overseas. Statistical details of Gradient Forest are described in Ellis et al (2012), and example ecological applications are described in Pitcher et al (2010, 2012). Further information is available at http://r-forge.r-project.org/projects/gradientforest/.

After the multiple environmental gradients have all been transformed to a common biological scale, principal components analysis (PCA) is used to capture the majority of compositional variation associated with environmental gradients in as few dimensions as possible. A colour ramp is applied to the PCA ordination (e.g. red-green-blue in three dimensions, or a colour wheel around the first two dimensions) to allow visualisation of compositional patterns in 2-D PCA-space and in mapped geographic space. The visualisation in PCA-space may be called 'biological-space' — it is a 'bi-plot', with vectors showing the direction of the major environmental drivers, and provides a colour key for the corresponding geographic map to facilitate interpretation.

The continuous variation in composition in biological space was clustered to represent expected species-assemblage groups, which were also mapped in biological space and geographic space. Determining the most appropriate number of clusters, or predicted assemblages, for a region is non-exact — several guides have been trialled previously (Pitcher et al 2011). This number should be guided by the original biological survey data as much as possible, although this is not straightforward for the case of several contributing surveys each having only partial coverage of a region. A two-step approach was taken. First, multivariate regression trees (MRT, R package mvpart) were applied to each biological survey separately to obtain an objective number of groups (i.e. terminal nodes) for sampled sites in each dataset by partitioning on environmental variables using cross-validation (mvpart 1SE criterion). The resulting number of terminal nodes sets a minimum constraint on the number of clusters in biological space; i.e. the number of clusters in the whole region must be sufficient to split each set of survey sites into at least the number of MRT terminal nodes. The second step assessed which regional clustering — over a plausible range of numbers of clusters — taken as a factor, accounted for most variation in the constituent biological survey datasets. This involved linking each candidate clustering back to the biological survey sites and using a multivariate analysis of variance method (distance-based redundancy analysis, db-RDA, Legendre and Anderson 1999). The db-RDA provides a multivariate F-ratio test statistic, a large value of which would indicate evidence that a given clustering has captured structure in the survey sample data. The F-ratio for each survey in the region was obtained, for each regional clustering, and the geometric mean of these was used as the diagnostic. Subject to the step one minimum constraint, the clustering with the largest mean F-ratio was preferred.

3.2.2 Application in this project

It was necessary to use a two-scale approach for characterising seabed assemblages nationally because a single-step approach would have masked important local-scale patterns evidenced by local-scale survey datasets. A secondary reason was computational efficiency. Hence, first the entire national grid was clustered into larger regions within which separate regional analyses were nested. At both scales the analyses involved using Gradient Forest, as described in the previous section, to quantify the magnitude of compositional changes along environmental gradients, for every species for which sufficient data were available, in every available biological survey dataset.

The initial whole-of-Australia characterisation involved analyses of national scale and other large extent (>10° Lat or Lon) surveys including the Soviet fish-trawl surveys, CSIRO exploratory fish-trawl surveys (Courageous, Soela, early NWS, Orange Roughy), the CSIRO WA slope voyage of discovery, the GBR seabed biodiversity survey, NSW FRV Kapala fish-trawl surveys, and combined SET and GAB fishery independent surveys. In the national-scale analysis, only large-scale oceanographic variables (annual means), depth and latitude and longitude were included — seasonal variability and local habitat variables (e.g. sediments) were excluded. A range of clusterings from 5 to 32 national clusters was examined to define the regions in which to nest the regional analyses. A pragmatic number of regions was required, with a pattern that reflected established biogeographic patterns. Ultimately, the national regions were based on a clustering with eight groups but with additional splits added near Northwest Cape, Sandy Cape and south-west of Torres Strait that were stable at clusterings with higher numbers of groups, producing a final total of 11 national regions.

Within each of the 11 national regions, separate regional analyses used the same method; however, potentially all 41 environmental variables were used (subject to testing their utility) including seasonal variability and local scale habitat variables (e.g. sediments) — latitude and longitude were excluded. Regional analyses utilized all biological datasets that had an adequate number of sites within the region, as well as subsets of the national-scale surveys determined by constituent voyages that were substantively within the region.

Within each region, multiple datasets (4–20) contributed to the characterisation, potentially including one or more survey methods: fish trawl, various medium trawls, benthic sled, grab, or video. The combined information from analyses of these datasets provided the functions for transforming the regional environmental gradients to a multi-dimensional biological space, as described in the previous section, which was then mapped in geographic space. The continuous compositional change represented by the biological space was then clustered into assemblages, with the final number of assemblages selected based on the guidance provided by the MRT and db-RDA analyses described in the previous section.

3.3 Assessments

Each mapped assemblage provided the basic unit of assessment and after the assemblage maps and trawl effort and closures datasets were produced for each of the 11 national regions, the quantitative overlap assessments comprised relatively straightforward spatial analyses. First, the various types of spatial management, including CMRs, other MPAs, and fishery closures that permanently prohibit trawling (Figure 2, b) were overlaid on the assemblage maps and the area of spatial management in each mapped assemblage was quantified as a percentage of the area of each assemblage. Second, the mapped multi-year trawl footprint of all fisheries (see Table 2, 'uniform') was overlaid on the corresponding assemblage map, and the area of trawl footprint in each assemblage was quantified as a percentage of the area of each assemblage. As an indicator of trawl-effort intensity, the average annual total trawl swept area in each assemblage was also quantified as a percentage. This information was tabulated for each assemblage in each region. The level of exposure of each assemblage to trawling, and protection through spatial management, were also mapped and plotted in a format analogous to previous presentations (Pitcher et al 2016c).

To provide an overall synthesis, all mapped assemblages were ordered by exposure to trawling footprint and total swept-area intensity as well as (the complement of) overlap in fishery closures and reserves. This ordered list supports prioritisation of the identity and requirement for assemblages to be the focus of future ERAs for habitat.

The trawl footprint exposure of assemblages is an indicator of *potential* risk but is not directly an assessment of risk of trawl impacts on habitats *per se*. Where possible, for any assemblages that appeared to be of higher potential risk — if suitable information was available — the possible risk implications were discussed with reference to the sensitivity (impact rates and recovery rates) of the constituent habitat-forming biota.

4 Results and Discussion

4.1 National-scale characterisation

The final 11 national regions (Figure 3) were largely consistent with the IMCRA 4.0 Provincial Bioregions (Commonwealth of Australia 2006). There was greater bio-physical heterogeneity associated with the environment in tropical and sub-tropical Australia compared with temperate Australia. This was indicated in the biplot by the relative compression of southern Australia, and in the clusterings by the greater number of groups in northern Australia. These national regions provided a large scale framework within which the meso-scale assemblages were defined.

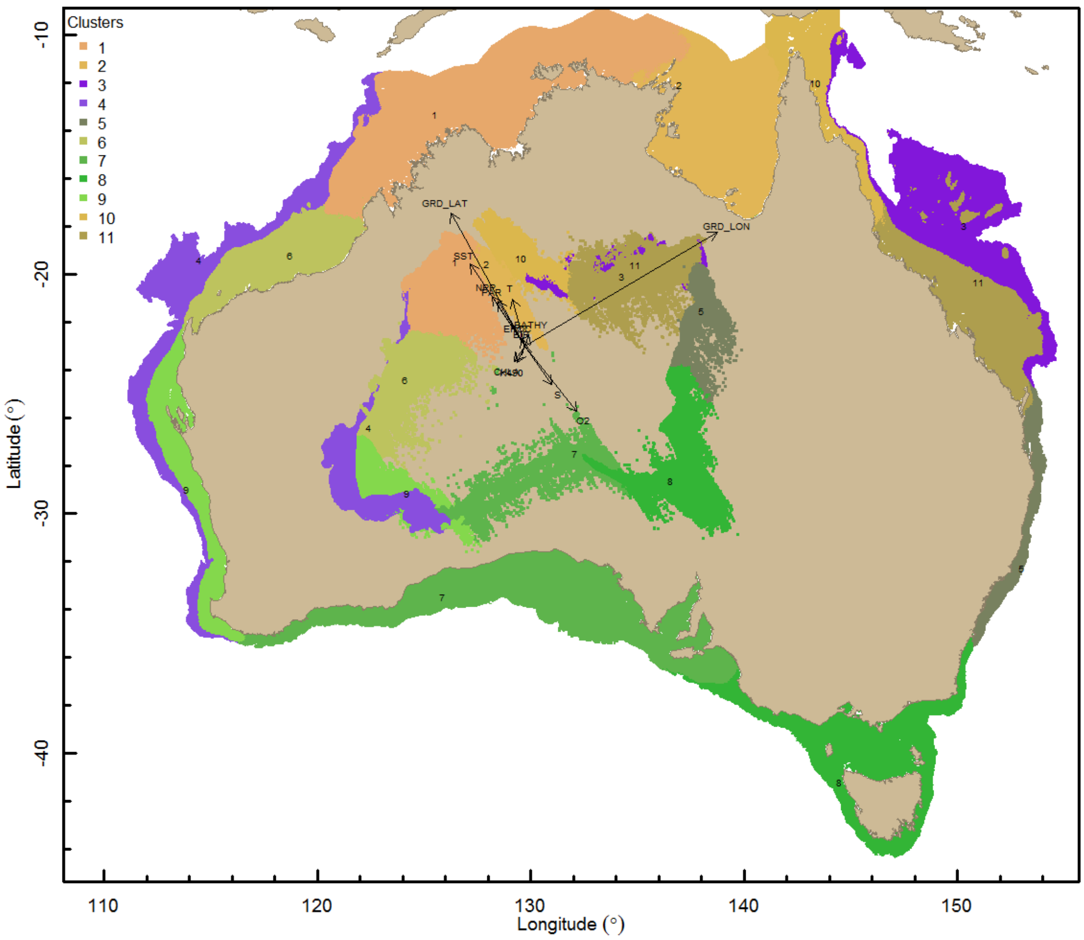

Figure 3 Map of Australia showing the national scale clustering into 11 regions for nested regional scale analyses of data and mapping assemblages. The biplot shows the first 2 dimensions of the multi-dimensional biological space, representing composition change in relation to vectors of the major environmental drivers (see Appendix 7.3) and longitude and latitude. Southern Australia was less heterogeneous than sub-tropical and tropical Australia.

4.2 Regional assemblage characterisation

Analyses of biological survey data and mapping of assemblages were completed for all 11 national regions, which encompassed all Commonwealth and state trawl fisheries on the mainland continental shelf and slope of Australia.

Step-by-step analysis results are shown here for the Gulf of Carpentaria region (#2) to illustrate the outputs from the procedure for assemblage characterisation and mapping; for all other regions only the final assemblage mapping is presented. Figure 4 shows the cumulative importance curves for each environmental variable for each survey dataset. Each curve represents the cumulative changes in the overall species composition (or turnover) along each environmental gradient, based on aggregating outputs from models fitted to each species that quantify changes in species abundance along each environmental gradient. Steep parts of curves indicate strong changes in species composition, whereas flat parts indicate little compositional change — often, the changes are non-linear along environmental gradients. The curves are standardised by the R^2 performance of each species model and the importance of each environmental variable, so all are in common units of predicted biotic composition change associated with the environment.

Environmental variables with greater influence are associated with larger changes in species composition (larger values on the Y-axis). The black line indicates the combined cumulative changes across all datasets, based on weighting by species R^2 performance, the number of species and sites in each dataset and the density of observations for each dataset along each gradient. The combined cumulative curves represent empirical functions for transforming each of the regional environmental variables (measured on many disparate scales) to a common scale that represents gradients in biological composition associated with the environment. After transforming, the principle components provide a multi-dimensional biological space (Figure 5, inset; first 2 dimensions only); that represents gradations in habitats and species and their similarity. Points close together in this space have similar composition (and colours) that differs from locations more distant in this space. Vectors indicate the direction and magnitude of influence of the major environmental variables. The biological space mapped into geographic space (Figure 5) represents the spatial distribution of these continuous changes in biological composition.

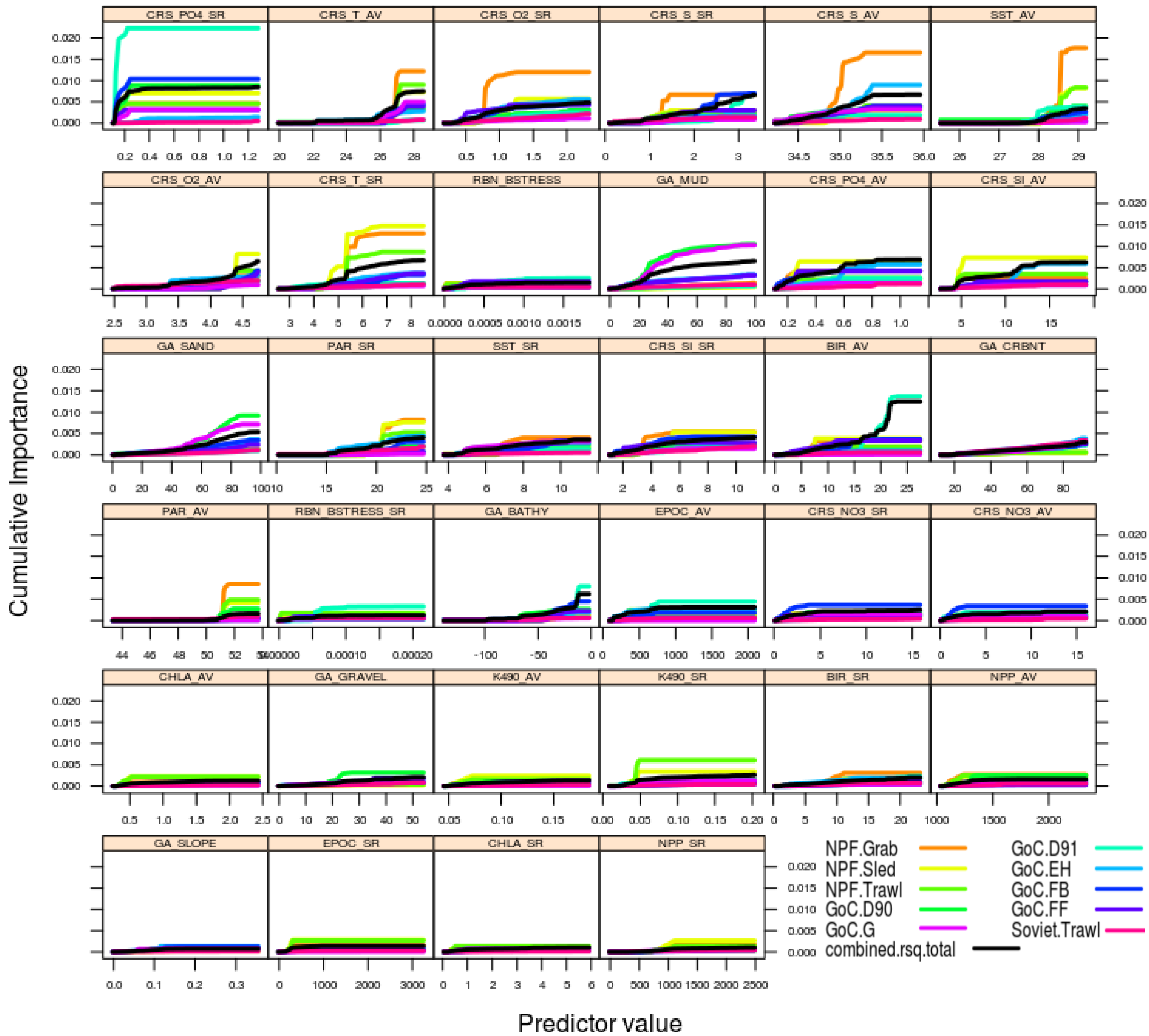

Figure 4 Gulf of Carpentaria region #2: transformation functions output from analysis of each dataset, for each environmental gradient (see Appendix 7.3) to cummulative biological importance (compositional change). NPF: Northern Prawn Fishery; GoC: Gulf of Carpentaria; D##: Dredge and year; G: grab; EH: Engle Hi-rise trawl; FB: Frank and Bryce trawl; FF: Florida-Flyer trawl.

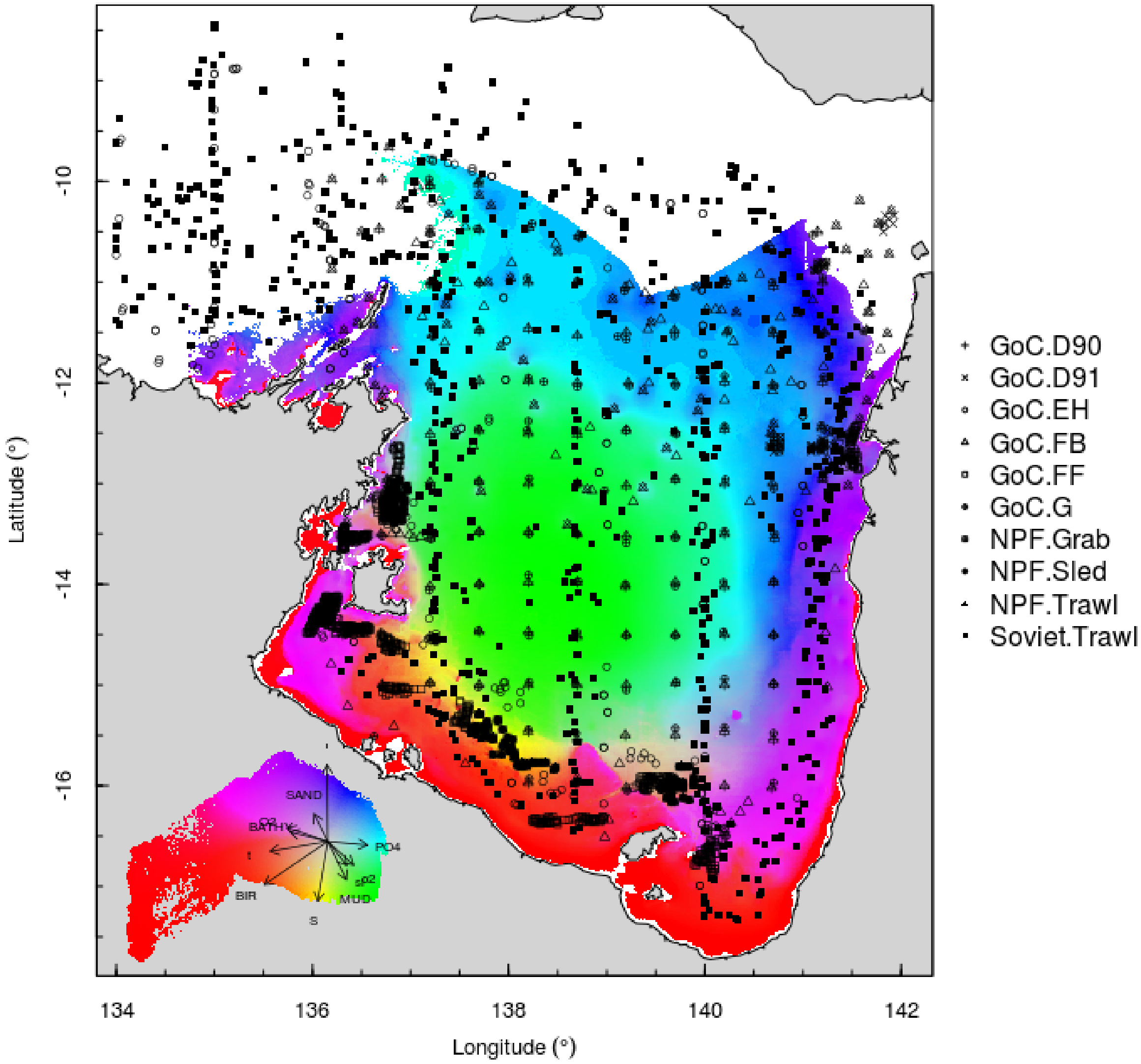

Figure 5 Gulf of Carpentaria region #2: map of continuous compositional change with survey sites overlaid (inset: first 2 dimensions of multi-dimensional biological space. See Appendix 7.3 for variable definitions; caps=annual means, lc=seasonal ranges). GoC: Gulf of Carpentaria; NPF: Northern Prawn Fishery; D##: Dredge and year; G: grab; EH: Engle Hi-rise trawl; FB: Frank and Bryce trawl; FF: Florida-Flyer trawl.

The assemblage classification needed by this project, and by many management applications, requires that the continuous biological space be clustered into groups — and that the number of groups is appropriate. Figure 6 shows a cross-validated MRT for one dataset (Gulf of Carpentaria Florida-Flyer surveys, GoC.FF) as an example of information contributing guidance on the selection of the appropriate number of assemblages for the region. This analysis provides statistical evidence that the sites for the GoC.FF surveys are divided into seven groups based on their sampled species composition. The regional biological space needed to be clustered into at least 13 groups in order to divide the grid cells corresponding to the GoC.FF sites into at least seven groups (Figure 7). Across the 10 datasets contributing to the region #2 characterisation, the MRT criterion for most was met by five or less regional clusters, one required at least six clusters and another at least seven. The db-RDA multivariate F-ratio indicated that the largest local maximum for ≥13 clusters occurred at 15 clusters (Figure 7), suggesting that a regional clustering into 15 assemblages captured somewhat more structure amongst all the survey datasets.

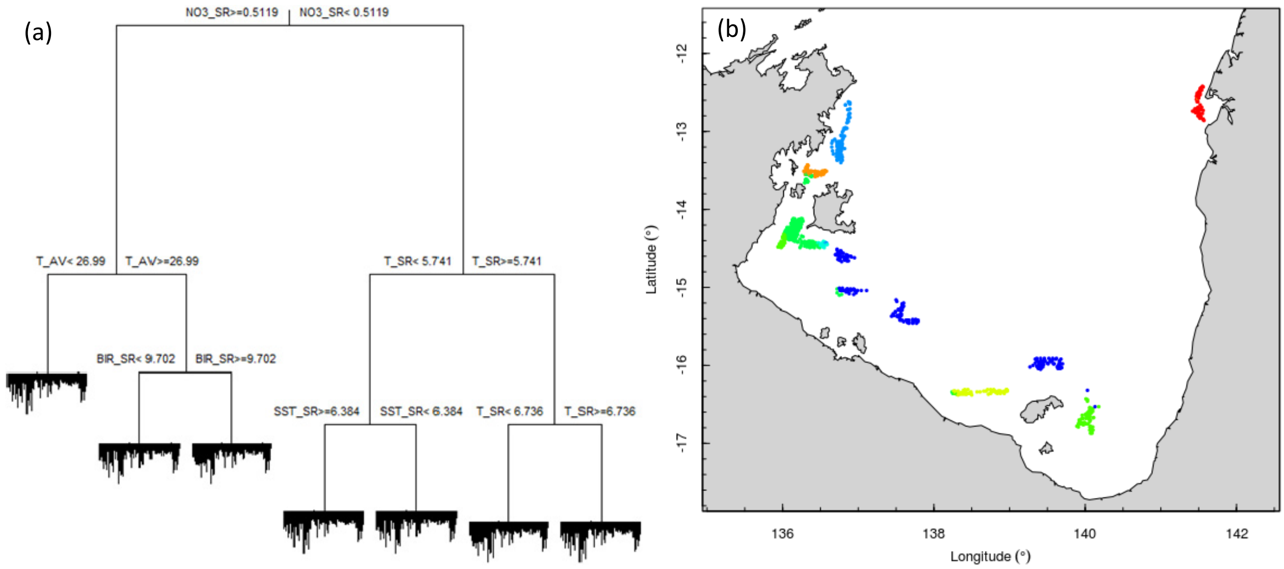

Figure 6 Gulf of Carpentaria region #2: (a) cross-validated MRT indicating evidence for 7 groups of sites for florida-flyer bycatch surveys (GoC.FF) (see Appendix 7.3 for variable definitions); (b) map of the distribution of the 7 MRT groups of GoC.FF sites.

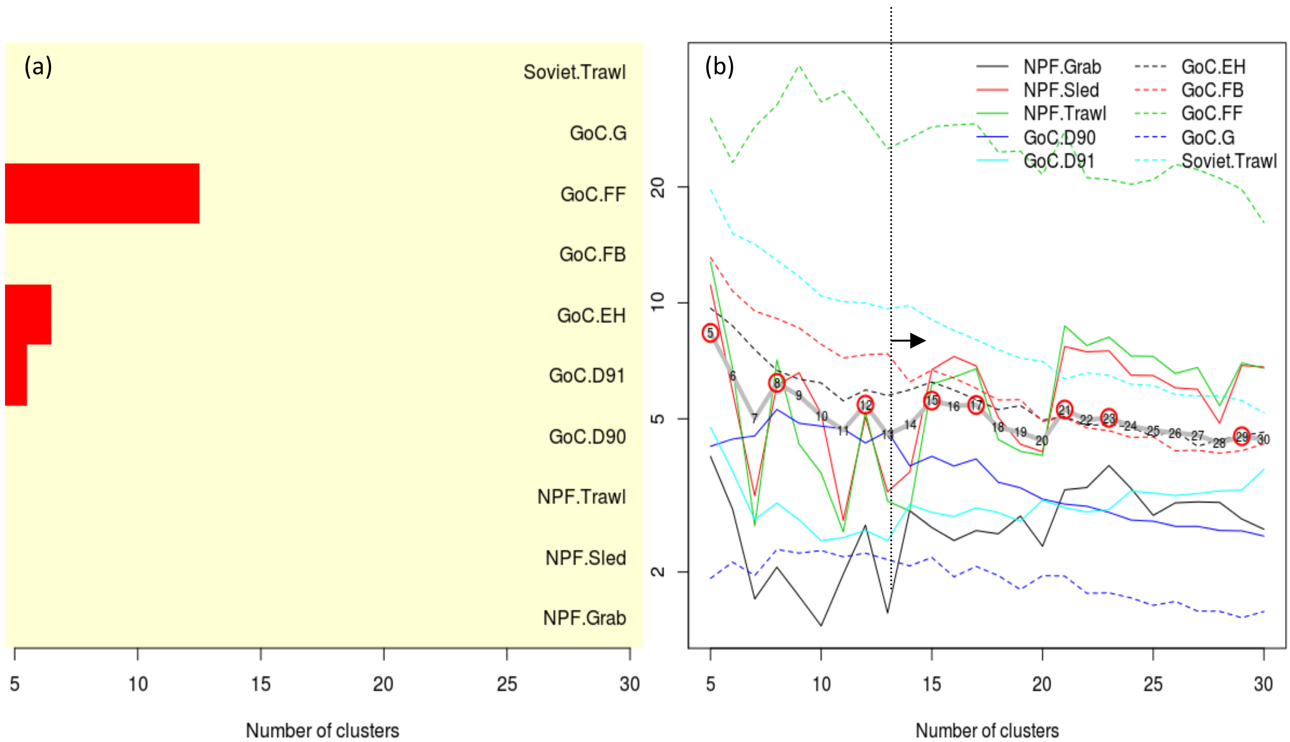

Figure 7 Gulf of Carpentaria region #2: (a) MRT clustering criterion for each dataset. (b) db-RDA F-ratio results of the variation in each dataset explained by the range of clusterings (5-30); thick grey numbered line shows overall weighted mean; vertical dotted line shows minimum clustering from the MRT criterion.

Figure 8 maps the spatial distribution of the 15 clusters, or assemblages, for region #2. Each assemblage (1–15) represents an area expected to have a relatively homogeneous composition of species that differs from neighbouring assemblages and increasingly from assemblages more distant in biological space. Given that assemblages are also defined by unique combinations of (transformed) environmental variables, they also represent areas that have relatively homogeneous environment, and hence also provide meso-scale surrogates for habitats, and may also be termed “ecoregions”.

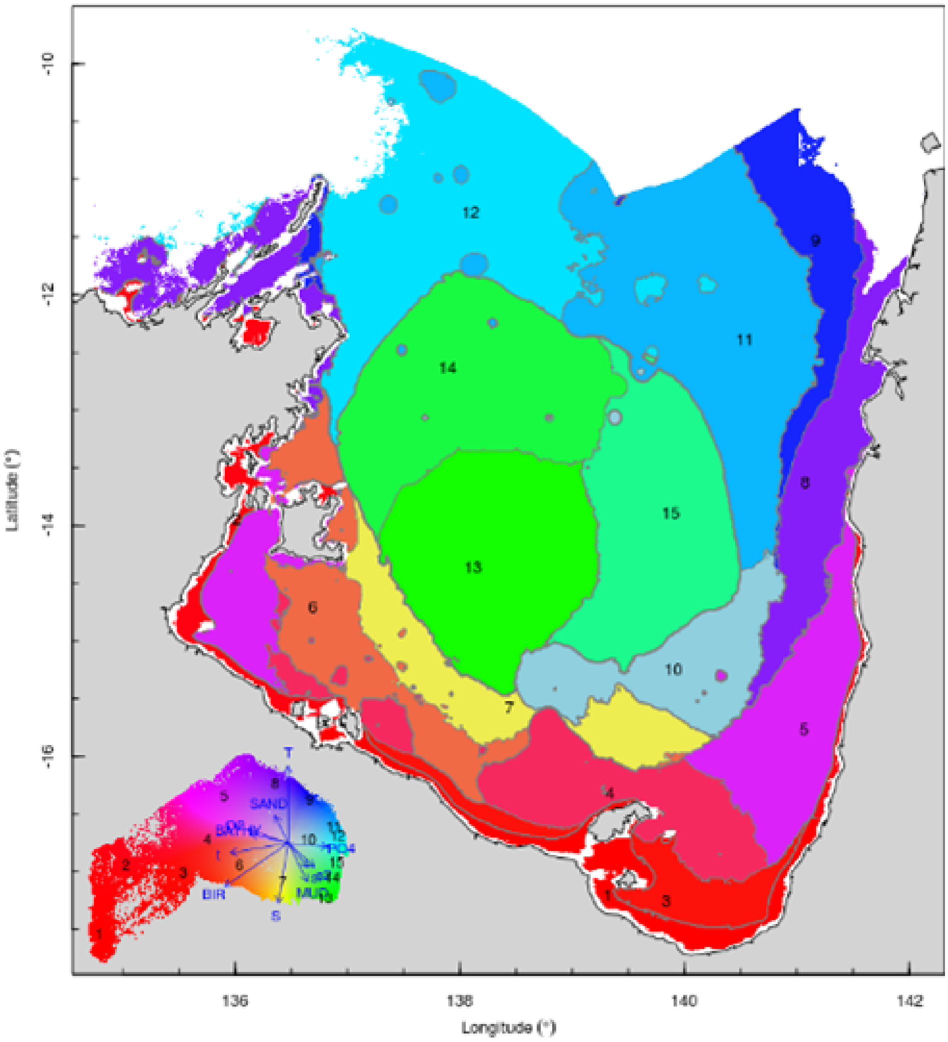

Figure 8 Gulf of Carpentaria region #2: map of distribution patterns of assemblages 1–15 and their compositional similarity (inset: first 2 dimensions of the multi-dimensional biological space representing gradations in habitats and species and their similarity, with vectors indicating the direction and magnitude of the major environmental variables. See Appendix 7.3 for variable definitions).

The same analysis procedure was applied in all 11 regions to characterise and map seabed assemblages (Figure 9 to Figure 18). In total, 217 unique assemblages were mapped nationally. The regional assemblage maps were reviewed by co-investigators and stakeholders for feedback prior to finalising. After the regional assemblage maps were complete, the overlap with fishery closures and marine reserves, and with trawl footprints, was calculated as was done for FRDC Project 2014-204 (Pitcher et al 2016c). The overlap results for each assemblage may be referenced with the mapped assemblage distribution by using the combination of region number and assemblage number within each region.

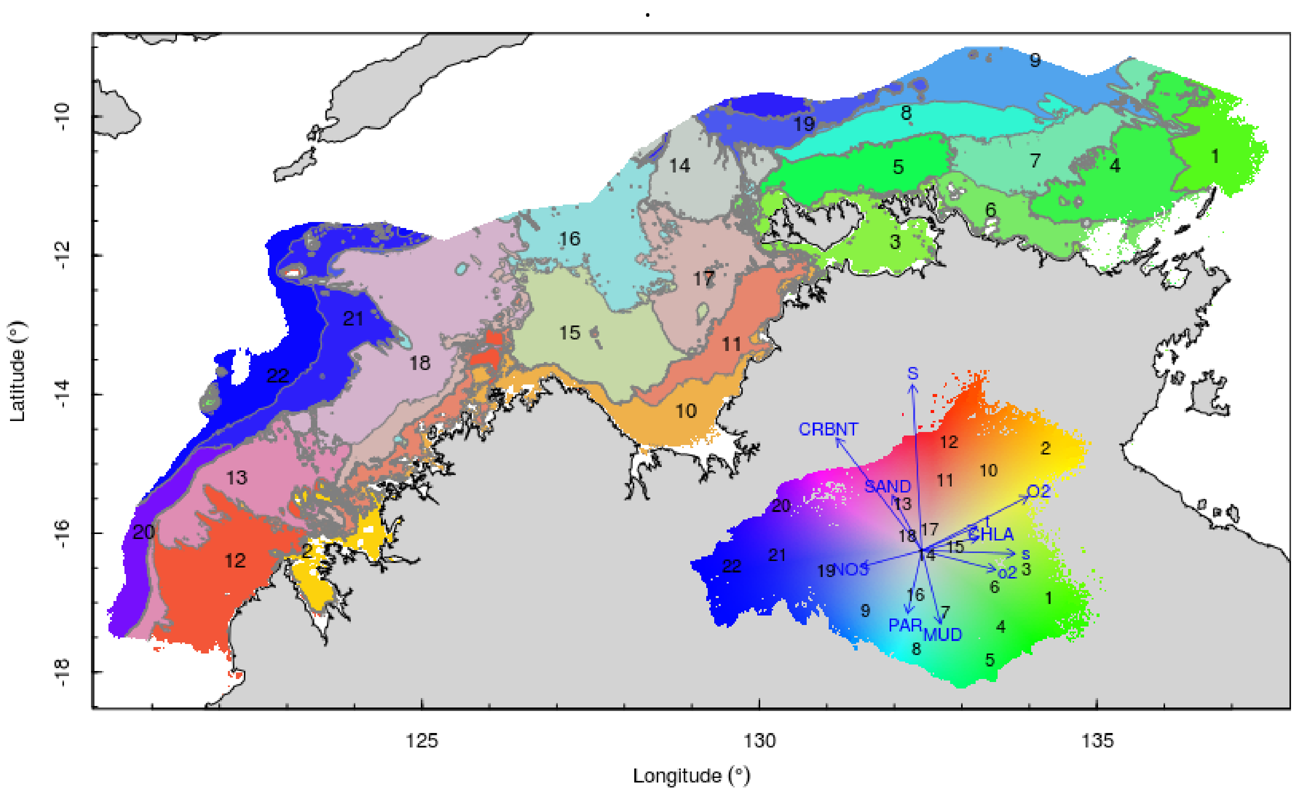

Figure 9 Arafura Sea / Timor Sea region #1: map of assemblage patterns and compositional similarity (inset: first 2 dimensions of multi-dimensional biological space representing gradations in habitats and species and their similarity, with vectors indicating the direction and magnitude of the major environmental variables. See Appendix 7.3 for variable definitions).

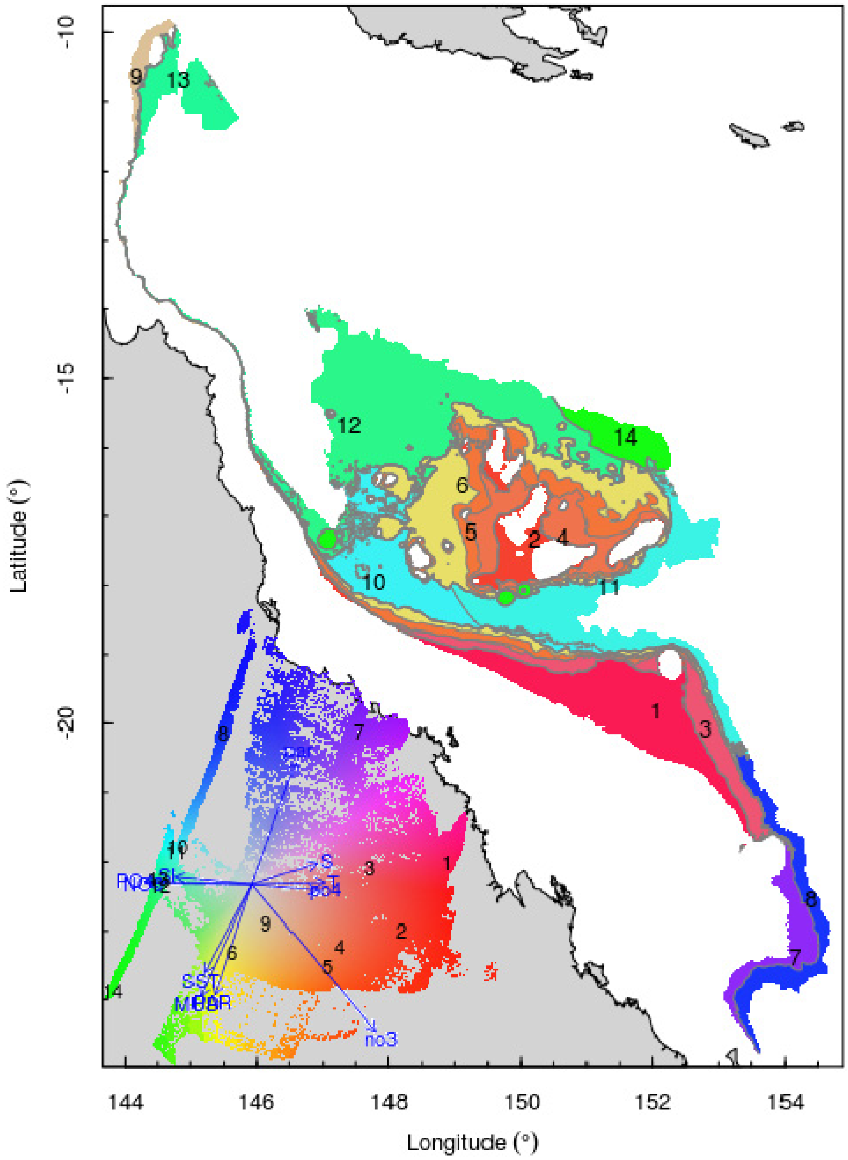

Figure 10 Northeast Australian slope and Coral Sea plateau region #3: map of assemblage patterns and compositional similarity (inset: first 2 dimensions of multi-dimensional biological space representing gradations in habitats and species and their similarity, with vectors indicating the direction and magnitude of the major environmental variables. See Appendix 7.3 for variable definitions).

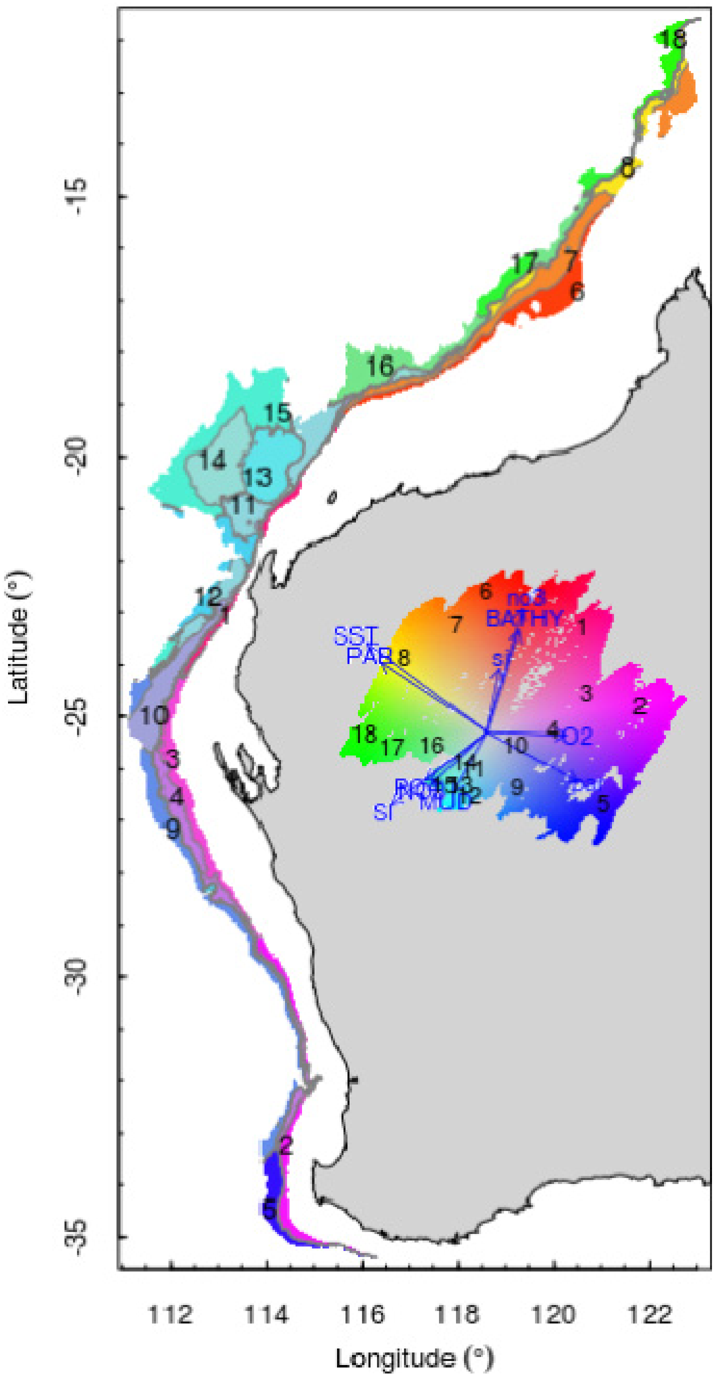

Figure 11 West Australian slope region #4: map of assemblage patterns and compositional similarity (inset: first 2 dimensions of multi-dimensional biological space representing gradations in habitats and species and their similarity, with vectors indicating the direction and magnitude of the major environmental variables. See Appendix 7.3 for variable definitions).

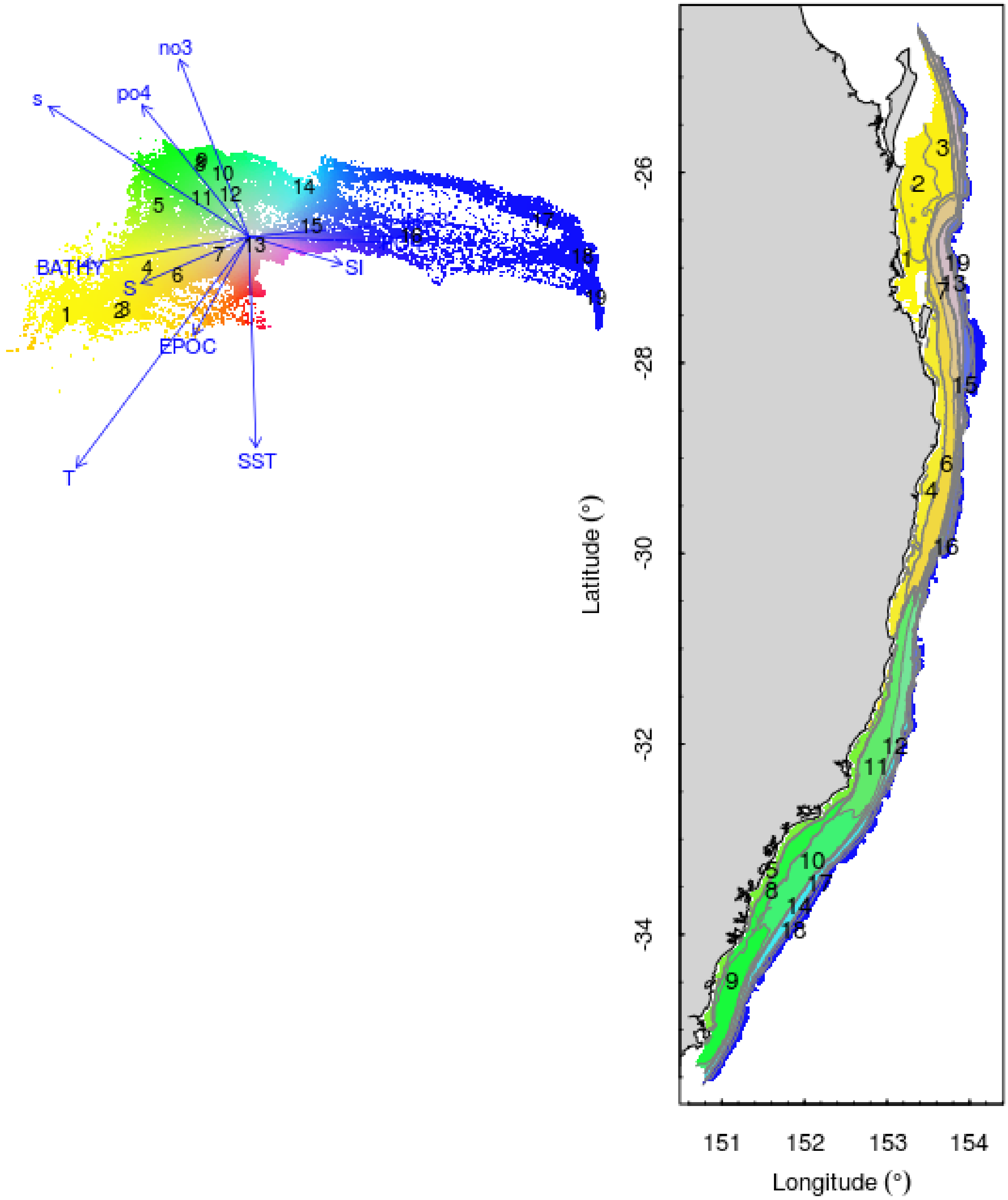

Figure 12 East Australian shelf and slope region #5: map of assemblage patterns and compositional similarity (inset: first 2 dimensions of multi-dimensional biological space representing gradations in habitats and species and their similarity, with vectors indicating the direction and magnitude of the major environmental variables. See Appendix 7.3 for variable definitions).

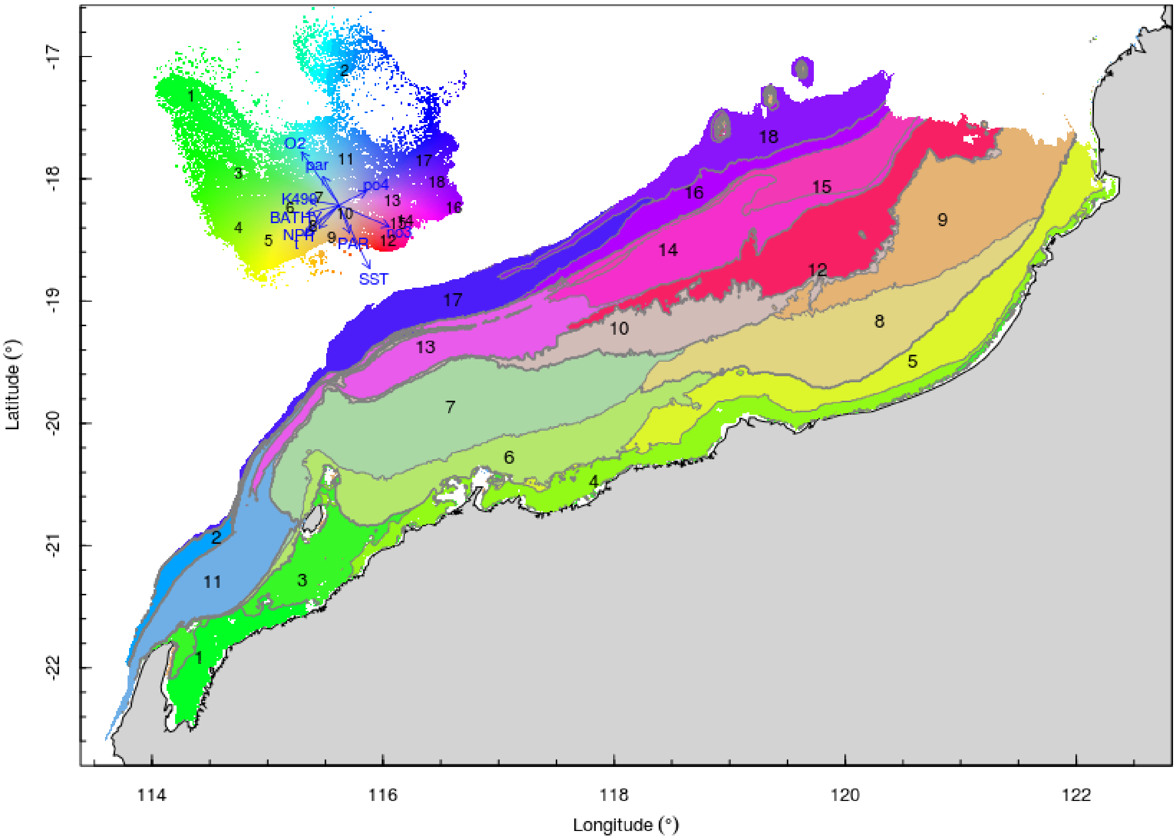

Figure 13 Northwest shelf region #6: map of assemblage patterns and compositional similarity (inset: first 2 dimensions of multi-dimensional biological space representing gradations in habitats and species and their similarity, with vectors indicating the direction and magnitude of the major environmental variables. See Appendix 7.3 for variable definitions).

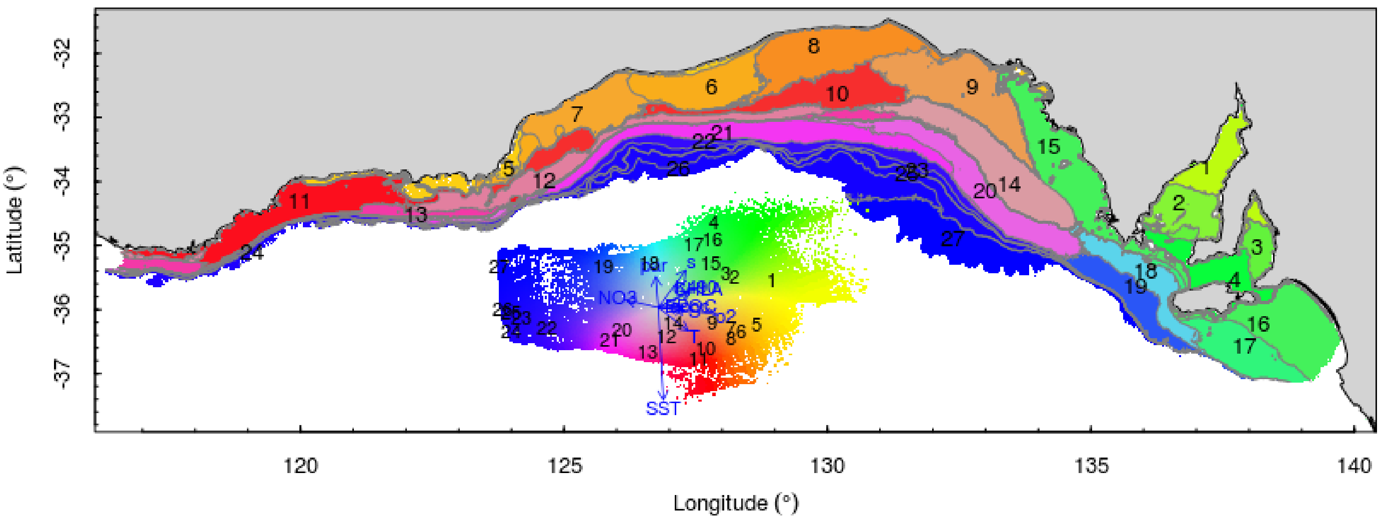

Figure 14 Southern Australian shelf and slope region #7: map of assemblage patterns and compositional similarity (inset: first 2 dimensions of multi-dimensional biological space representing gradations in habitats and species and their similarity, with vectors indicating the direction and magnitude of the major environmental variables. See Appendix 7.3 for variable definitions).

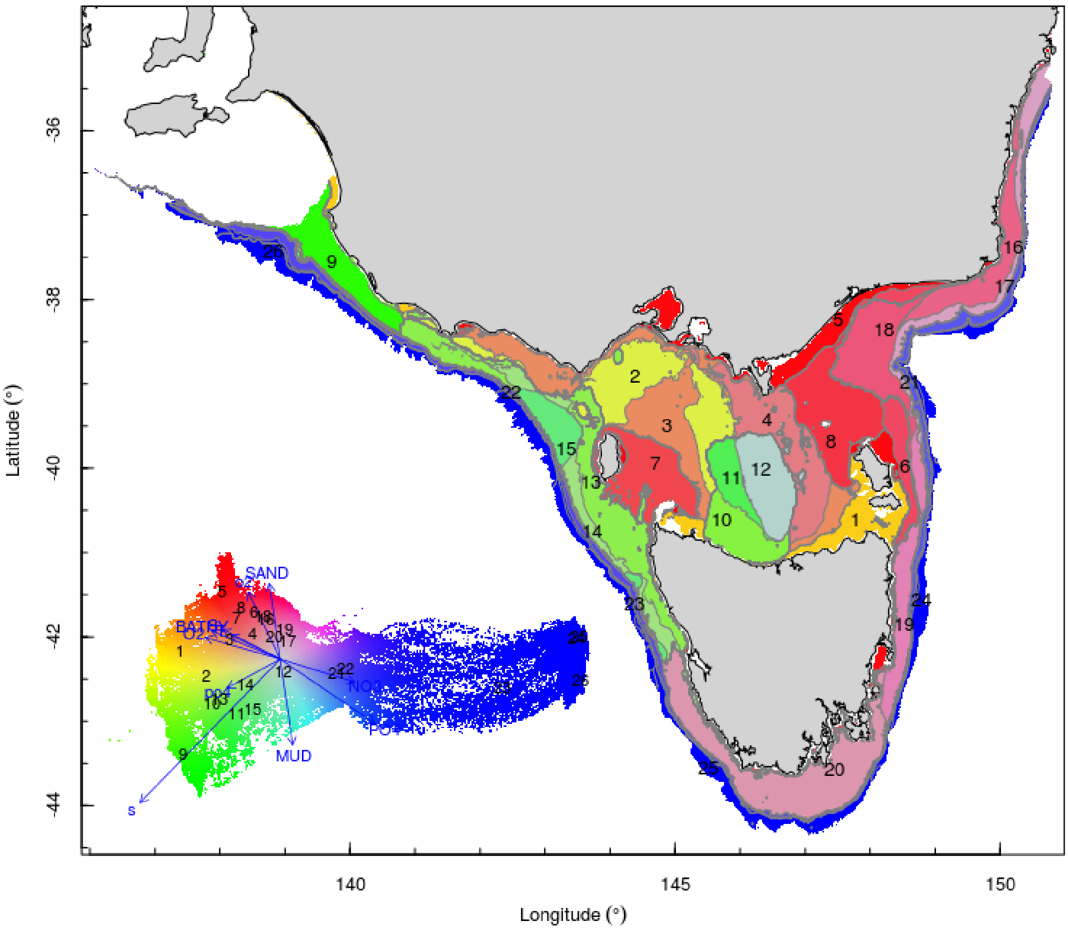

Figure 15 Southeast Australian shelf and slope region #8: map of assemblage patterns and compositional similarity (inset: first 2 dimensions of multi-dimensional biological space representing gradations in habitats and species and their similarity, with vectors indicating the direction and magnitude of the major environmental variables. See Appendix 7.3 for variable definitions).

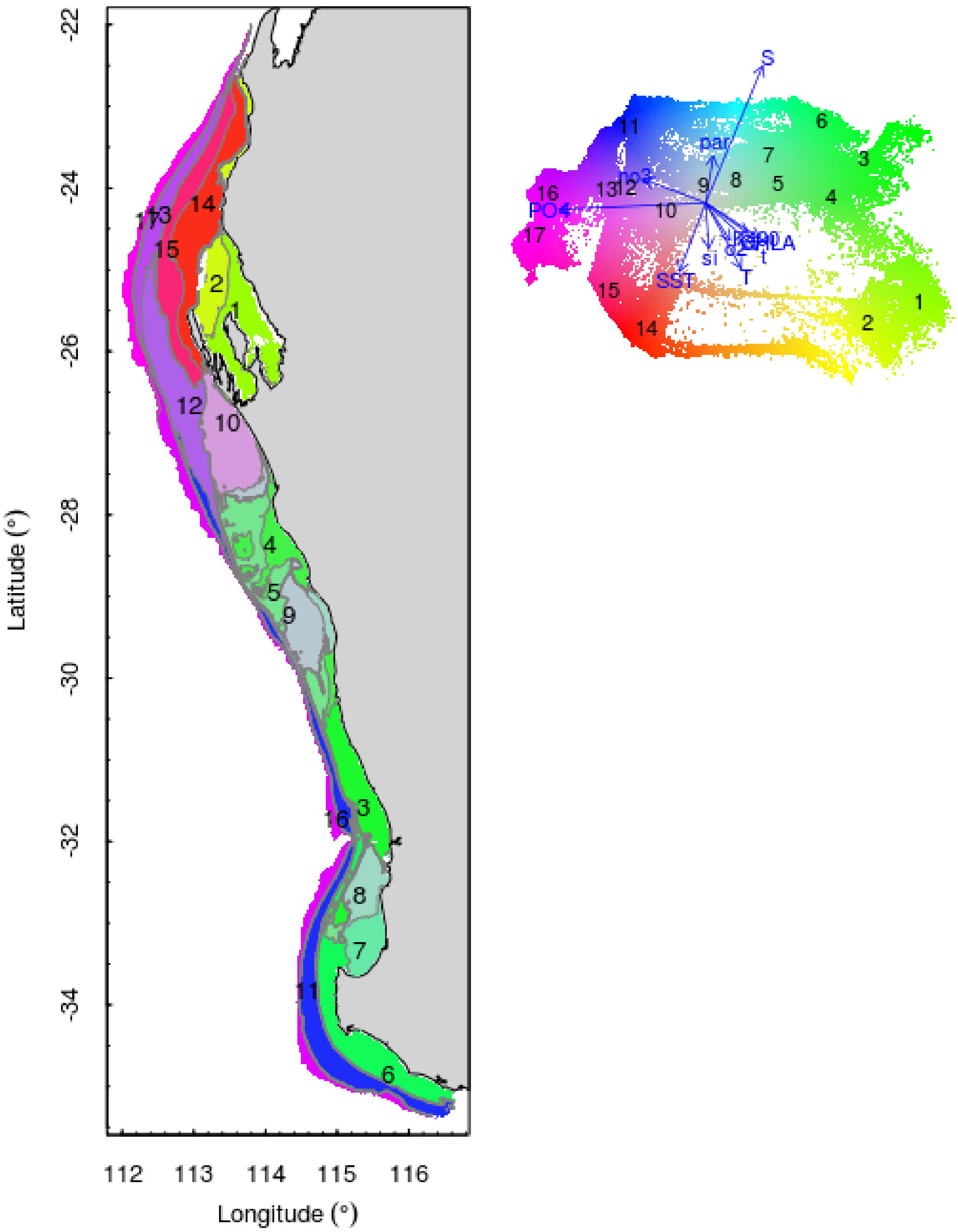

Figure 16 Southwest Australian shelf region #9: map of assemblage patterns and compositional similarity (inset: first 2 dimensions of multi-dimensional biological space representing gradations in habitats and species and their similarity, with vectors indicating the direction and magnitude of the major environmental variables. See Appendix 7.3 for variable definitions).

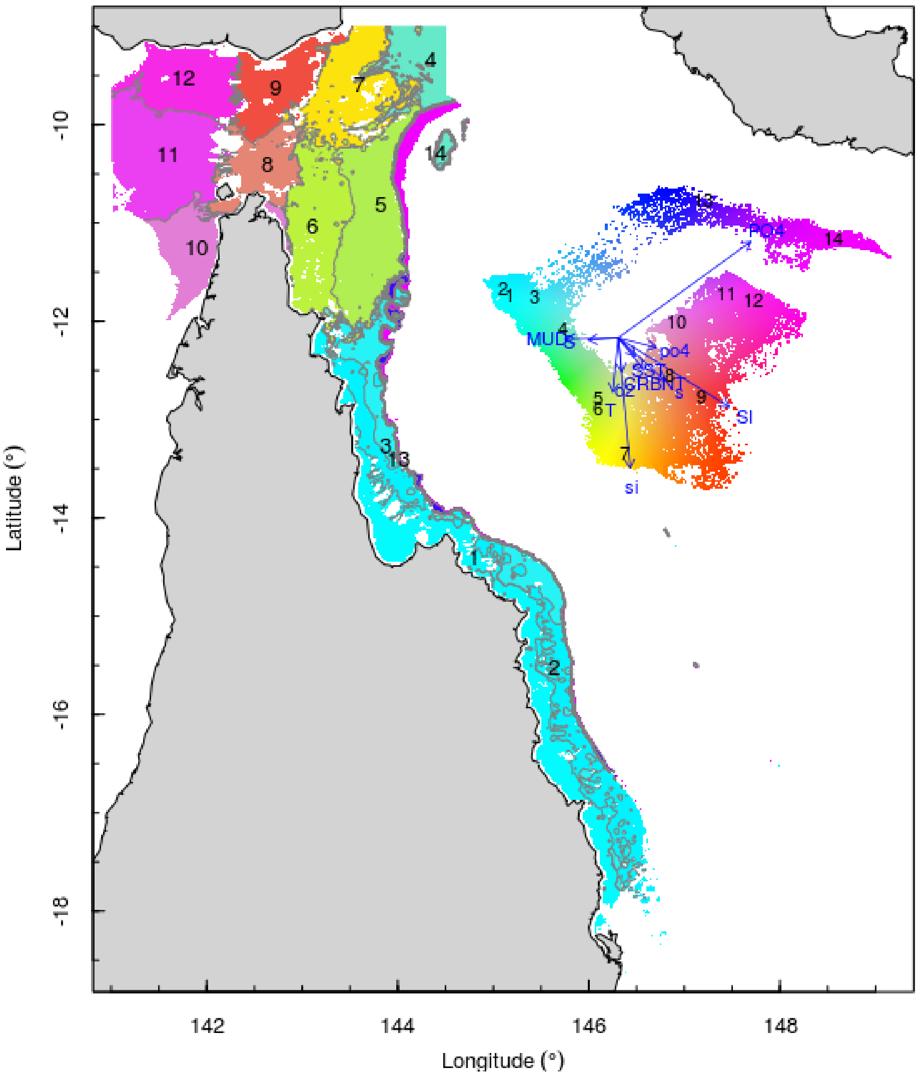

Figure 17 Northeast Australian shelf region #10: map of assemblage patterns and compositional similarity (inset: first 2 dimensions of multi-dimensional biological space representing gradations in habitats and species and their similarity, with vectors indicating the direction and magnitude of the major environmental variables. See Appendix 7.3 for variable definitions).

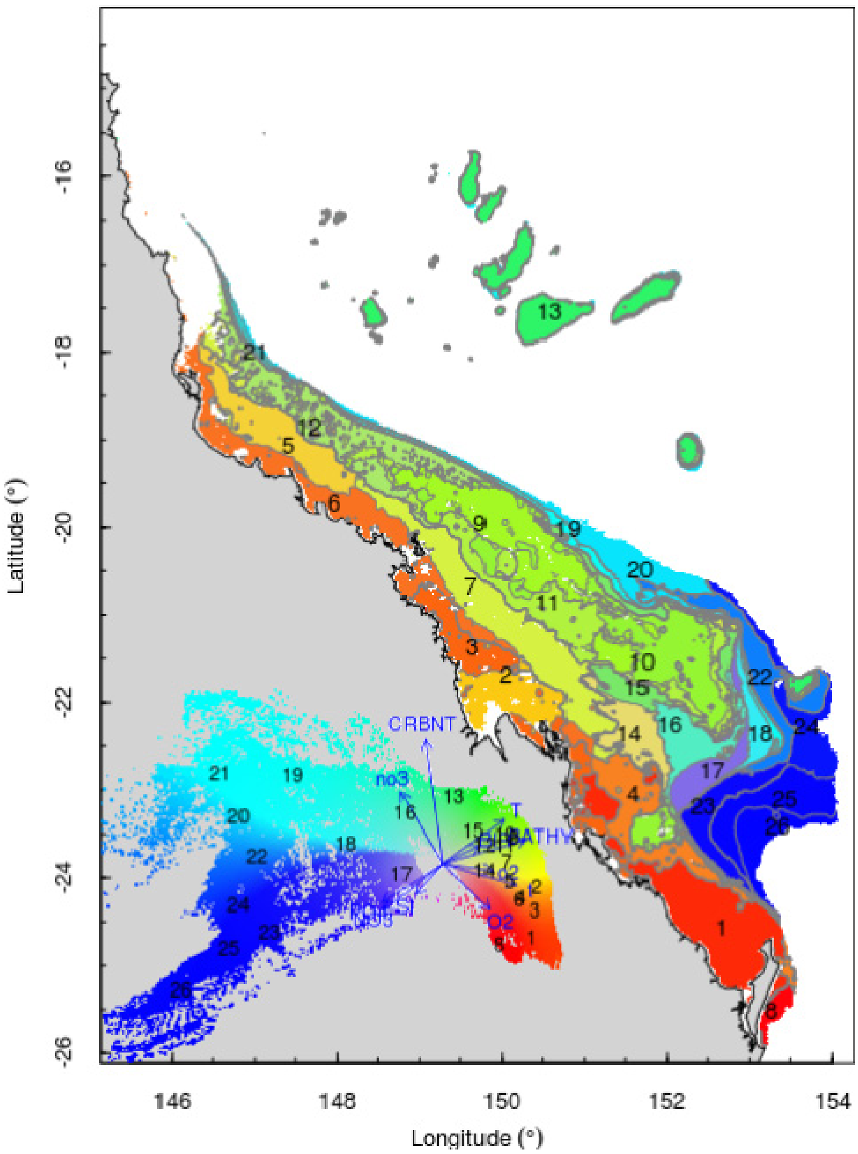

Figure 18 Southern GBR shelf region #11: map of assemblage patterns and compositional similarity (inset: first 2 dimensions of multi-dimensional biological space representing gradations in habitats and species and their similarity, with vectors indicating the direction and magnitude of the major environmental variables. See Appendix 7.3 for variable definitions).

4.3 Assessments

After finalising the assemblages (as mapped in Figure 8 to Figure 18), the final estimates of overlap with demersal trawl fishing effort and intensity with each assemblage, and inclusion of each assemblage in closures and reserves, was calculated — providing identification of which mapped assemblages and fisheries nationally may be priorities for future more detailed habitat status assessments and ERAs.

The overlap of trawl effort with the mapped assemblages is presented in the following sections as a percentage by area of each assemblage, for trawl footprint (using the uniform assumption for the within grid-cell distribution of the average annual effort, which represents a multi-year trawl footprint) and for average annual total trawl-swept area as an indicator of trawl-effort intensity (see section 3.1.4). The percentage by area of each assemblage protected from trawling by spatial management is also mapped. These results are tabulated in detail in Appendix 7.7.

4.3.1 Trawl footprints in assemblages

The extent of overlap of the combined footprint of all demersal trawl fisheries with each of the 217 national assemblages is mapped in Figure 19 and tabled in Appendix 7.7. This represents the percentage by area of each assemblage estimated to be trawled one or more times over a multi-year period (assuming a uniform distribution of trawl effort within cells), such that overlapping effort in grid cells with swept-area ratio >1 is counted only once (see Table 2, 'uniform').

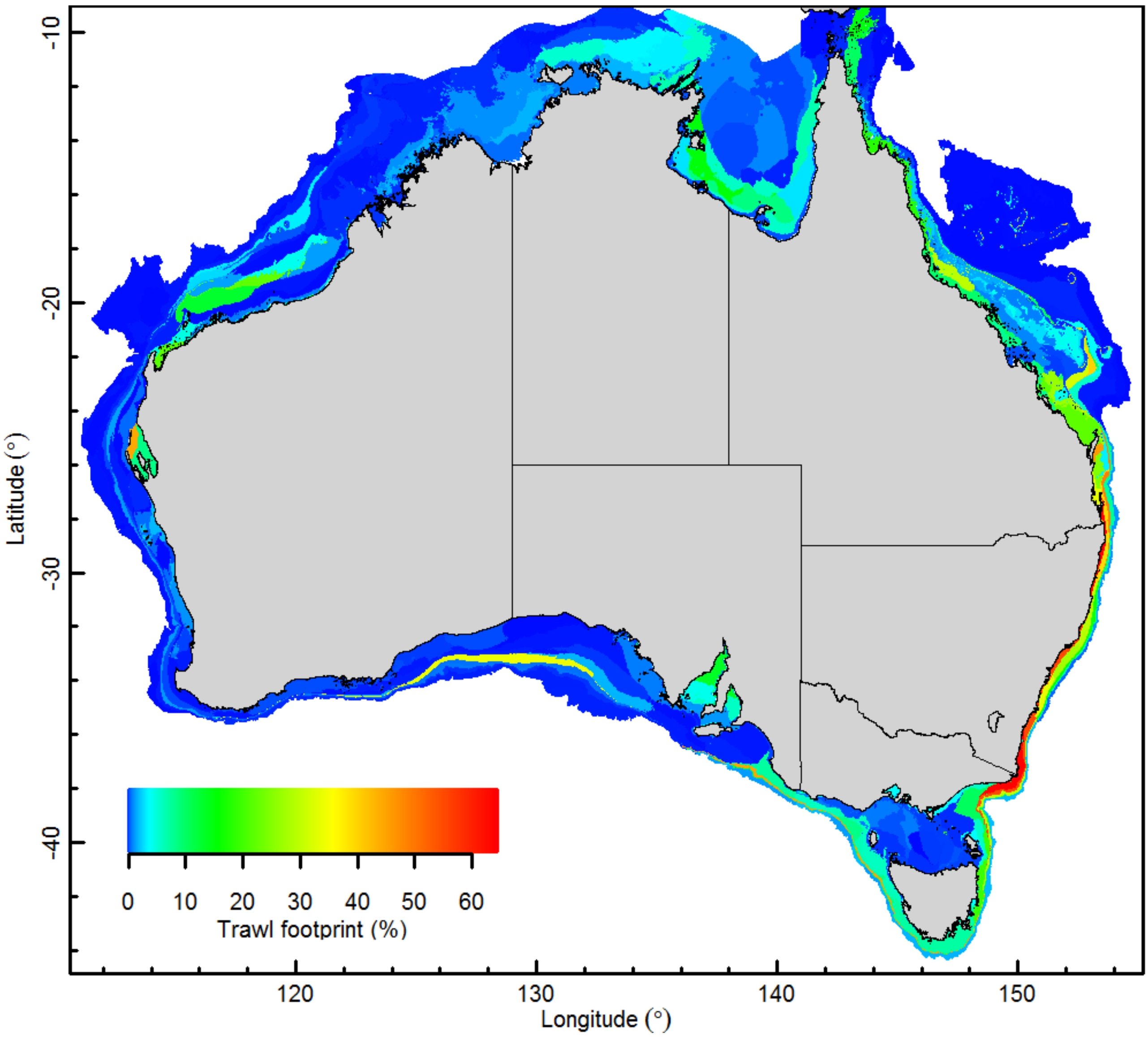

Figure 19 National map of all assemblages (0–1500 m), showing the 'uniform' estimate of the trawl footprint area in each assemblage as a percentage of the area of each assemblage.

Across all assemblages, trawl footprints ranged from 0 to 64.4%, with a mean of 6.2%. Twenty-one assemblages (9.7%) had no trawling (0% footprint) and 168 assemblages (77.4%) had less than the mean footprint (6.2%). However, 15 assemblages (6.9%) had trawl footprints greater than 30% of assemblage area. Most of these occur on the east coast of Australia (Figure 19), from eastern Bass Strait/Victoria and along the NSW shelf, into southern Queensland and the Great Barrier Reef off the Swains Reefs. Others occurred off western Tasmania to SE South Australia on the upper slope, inside Shark Bay, and near the shelf break in the Great Australian Bight. These assemblages are trawled by one or more of several fisheries including: the Commonwealth SET and GAB, NSW Ocean Trawl Fish and Ocean Trawl Prawn, Queensland East Coast Trawl (Eastern King Prawn sector, EKP), and WA Shark Bay Prawn and Scallop.

4.3.2 Trawl swept-area in assemblages

The average annual total swept area of trawling within each assemblage is mapped in Figure 20 and tabled in Appendix 7.7, as a percentage of the total area of each assemblage. This is an indicator of the overall relative intensity of trawling in each assemblage.

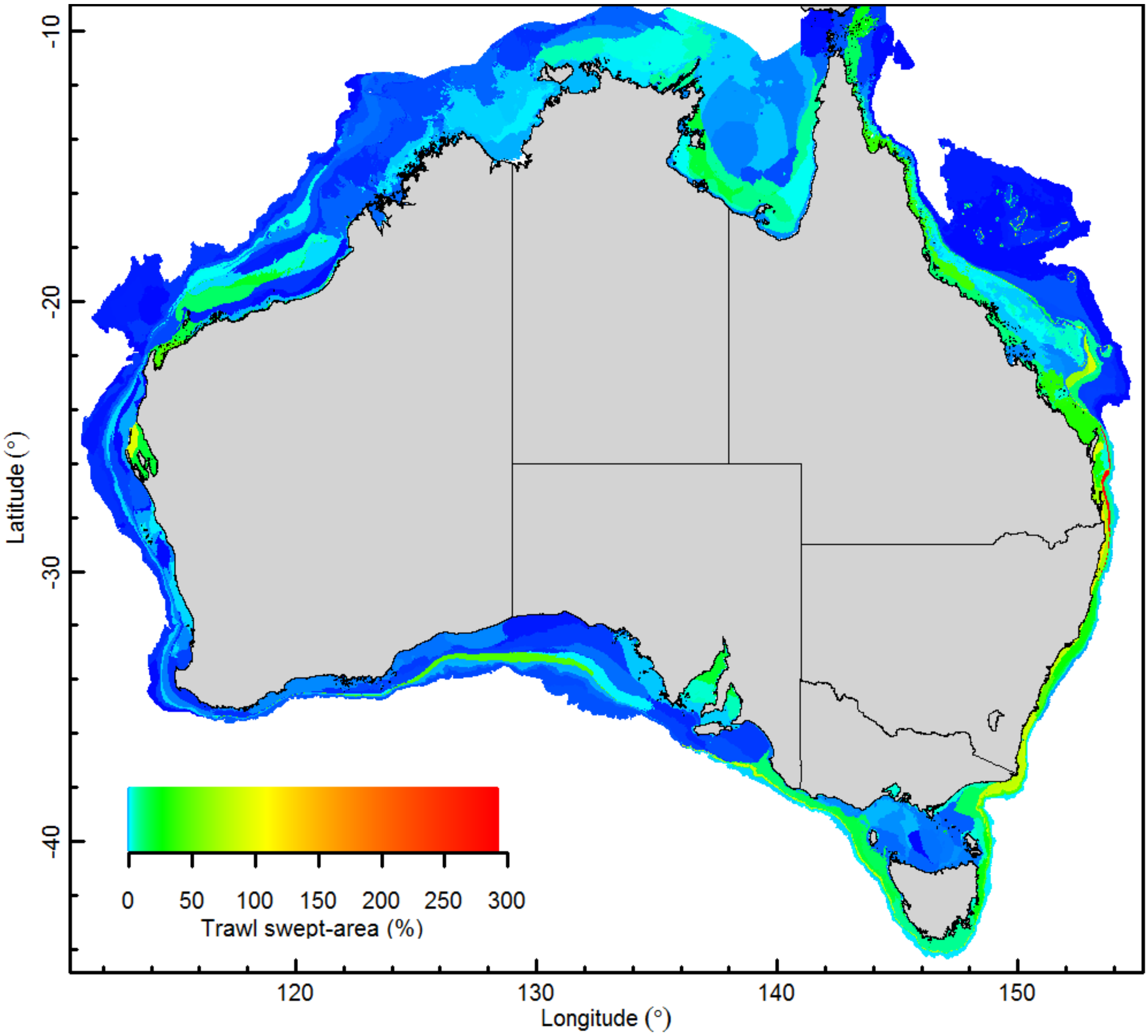

Figure 20 National map of all assemblages (0–1500 m), showing overall average total annual swept area of trawling in each assemblage as a percentage of the area of each assemblage.

Across all assemblages, total annual trawl swept area ranged from 0 to 291%, with a mean of 10.7%. As before, 21 assemblages (9.7%) had no trawling (0% footprint) and 172 assemblages (79.3%) had less than the mean total swept area (10.7%). However, 16 assemblages (7.4%) had trawl total swept areas greater than 45% of assemblage area. Again, most of these occur on the east coast of Australia (Figure 20), from southern Queensland/Swains, along the NSW shelf, and into eastern Bass Strait/Victoria. Others occurred inside Shark Bay, off western Tasmania to SE South Australia on the upper slope, and near the shelf break in the Great Australian Bight. These same assemblages are trawled by one or more of several fisheries including: the Commonwealth SET and GAB, NSW Ocean Trawl Fish and Ocean Trawl Prawn, Queensland EKP Sector, and WA Shark Bay Prawn and Scallop. Assemblages 7 and 4 in region 5 (Figure 12) stood out, with total swept area percentages of 291% and 122% respectively. Trawl effort in assemblage 7 is the most intensive nationally, primarily due to the Queensland EKP Sector; effort in assemblage 4 is due to both the Queensland EKP Sector and the NSW Ocean Prawn Trawl.

4.3.3 Assemblages in areas closed to trawling

The intersection of the mapped assemblages with areas permanently closed to trawling under fisheries and/or environmental legislation is mapped in Figure 21 and tabled in Appendix 7.7, as a percentage of the total area of each assemblage. This is an indicator of the overall relative amount of protection from trawling in each assemblage.

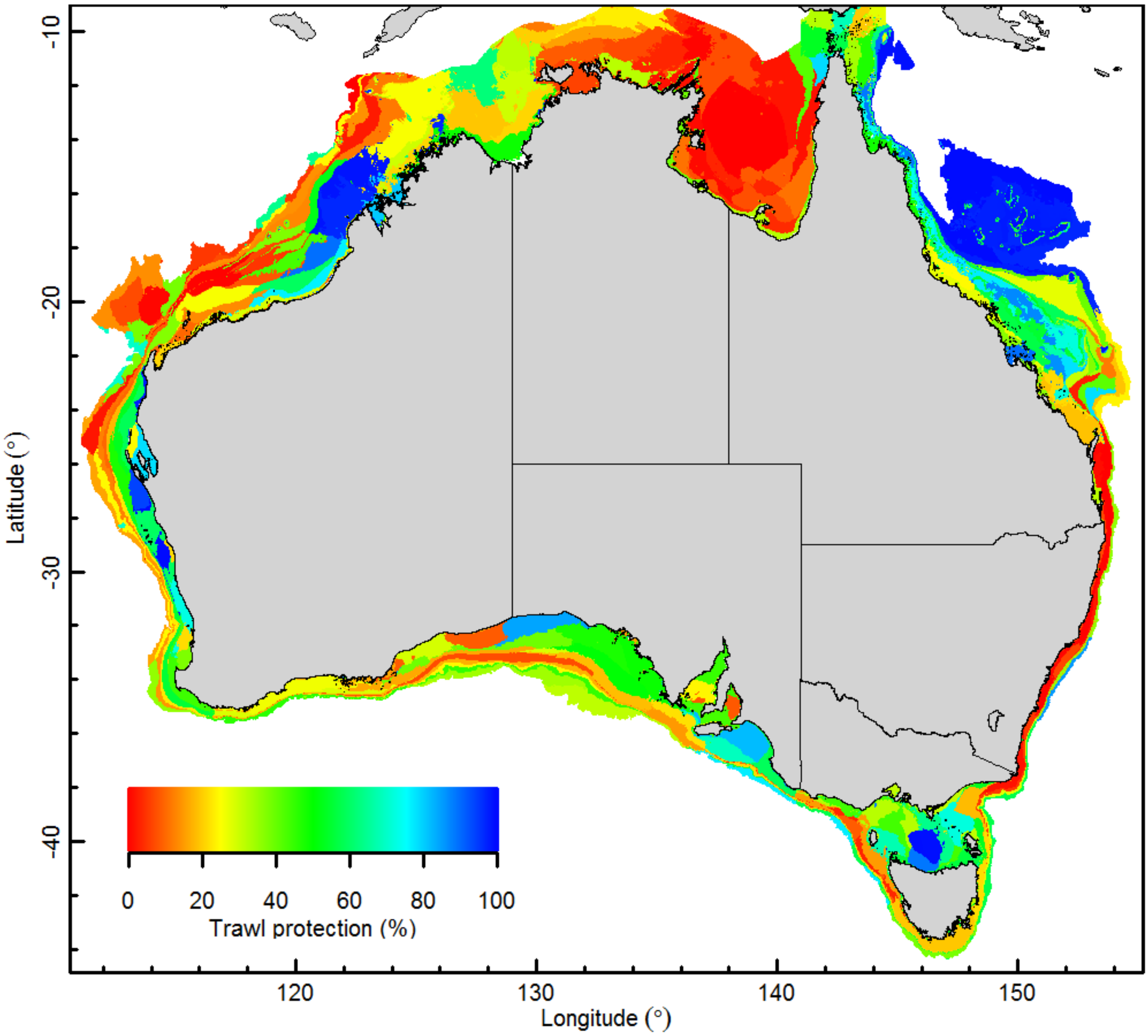

Figure 21 National map of all assemblages (0–1500 m), showing overall percentage by area of each mapped demersal assemblage overlapping in trawl fishery closures and/or marine parks/reserves that prohibit trawling.

Across all assemblages, area closed to trawling ranged from 0 to 100%, with a mean of ~38%. Six assemblages (2.8%) had no areas closed to trawling and 126 assemblages (58.1%) had less than the mean percent of area closed (38%). However, 77 assemblages (35.5%) had less than 20% of their area in closures and trawl footprints in these assemblages ranged from 0 to 64% (with 59 having less than the mean footprint of 10.5%). Most of the assemblages with high trawl footprints and swept areas on the east coast of Australia also had low protection (Figure 21), including shelf areas from eastern Bass Strait / Victoria along the NSW shelf into southern Queensland/Swains, upper slope in western Tasmania to SE South Australia, and Great Australian Bight shelf break. As before, these assemblages are trawled by one of more of several fisheries including: the Commonwealth SET and GAB, NSW Ocean Trawl Fish and Ocean Trawl Prawn, and Queensland EKP Sector. However, other large areas of assemblages with low protection occurred in northern Australia, including assemblages trawled by the Northern Prawn Fishery, the NT Northern Demersal Fishfish Trawl Fishery and the Qld Gulf Developmental Fish Trawl — and in northwest and west Australian shelf and slope areas, including assemblages trawled by Commonwealth slope trawl fisheries and some WA State trawl fisheries.

4.4 Conclusions

The percentage of each assemblage exposed to trawl footprints, as well as total swept area, and included in areas closed to trawling are factors that contribute to the potential for habitat risk from trawling and hence influence their priority for future habitat risk assessment (Figure 22, Appendix 7.7). Another factor is the intensity of trawling on the trawl-exposed portion of each assemblage (i.e. within the trawl footprint) — typically, the exposed portions of more heavily trawled assemblages are trawled with an average intensity of about twice annually.

Across all Australia nationally, encompassing all mainland continental shelf and slope trawl fisheries, there were relatively few assemblages that had both high exposure to trawling and low inclusion in closed areas (Figure 22, Appendix 7.7). A number of trawl-exposed assemblages also had substantive percentage inclusion in closed areas. Most assemblages had little or no exposure to trawling, including a large number also with little or no protection in closures as well as those with high levels of protection in closures. Those assemblages towards the top-right of Figure 22, and top of Appendix 7.7, should be considered higher priority for future habitat ERAs, those lower in the table may be medium priority, whereas those lowest in the table may be low priority. However, the ordered list represents relative potential for risk, and does not necessarily imply confirmed risk to habitats. Sensitive habitats may or may not occur in trawl exposed areas of assemblages. Further, some assemblages with moderate trawl footprints may have substantive risk if they contain significant areas of sensitive habitats and/or if trawling coincides with sensitive habitats. Assessment of the actual level of risk in priority assemblages requires information on the occurrence and landscape distribution of habitats susceptible to trawl impacts, their gear-specific impact rates, resilience and recovery rates, and quantitative estimation of their status. For most assemblages, occurrence and distribution information is lacking, particularly for the trawl exposed areas of eastern Australia in NSW and southern Queensland — or inadequate, particularly for the trawl exposed areas of southeast Australia and the GAB (see section 4.4.1).

The results for Commonwealth trawl fisheries were consistent with previous results of FRDC 2014-204 (Pitcher et al 2016c).

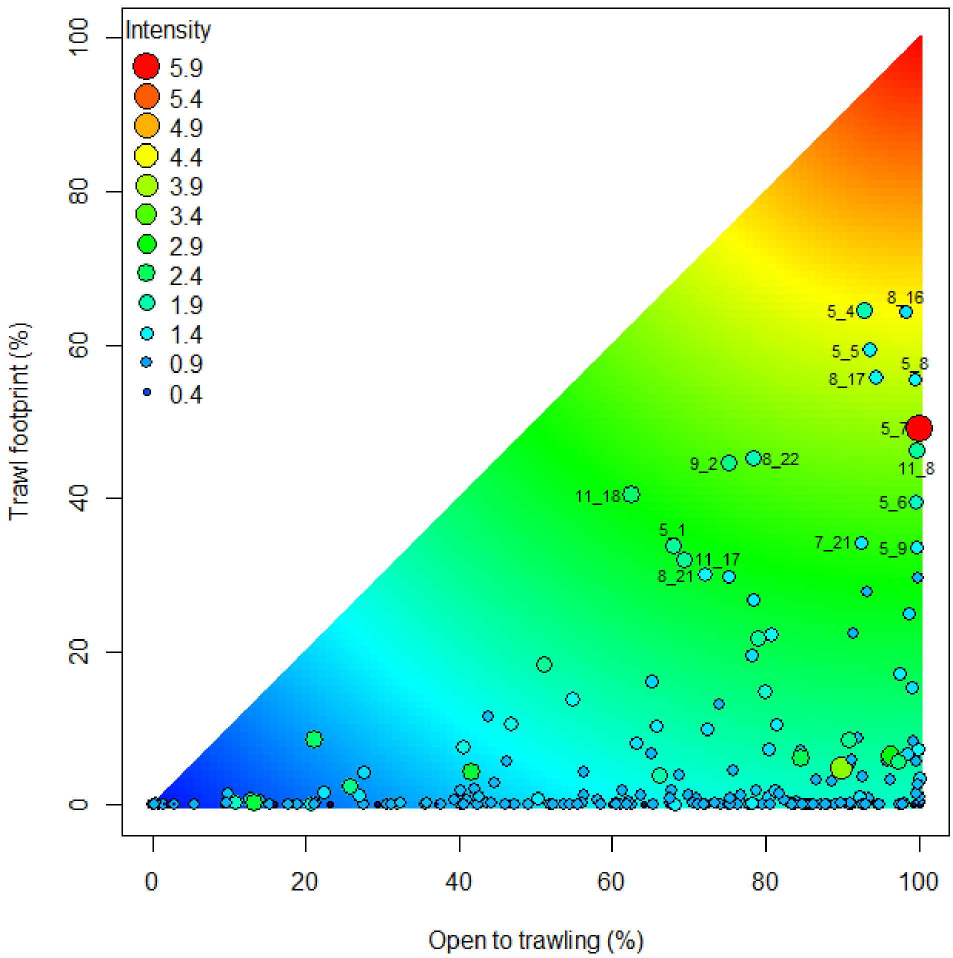

Figure 22 Plot of percentage of area of each assemblage open to potential trawling against exposure to effort as trawl footprint. The intensity of trawling in the assemblage is represented by the points as the average total annual swept area divided by the trawled footprint area. Background colour indicates relative potential risk (blue: lower, red: higher). Higher priority assemblages are labelled (Region#_Assemblage#).

4.4.1 High potential risk assemblages

Here we describe what is known (if anything) about the likely actual risk implications for any sensitive habitat-forming benthos biota (where data are available) in assemblages with high exposure to trawl fisheries, considering current spatial management.

Most highly exposed assemblages occur in region #5 on the Australian east coast from southern Queensland to southern NSW and include assemblage #s 7, 4, 5, 8, 6, 1, 9 (see Figure 12) and to a lesser extent assemblage #s 11, 2 and 10. Although substantive trawl bycatch information is available for much of region #5 (see sections 3.1.1 and 7.2), there is almost no information on the distribution and abundance of sensitive habitat-forming benthos throughout almost all of the region — except for parts of assemblage #1 (Stevens 2004), which also has 32.1% protection due to Moreton Bay Marine Park zoning.

Three highly exposed assemblages occur in region #11 in the southern GBR including assemblage #s 8, 18, 17 (see Figure 18). Again, while varying amounts of trawl bycatch data are available for these assemblages, there is essentially no information on the distribution and abundance of sensitive habitat-forming benthos for these assemblages. It is known that long-lived vulnerable deep-water elasmobranch species occur in assemblages #18 and 17 (Last et al 2014; Rigby et al 2016), and these assemblages in the deep-water EKP fishery have previously been identified as a high priority for ERA (Pears et al 2012). In other parts of the GBR shelf, sessille habitat-forming benthos have previously been comprehensively assessed (Pitcher et al 2007a; Pitcher et al 2016a).

Three highly exposed assemblages also occur in region #8 in south-eastern Australia including assemblages #16, 17, 22 (see Figure 15), and to a lesser extent assemblage #21. Some information on the distribution and abundance of habitat-forming benthos is available for region #8 that indicates sensitive habitat types are present in these more exposed assemblages (e.g. Williams et al 2006, 2009). These include, for example, sub-cropping friable sandstone supporting large habitat-forming gorgonians and sponges within exposed mid-shelf assemblages; aggregations of relict stalked crinoid *Metacrinus cyaneus* restricted within a few exposed shelf-break assemblages; ribbons of delicate bryozoan communities restricted to a narrow depth range within many shelf-edge assemblages, some of which are exposed; and tree-forming octocorals and black corals restricted to high flow, steep banks in some exposed upper-slope assemblages. These vulnerable types are potentially accessible to trawling and may be at risk (Williams et al 2011). A regional landscape-scale status assessment of habitat-forming benthos biota types has been completed (Pitcher et al 2015) and indicated that the SE region-wide status of 10 sensitive benthos types ranged between ~80–93% of pre-trawl status when trawl effort peaked in 2005, and subsequently was predicted to recover by ~1–3% over the following decade. However, some types were severely depleted within eco-regions corresponding to current assemblages #16, 17, 22. Further field research is required to quantify the distribution and status of habitats in these assemblages and the ongoing risks.

Other highly exposed assemblages include Shark Bay (region #9, assemblage #2, Figure 16) and outer Great Australian Bight (region #7, assemblage #21, Figure 14). In Shark Bay, the presence of sensitive habitat-forming biological components (e.g. sponges, soft corals, gorgonians) is indicated from prawn-trawl bycatch surveys (Kangas et al 2007) and at least some of these benthos are exposed to trawling (Mazor et al 2017) but a status assessment has not yet been completed. Similarly, in the outer Great Australian Bight (region #7), the presence of sensitive habitat-forming biological components (e.g. sponges and bryozoans) is indicated in the eastern part of assemblage #21 from epibenthic sled surveys (Ward et al 2003); some of which are exposed to trawling (Mazor et al 2017), though again a status assessment has not yet been completed.

As a further indication of likely actual habitat risks — at least for relatively resilient unconsolidated mud, sand and gravel habitats — Appendix 7.8 summarises for the assemblages mapped herein, preliminary 'relative benthic status' (RBS) results from a current related project. These preliminary results reflect both the footprint map (Figure 19) and the swept area map (Figure 20) in section 4.3, and the ~same assemblages are at highest risk as are prioritised in Appendix 7.7, although in a slightly different order. RBS can also be applied to sensitive habitat-forming benthos; but requires distribution information for these biota. RBS assessment also provides additional statistics for benthic status that can be used to define risk; for example, that >80% of each habitat should be in >80% status. A number of assemblages in the east, southeast and northeast regions (#5, #8, #11) would not meet this 80% criterion even for relatively resilient sedimentary habitats. RBS can be used to implement quantitative (level 3) risk assessments for habitats, and to evaluate alternative interventions that may be considered to manage risk to habitats.

4.4.2 Uncertainty

Like most research, these assessments of assemblage exposure and protection are subject to uncertainties. These uncertainties include but may not be limited to the mapping of trawl footprints and of assemblages.

The estimates of trawl footprints have a number of caveats. The source trawl effort data (e.g. logbook records or VMS data) used for gridding are not free of errors or inaccuracies. For example, trawling locations in fishers logbooks are recorded by hand with typical resolution of 1 minute, and subsequent data entry is also manual — both may introduce data errors. The gridding process for logbook data can only assume that trawls were linear between recorded start and end positions, whereas actual trawls may follow depth contours or other seabed features. VMS data does not have the same manual errors, but trawling activity is not distinguished from other activities such as steaming or approaching an anchorage or harbour. Instead, trawling activity is inferred by calculating the average vessel speed between sequential VMS positions, which may be 1–2 hours apart, and filtering out sequences of positions where speed is too high or too low to represent likely trawling activity. Once filtered, trawling is assumed to be linear between sequential VMS positions whereas, as with logbook positions, real trawls are unlikely to be linear. In some fisheries, logbook positions may be recorded only once per fishing day to a coarse grid (e.g. 0.1 degree), and/or trawl positions may not be recorded for all trawls. Once gridded, the conversion of trawl effort data (as annual hours or kms per grid cell) to swept-area ratios requires information on trawling speeds, gear sizes and gear spreads. In some cases, logbooks record speeds and gear sizes, but in most cases information on typical fleet trawl speeds and gear parameters was provided by industry representatives or researchers familiar with each fishery. The uncertainty is in these parameters unknown.

The assemblages defined and mapped as the unit of assessment in this project are surrogates for habitats at meso-scales. Assemblages were used to make progress given the scarcity of available data for habitats (in the 'traditional' or common-use sense) and their distributions in most fisheries. The assemblage mapping has uncertainties beyond determining the appropriate number of assemblages for a region (see Methods). First, the different sampling gears used by different surveys in the various regions (Table 1, Figure 1) sample different, possibly overlapping, components of the biota as noted in section 3.1.1. No regions have been comprehensively sampled by all types of gears and many areas have been sampled by only one gear type, which may bias the bio-physical relationships used to define assemblages to those for subsets of biota. Further, not all variation in demersal species composition is explained by relationships with environmental variables. Typically more than half the species present in a biological survey dataset are too rare for analysis, and of those having adequate occurrence perhaps a third show no statistical relationship with the environment — and further, of those that have a relationship, on average 10–45% of their variation in abundance could be successfully predicted by environmental variables (see also e.g. Pitcher et al 2012). In addition, representation of multi-species compositional patterns by means of environmental variables also has uncertainty, for which there is no established method of quantification. Initial approaches (Ellis and Pitcher 2011) indicate that uncertainty in mapping composition is spatially variable and (like other analyses) related to data density and quality; uncertainty is higher where data are sparse and poor. The magnitude of uncertainty in composition in 'biological space' (as represented by the biplots in figures) was also a relevant consideration influencing the selection of the appropriate number of assemblages. Too many assemblages would mean that the clusters in biological space would be smaller than the uncertainty and could not be justified; hence, the guide used to indicate the number of assemblages (see Methods) was as robust as possible given the partial coverage of regions by the multiple datasets used. Given also that in reality demersal species composition patterns change in a continuous manner — although not uniformly — along environmental gradients (e.g. see Figure 5), the imposition of any assemblage boundaries is artificial. That is, their boundaries also have uncertainty and are non-exact.

While the strength of the predicted assemblage approach used in this project is that a full-coverage spatial mapping approach can be taken — and applied consistently Australia-wide — when habitat data *per se* are not available, the weakness is that only potential risk can be assessed not actual habitat risk, due to the lack of information on susceptible habitat components within assemblages and their fine-scale distribution relative to trawling. The project could not directly consider habitat impacts *per se*, and did not address past trawl footprints or historical impacts. Thus, the outputs are a progress step that helps focus future priorities, and these priorities will need to take into account the uncertainties above when deciding which of the more exposed/less protected assemblages to assess, and when assessing habitat risk in those assemblages by acquiring robust data regarding the distribution of habitats, and biological components of habitat, that are susceptible to trawl impacts.

4.5 Implications

This study has provided — for all Australian continental demersal trawl fisheries — a consistent spatial approach for mapping seabed assemblages and assessing exposure and protection of the demersal environment, *in lieu* of habitat data *per se* which is lacking for most regions. The results demonstrate that the majority of assemblages have little or no exposure to trawling, independent of their level of protection in reserves or trawl closures. It is highly probable that this majority is subject to negligible substantive risk from demersal trawling. The results also demonstrate that relatively few seabed assemblages within fishery jurisdictions have high exposure to trawling and therefore potential for risk to sensitive habitats if they occur in these areas. Thus, limited resources for future habitat ERAs can be focussed on the small number of more highly exposed assemblages, including those with lower levels of protection, to determine whether sensitive habitats are present and where they are distributed, and to assess whether they are at substantive risk from trawling. This focus will assist with more efficient application of resources regarding research and management expenditure on ERAs for habitats. Ultimately such assessments are expected to lead to reduction in environmental risks due to trawling, enhanced environmental sustainability and social licence, and management authorities meeting their obligations regarding environmental legislation. The beneficiaries of these outcomes include the demersal trawl fishing industries and their management authorities; other stakeholders with responsibilities for sustainable use of the marine environment such as the Commonwealth and state departments with responsibilities for the environment; and the Australian community.

4.6 Recommendations

Further discussions of the project's outputs, with management authorities as well as industry associations, trawl fishers, and consultative management and scientific committees, are recommended to decide the final priority of assemblages for future habitat risk assessments. These discussions are particularly critical for those fisheries that trawl the more exposed seabed assemblages in eastern and south-eastern Australia and as identified elsewhere. Decisions regarding priorities should be conservative, to take precautionary account of the uncertainties in the current outputs (section 4.4.2). Discussions should address the lack of essential data for most trawl-exposed assemblages and consider the research that is required to determine whether sensitive habitats or habitat-forming benthos or vulnerable species (also including e.g. elasmobranchs) are present within the priority assemblages (and to map their distributions and abundance) and to assess whether or not they are at substantive risk from trawling. The potential methods that may be suitable for this mapping and assessment should also be considered. The initial information identified in section 4.4.1 may assist this process.

4.7 Further development

This project focussed on all Australian continental demersal trawl and dredge fisheries — it mapped assemblages that straddled these jurisdictions including both state and Commonwealth bottom-trawl fisheries. Significantly this included and accounted for cumulative trawl footprints on assemblages that extended across jurisdictions. It did not include other non-trawl bottom-contact fisheries, such as bottom long-lining or seining, that interact with seabed habitats — although these additional exposures have smaller footprints than trawling and are not expected to substantively change the relative potential risk of assemblages determined herein. Nevertheless, the cumulative impacts of these other fisheries should be included in future risk assessments.

The consistent national approach used by this project to quantify trawl exposure of demersal assemblages may be readily updated at intervals deemed appropriate, simply by updating the spatial trawl-footprint mapping of each fishery for more recent periods of effort data. In this way changes and trends in trawl footprints over time may be tracked — contributing to the ultimate outcome of achieving and demonstrating habitat sustainability for all demersal trawl fisheries in Australia. In this context, the recommended future research to map distributions of sensitive habitats and assess actual risks to habitats is essential to ensure this ultimate outcome.

Future habitat ERAs should also consider and evaluate a range of potential habitat risk management responses, where these are required. Responses may include, but are not limited to: spatial management (e.g. closures around sensitive habitats); move-on rules (if sensitive benthos are caught); effort management (e.g. re-structuring towards MEY target); gear management (e.g. low-impact gear modifications). Each approach, individually or in combination, has previously been successful depending on specific circumstances and context (McConnaughey et al. 2016). A previous FRDC project (2011/010) demonstrated that novel gear designs (e.g. 'batwing' otter board; 'soft brush' ground gear) reduced bottom contact of these components substantially and could be expected to lead to significantly less benthos impact (Broadhurst et al 2015; McHugh et al 2015a, 2015b).

5 Extension and Adoption

Project extension aimed to communicate project results and outputs back to key stakeholders, including fishery managers, industry representatives, and consultative committees (with their broader stakeholder representation) of all state and Commonwealth trawl fisheries. AFMA, and state fishery management authorities via co-investigators (CIs), were consulted during project development and after commencement to confirm objectives and identify suitable consultation meetings. Initially, in each case, it was agreed to defer attendance and presentations at such meetings until critical results had become available. Nevertheless, in the first year of the project, CIs briefed their industry stakeholders and fishery managers during scheduled consultation meetings in NSW, SA, WA, NT regarding the objectives of the project, using the FRDC 2014-204 final report as illustration where appropriate. Similarly, SETFIA and NPF Industry were also advised that the current project would include Commonwealth fisheries using the same methods as FRDC 2014-204 but in a national analysis along with all other continental demersal trawl fisheries. Specific consultation meetings were conducted with Fisheries Queensland trawl fishery managers, and PIRSA trawl fishery managers and industry representatives regarding data access and extension strategies. The project was also outlined at the ACPF LIFE (low impact fuel efficient) Workshop on 7 February 2017 in Sydney.

Initial project results were produced by June 2017, in the form of preliminary assemblage maps for each region and the June 2017 milestone progress report, which were circulated to CIs and stakeholders for feedback prior to finalising the regional assemblage maps. After finalising the assemblages and conducting the footprint analyses and overlays, the main project results were circulated in mid-October 2017 along with requests for suitable consultation meetings and dates to present these outputs — as per the extension plan. Circulation included the CIs, and subsequently to respective state trawl managers and stakeholders, as well as to AFMA and Commonwealth trawl fisheries representatives.

Project results have been presented at meetings of the Victorian inshore trawl fishery (December 2017, Lakes Entrance, by CI BL); FRDC NP1 Steering Committee (February 2018, included FRDC, AFMA, some members of the ERA Technical Working Group, Sydney Fish Market); Shark Bay prawn and scallop fisheries management advisory meeting (February 2018, Fremantle) and north coast prawn fisheries; WA DPIRD (Hillarys); PIRSA and SA Spencer Gulf and Gulf St Vincent prawn fisheries (March 2018, Adelaide) including Executive Officer GABIA; IMAS Taroona, Tasmanian Crustacean Fisheries Advisory Committee, and Parks Australia (April 2018, Hobart); and QDAF (June 2018, Brisbane). Future presentations to relevant managers and/or stakeholders are intended in New South Wales, Northern Territory, and in Canberra (AFMA and FRDC).

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7 Appendices

7.1 Appendix 1: Existing biological survey datasets

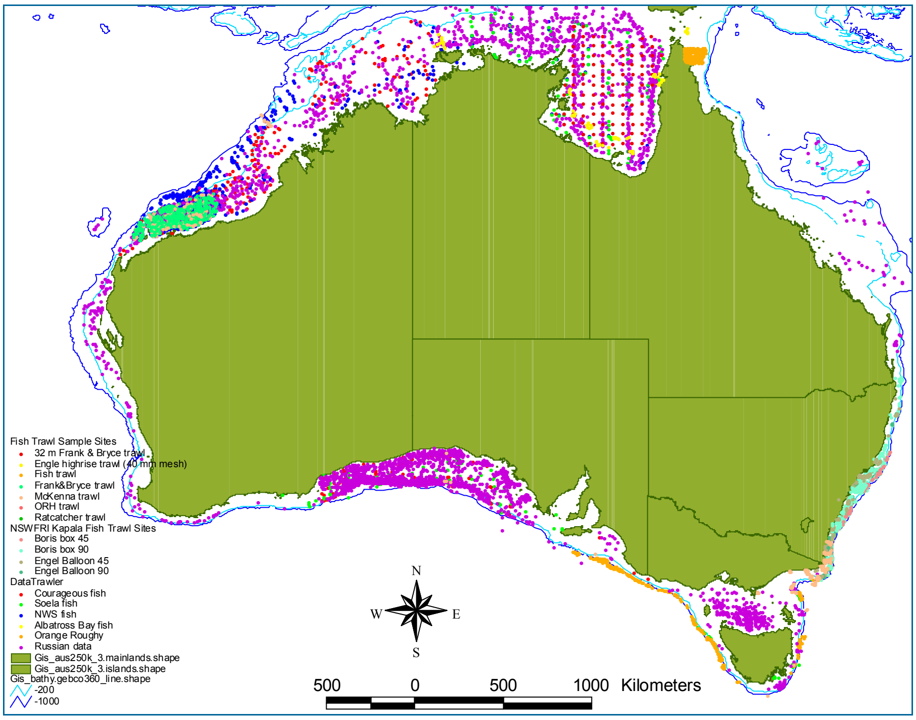

Figure 23 Existing available fish-trawl datasets comprising primarily larger species of fishes.

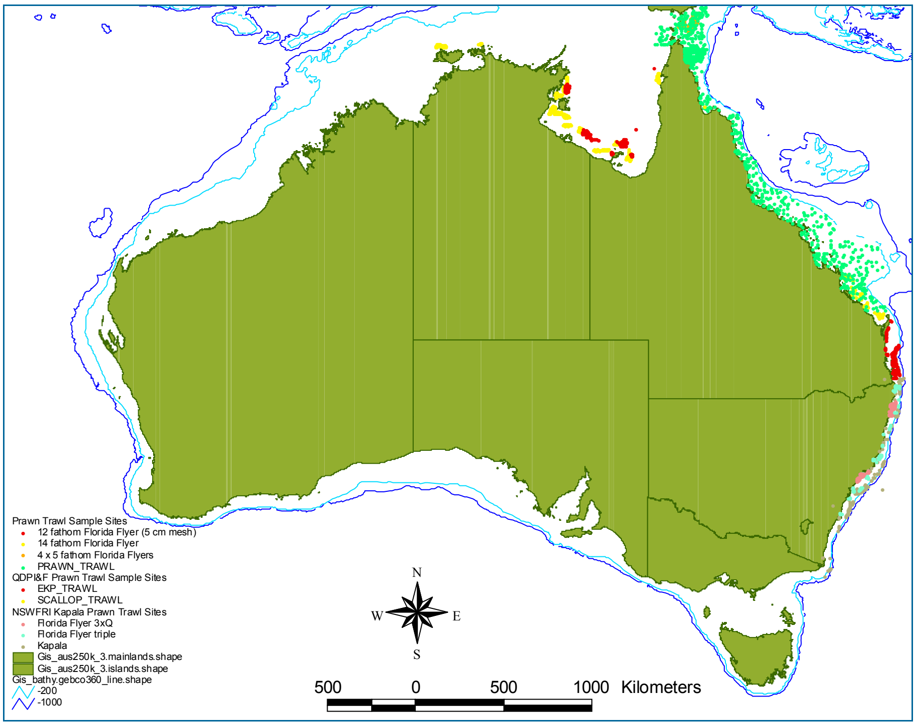

Figure 24 Existing available medium-trawl datasets comprising smaller species of fishes and mobile invertebrates.

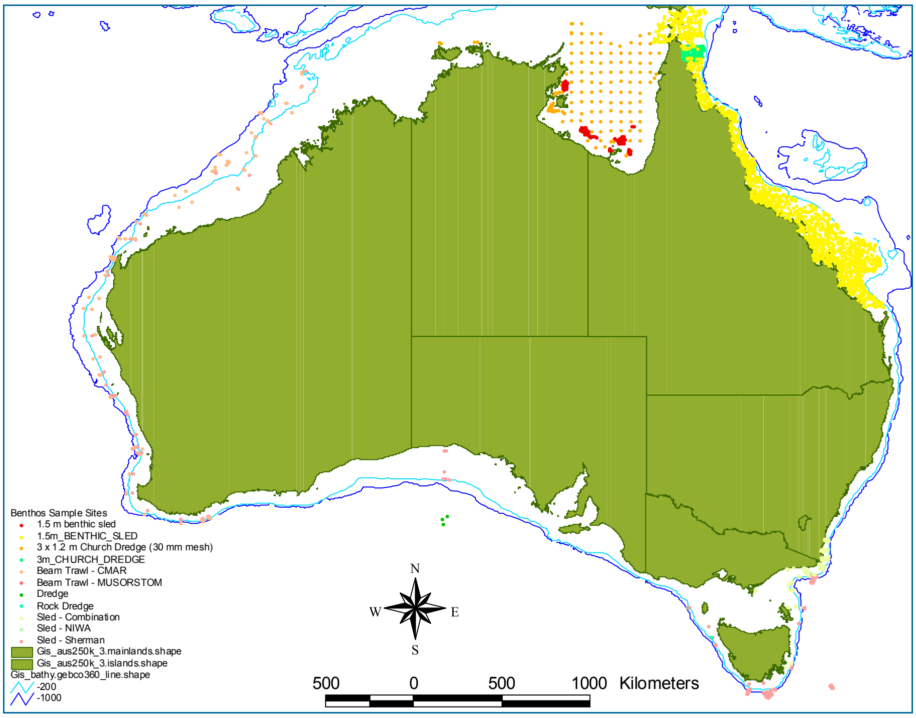

Figure 25 Existing available epibenthic-sled datasets comprising mobile and sessile invertebrates.

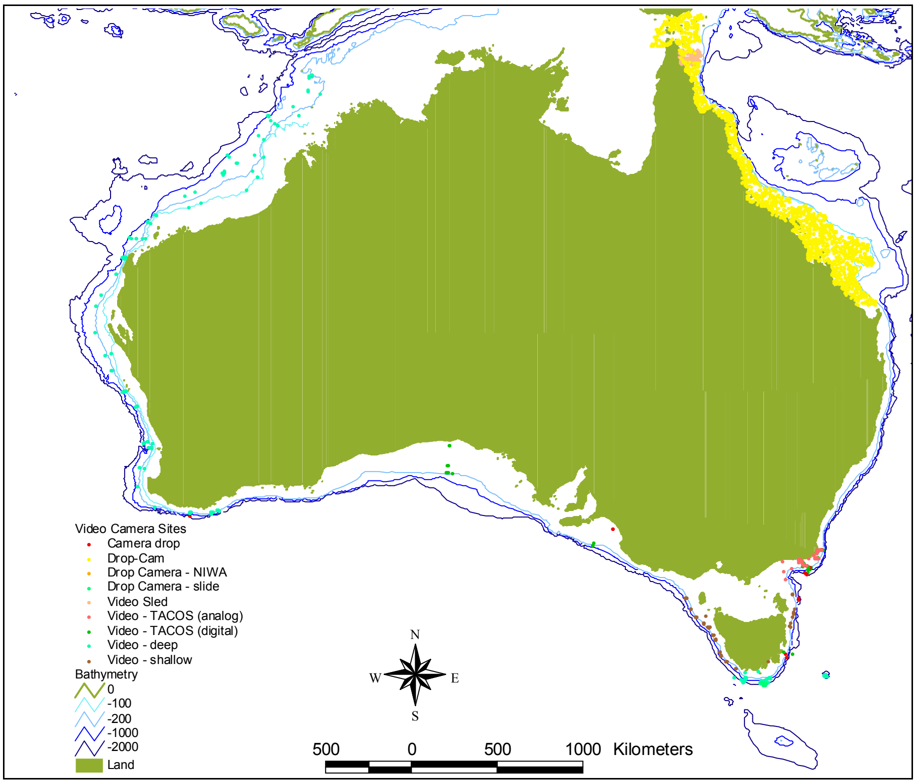

Figure 26 Existing available video/photo datasets comprising seabed habitat information.

7.2 Appendix 2: List of biological survey data sources

7.2.1 Existing CSIRO Survey datasets:

Benthic habitat surveys: Southern Surveyor Voyage SS 01/2000 Biological Data Overview. MarLIN # 5746 : http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=5746

Benthic Habitats Video Image compilation for SE Australia. MarLIN # 14436 : http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=14436

Biodiversity Survey for SE MPA's including the Tasmanian Sea Mounts Marine Reserve, Southern Surveyor Voyage SS 02/2007 (Williams et al 2008) MarLIN # 6939 http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=6939

Biological Data from CMR Research Vessels from the Australian North West Shelf, Part I (1982-1997 "North West Shelf Study" database). A compilation of biological data from voyages SO 5/82, SO 6/82, SO 1/83, SO 2/83, SO 3/83, SO 4/83, SO 5/83, SO 6/86, SO 7/87, SO 5/88, PoE 4/89, SS 02/90, SS 04/91, SS 08/95, and SS 07/97 (Brodie et al 2006; see individual MarLIN records for these voyages).

Demersal fauna of the continental slope off Western Australia - Voyage SS 01/91 (Williams et al 1996). MarLIN # 4951 : http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=4951

FRV 'Courageous' Fish-trawl surveys, 1978–1979, CSIRO
includes FRV Courageous voyages: COUR197831, COUR197832, COUR197833, COUR197834, COUR197835, COUR197945, COUR197946, COUR197947, COUR197949, COUR197950, COUR197951, COUR197952 (see individual MarLIN records for these voyages, http://www.marine.csiro.au/marq/ search).

FRV 'Soela' regional exploratory fishery surveys, 1980–1984, CSIRO.
includes Soela voyages: SO198001, SO198003, SO198004, SO198005, SO198006, SO198007, SO198102, SO198102, SO198105, SO198202, SO198204, SO198401, SO198402, SO198403, SO198404, SO198405, SO198406 (see individual MarLIN records for these voyages, http://www.marine.csiro.au/marq/ search).

Gulf of Carpentaria Fish Data, 1990-1993, CSIRO (Blaber et al 1993); includes Southern Surveyor voyages: SS199003, SS199105, SS199301. MarLIN # : 3202 http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=3202

Gulf of Carpentaria survey, Southern Surveyor 1990-03, CSIRO.
beam trawl megabenthos samples (Long et al 1995), MarLIN # : 4682 http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=4682
grab infauna samples (Long et al 1994), MarLIN # : 4679 http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=4679

Mapping & Characterisation of the BioPhysical Attributes of the Torres Strait (Pitcher et al 2007b).
Epibenthic Sled, MarLIN # 7044 : http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=7044
Prawn Trawl, MarLIN # 7045 :

http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=7045
Towed Video, MarLIN # 7046 :
http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=7046

NPF bycatch sustainability surveys, 1997-1998, CSIRO (Stobutzki et al 2000),
Southern Surveyor voyages: SS199702, SS199708, SS199803. MarLIN # : 4941, 4939, 4971
http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=4941
http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=4939
http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=4971

Orange Roughy Surveys, 1988-1989, CSIRO (Bulman et al 1994),
includes Soela voyages: SO198801, SO198802, SO198803, SO198901, SO198902, SO198903.

South East Fishery (SEF) Ecosystem Study 1993-1996 (Bax & Williams 2000):
Benthic Faunal Survey Data. MarLIN # 5248 :
http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=5248
Fish Surveys. MarLIN # 5245 :
http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=5245

Soviet trawl surveys 1969–1977, data compilation, CSIRO (Koslow et al, 1999)
includes voyages: ALBA196909, ALBA197009, ALBA197103, ALBA197310, BACA197506, BERG196503, BERG196601, BERG196705, EQUA197109, KAME197607, KORI196802, LIRA196702, LIRA196806, LIRA197304, MY-TIC197803, P-DER197210, P-DER197405, P-DER197512, P-DER197701, POSE197107, POSE197704, PROM196811, PROM197002, RADU196608, RADU197206, RADU197503, SESK196601, SHAN197405, SRTM196903, SUTC196807, TICH197703, TICH197710.

Tasmanian Seamounts Study 1997: Benthic Faunal Survey Data (Koslow & Gowlett-Holmes 1998).
MarLIN # 5256 :
http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=5256

Torres Strait Seabed & Water-Column Data Collation, Modeling & Characterisation (Pitcher et al 2004).
'Low-Level' Bio-survey data compilation, Neptune # 1028 :
http://www.marine.csiro.au/nddq/ndd_search.Browse_Citation?txtSession=1028
'Medium-Level' Bio-survey data compilation, Neptune # 1025 :
http://www.marine.csiro.au/nddq/ndd_search.Browse_Citation?txtSession=1025

Voyage of discovery - benthic biodiversity of the deep continental shelf & slope in Western Australia
South West Region, SS10/2005, (Williams et al 2010a), MarLIN # 6937 :
http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=6937
North West Region, SS05/2007, (Williams et al 2010b),MarLIN # 6938 :
http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=6938

7.2.2 Surveys by other research agencies, most collated by FRDC Project 2014-204:

Queensland East Coast Prawn Trawl Fishery bycatch surveys, QDAF (Courtney et al 2007).

'Kapala' trawl surveys dataset, 1975–2006, NSW DPI (Ken Graham, pers comm.).

Bass Strait Survey 1979-1983 collections, Museum Victoria (Wilson & Poore 1987; O'Hara 2002)

Eastern Great Australian Bight sled and grab survey dataset, 2002, SARDI (Ward et al 2003)

Eastern Great Australian Bight benthic sled survey dataset, 2006, SARDI (Currie et al 2008).

Eastern Great Australian Bight grab infauna survey dataset, 2006, SARDI (Currie et al 2007).

Northern Australian Groundfish Stock survey, 1990 & 1992, NT Fisheries (Ramm 1997).

SESSF CTS Fishery Independent Surveys dataset, Fishwell Consulting/AFMA (Knuckey et al 2015).

SESSF GAB Fishery Independent Surveys dataset, Fishwell Consulting/AFMA (Knuckey et al 2017).

Shark Bay and Exmouth Gulf Biodiversity survey, Western Australia Fisheries (Kangas et al 2007).

7.2.3 Additional survey datasets collated by the current project:

CSIRO Pilbara seabed biodiversity survey (PMCP) — Pitcher et al (2016b)

CSIRO Southern Surveyor NPF voyage 03/2005, — Bustamante, et al (2011).

CSIRO Soela voyage 06/1985, Coral Sea — Last et al (2014)

CSIRO NWS effects of trawl benthos photo surveys — F. Althaus unpub. in Fulton et al (2006)

CSIRO/AIMS Kimberley benthic survey 2014–16 (WAMSI) — CSIRO/AIMS unpublished data

NSW DPI fish trawl observer data — Liggins (1996).

NSW DPI prawn trawl bycatch project — Macbeth et al (2008).

SARDI Spencer Gulf bycatch survey, SA — Currie et al (2009).

SARDI Gulf St Vincent bycatch survey, SA — SARDI unpublished data

WA DPIRD northern demersal finfish trawl and trap survey — Newman et al (2012).

WA DPIRD south west trawl survey — Laurenson et al (1993).

IMAS Scallop dredge bycatch survey, Tasmania — Semmens et al (2015)

TAFI demersal fish-trawl surveys, Tasmania — Jordan (1997)

Deepwater Eastern King Prawn Fishery elasmobranch bycatch — Rigby et al (2016)

Moreton Bay seabed habitats survey — Stevens (2004)

Craigmin trawl survey, Queensland, 1980, Commonwealth DPI — Hughes (1981)

Southern Intruder trawl survey, Queensland, 1983, Qld DPIF — Dredge & Gardiner (1985)

Queensland DAF observer data — Fisheries Queensland, unpublished data.

7.3 Appendix 3: List of mapped environmental variables

Table 3 Environmental variables mapped to the Australian EEZ, available to the project

#	Variable	Description
1	GA_BATHY	Bathymetry (depth) from Geoscience Australia digital elevation model (DEM) – metres
2	GA_SLOPE	Slope derived from Geoscience Australia bathymetry DEM – degrees
3	GA_ASPECT	Aspect of slope derived from Geoscience Australia bathymetry DEM – degrees T
4	GA_MUD	Sediment % mud grainsize fraction, (Ø < 63 µm) from Geoscience Australia
5	GA_SAND	Sediment % sand grainsize fraction, (63 µm < Ø < 2 mm) from Geoscience Australia
6	GA_GRAVEL	Sediment % gravel grainsize fraction, (Ø > 2 mm) from Geoscience Australia
7	GA_CRBNT	Sediment % carbonate ($CaCO_3$) composition, from Geoscience Australia
8	RBN_BSTRESS	Seabed current stress, RMS mean from CSIRO 'ribbon' model – Nm^{-2}
9	RBN_BSTRESS_SR	Seabed current stress, Seasonal Range
10	CRS_NO3_AV	Nitrate bottom water annual average NO3 from CARS – µM
11	CRS_NO3_SR	Nitrate Seasonal Range
12	CRS_PO4_AV	Phosphate bottom water annual average PO4 from CARS – µM
13	CRS_PO4_SR	Phosphate Seasonal Range
14	CRS_O2_AV	Oxygen bottom water annual average O2 from CARS – ml L^{-1}
15	CRS_O2_SR	Oxygen Seasonal Range
16	CRS_S_AV	Salinity bottom water annual average S from CARS – ‰ (ppt)
17	CRS_S_SR	Salinity Seasonal Range
18	CRS_T_AV	Temperature bottom water annual average T from CARS – °C
19	CRS_T_SR	Temperature Seasonal Range
20	CRS_SI_AV	Silicate bottom water annual average Si from CARS – µM
21	CRS_SI_SR	Silicate Seasonal Range
22	SW_CHLA_AV	Chlorophyll annual average from SeaWiFS – mg m^{-3}
23	SW_CHLA_SR	Chlorophyll Seasonal Range
24	SW_K490_AV	Attenuation coefficient at wavelength 490nm annual average from SeaWiFS – m^{-1}
25	SW_K490_SR	Attenuation coefficient Seasonal Range
26	MT_SST_AV	Sea Surface Temperature annual average from Modis – °C
27	MT_SST_SR	Sea Surface Temperature Seasonal Range
28	NPP_AV	Net Primary Production annual average from SeaWiFS – mg C m^{-2} d^{-1}
29	NPP_SR	Net Primary Production seasonal range
30	PAR_AV	Photosynthetically Active Radiation (PAR) from MODIS – Einsteins m-2day-1
31	PAR_SR	Photosynthetically Active Radiation seasonal range
32	BIR_AV	Benthic Irradiance annual average, BIR = PAR × exp(-K490 * Depth)
33	BIR_SR	Benthic Irradiance Seasonal Range
34	EPOC_AV	Exported Particulate Organic Carbon flux annual average from SeaWiFS – mg C m^{-2} d^{-1}
35	EPOC_SR	Exported Particulate Organic Carbon seasonal range
36	TERAN_CHAN	Terrain channel, probability of membership of topographic shape "channel" (Lucieer, 2007)
37	TERAN_PASS	Terrain pass, probability of membership of topographic shape "pass" (Lucieer, 2007)
38	TERAN_PEAK	Terrain peak, probability of membership of topographic shape "peak" (Lucieer, 2007)
39	TERAN_PIT	Terrain pit, probability of membership of topographic shape "pit" (Lucieer, 2007)
40	TERAN_PLAN	Terrain plane, probability of membership of topographic shape "plane" (Lucieer, 2007)
41	TERAN_RIDG	Terrain ridge, probability of membership of topographic shape "ridge" (Lucieer, 2007)

7.4 Appendix 4: Maps of re-gridded ocean colour variables

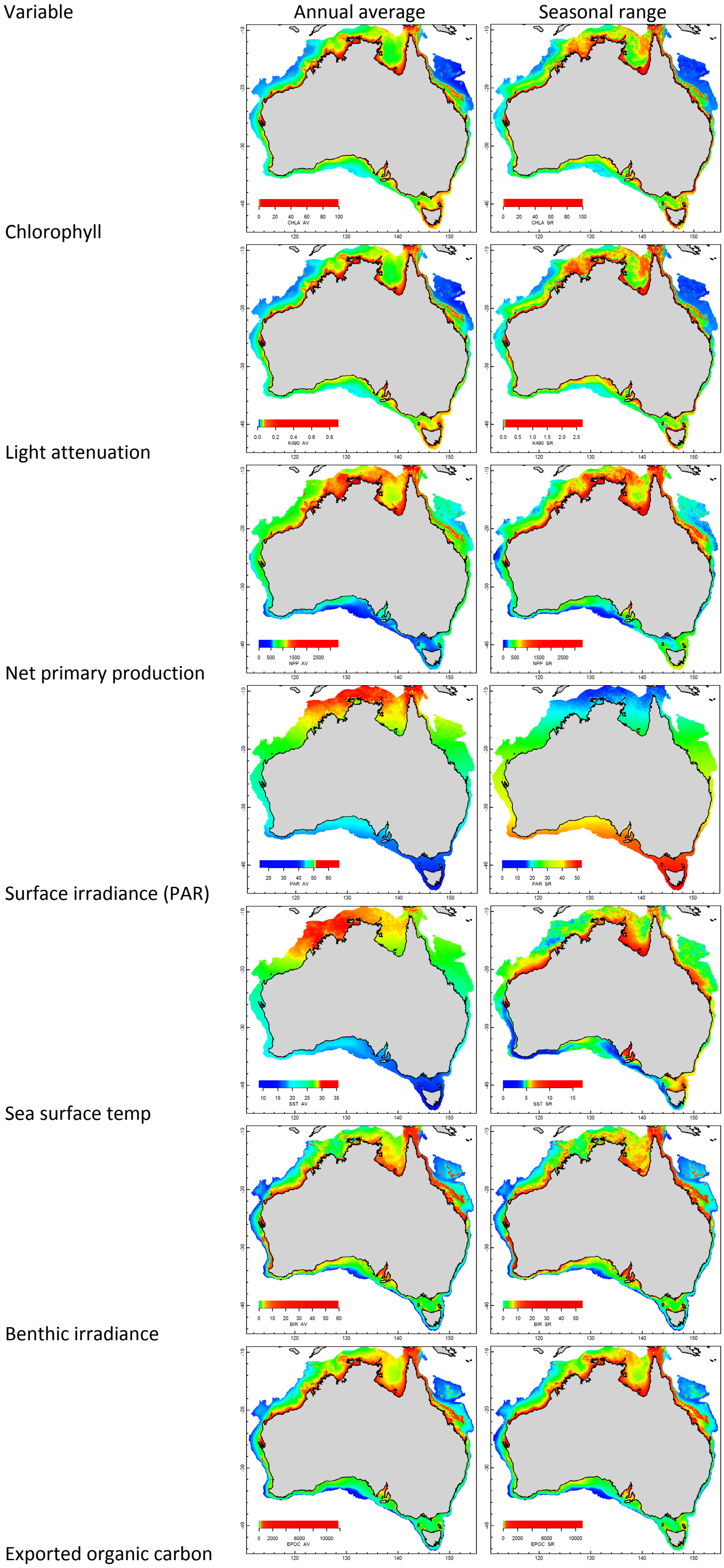

Figure 27 Maps of the re-gridded Ocean Colour derived variables, at 0.01° resolution.

7.5 Appendix 5: Maps of re-gridded DEM, sediment, terrain & bed-stress

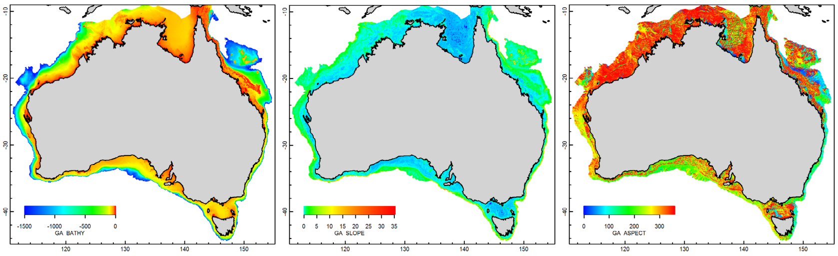

Figure 28 Maps of the re-gridded DEM variables: bathymetry, slope, aspect, at 0.01° resolution.

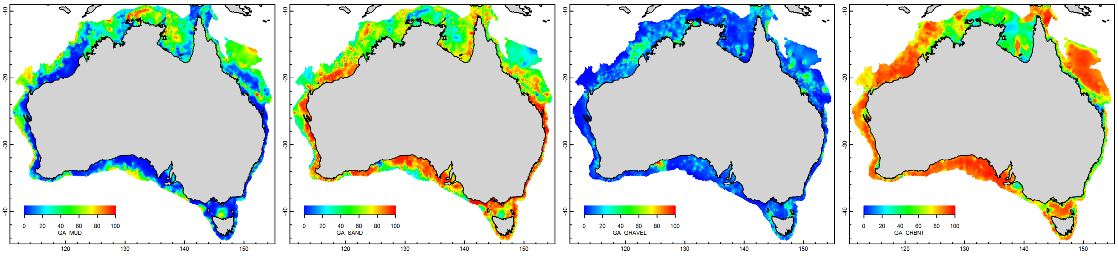

Figure 29 Maps of the re-gridded sediment variables: percent mud, sand, gravel and carbonate at 0.01° resolution.

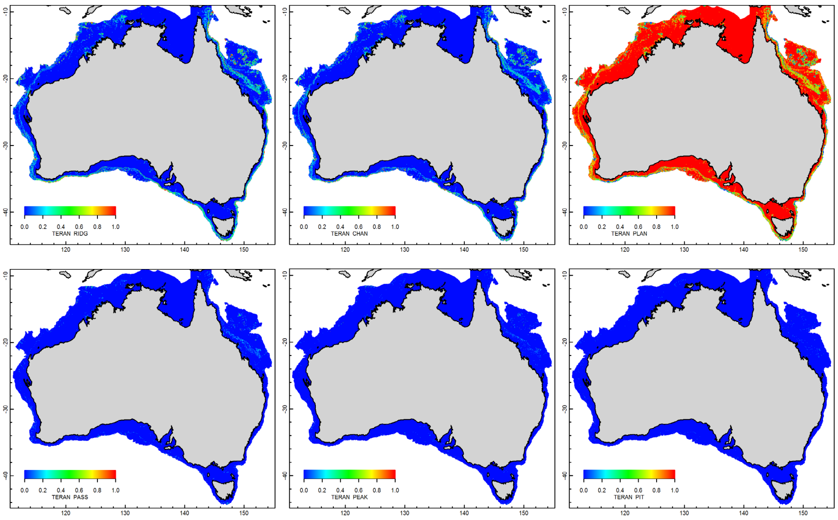

Figure 30 Maps of the re-gridded terrain variables: probability of ridge, channel, plane, pass, peak, pit, at 0.01°.

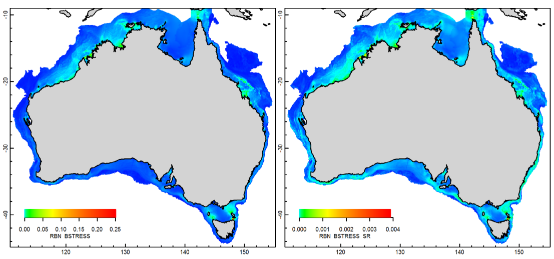

Figure 31 Maps of the updated & re-gridded seabed current stress variables: annual average and seasonal range.

7.6 Appendix 6: Maps of updated CSIRO Atlas of Regional Seas variables

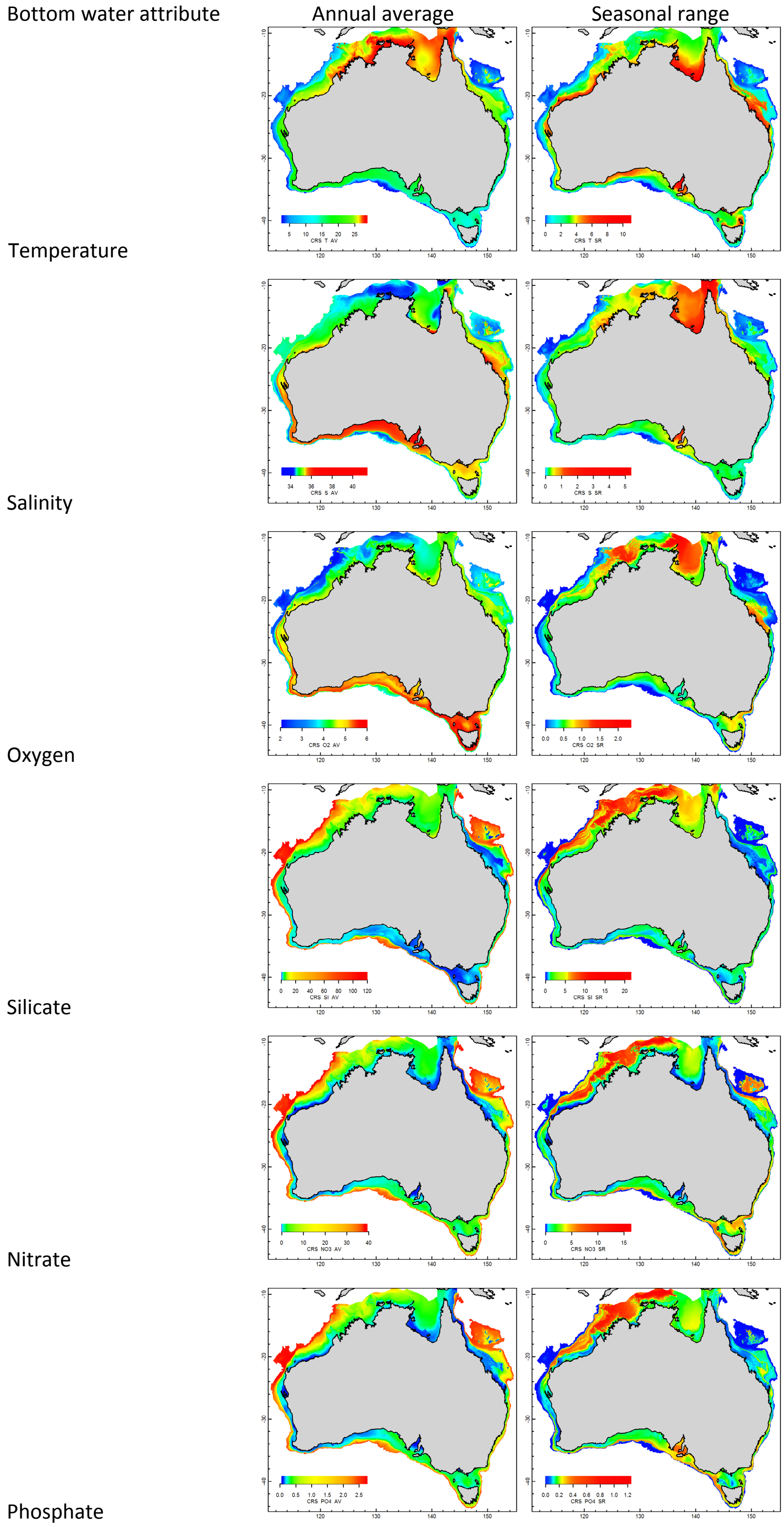

Figure 32 Maps of the updated and re-gridded CSIRO Atlas of Regional Seas (CARS) variables, at 0.01 degree.

7.7 Appendix 7: National assemblages trawl exposure and protection

Table 4 List of national assemblages, with areas (km²) for trawling and closures, in order of decreasing percentage trawl footprint and total swept area and increasing closure, indicative of relative priority for future habitat ERAs.

Region	Assemblage	Area(km²)	Cells trawled	Total swept	Footprint	Trawl closed	Reserve closed	Total closed	%Closed	% Trawled	% Swept	Intensity
5	7	4,121	3,672	12,003	2,023	0	0	0	0.00	49.09	291.24	5.93
5	4	4,252	4,201	5,192	2,740	118	185	303	7.13	64.44	122.11	1.90
5	5	2,621	2,379	2,411	1,552	0	169	169	6.43	59.21	91.99	1.55
11	8	1,403	1,260	1,309	649	0	6	6	0.40	46.24	93.28	2.02
8	17	6,518	6,387	5,595	3,624	258	159	364	5.58	55.60	85.85	1.54
8	16	7,162	7,096	5,895	4,607	0	121	121	1.69	64.33	82.31	1.28
9	2	4,105	2,862	3,925	1,833	1,020	4	1,020	24.84	44.65	95.63	2.14
5	8	2,827	2,737	2,264	1,571	0	15	15	0.52	55.58	80.07	1.44
8	22	6,994	5,565	5,972	3,160	1,293	419	1,512	21.61	45.18	85.39	1.89
11	18	4,958	3,045	4,595	2,001	612	1,793	1,860	37.53	40.35	92.69	2.30
5	6	5,311	5,263	3,757	2,096	0	18	18	0.33	39.46	70.74	1.79
5	1	2,309	1,769	1,601	781	130	714	741	32.12	33.81	69.33	2.05
11	17	4,805	3,355	3,195	1,541	1,080	1,424	1,470	30.61	32.06	66.50	2.07
5	9	3,251	2,841	1,533	1,092	9	0	9	0.28	33.60	47.14	1.40
7	21	20,739	13,890	9,444	7,108	109	1,455	1,564	7.54	34.27	45.54	1.33
6	1	3,768	1,858	1,685	820	792	3	795	21.09	21.76	44.71	2.05
8	21	5,538	4,377	2,518	1,654	1,520	377	1,544	27.89	29.87	45.47	1.52
11	5	9,415	7,706	3,883	2,804	124	2,339	2,340	24.85	29.78	41.24	1.38
11	4	9,178	6,871	3,253	2,460	8	1,990	1,990	21.68	26.81	35.45	1.32
11	1	16,773	13,295	5,617	3,726	80	3,155	3,230	19.25	22.21	33.49	1.51
5	11	4,569	3,917	1,391	1,350	0	5	5	0.11	29.56	30.45	1.03
5	2	4,473	3,874	1,385	1,116	0	55	55	1.23	24.96	30.97	1.24
5	10	4,599	3,447	1,321	1,278	308	0	308	6.71	27.79	28.72	1.03
10	1	15,105	7,546	5,715	2,771	1,946	7,387	7,404	49.02	18.35	37.84	2.06
6	3	6,832	1,118	1,224	327	563	390	700	10.24	4.78	17.92	3.74
8	14	6,365	2,487	1,195	407	98	170	237	3.72	6.40	18.77	2.93
10	7	9,848	3,196	2,487	1,454	1,974	0	1,974	20.05	14.77	25.26	1.71
5	12	3,022	2,123	702	516	65	10	75	2.48	17.09	23.23	1.36
8	19	6,630	4,068	1,656	1,301	329	1,200	1,451	21.88	19.62	24.98	1.27
6	10	9,728	7,737	2,179	2,169	780	46	826	8.49	22.30	22.40	1.00
8	15	5,097	1,169	887	427	112	354	465	9.13	8.38	17.41	2.08
8	13	14,289	3,982	2,097	856	726	1,484	2,207	15.45	5.99	14.68	2.45
2	6	19,890	12,156	3,864	3,034	94	83	177	0.89	15.25	19.43	1.27
11	23	5,473	1,967	681	308	11	152	152	2.78	5.63	12.45	2.21
5	14	2,453	1,224	473	396	854	0	854	34.82	16.16	19.30	1.19
7	1	8,447	4,881	1,736	1,151	3,441	1,172	3,817	45.19	13.63	20.55	1.51
8	18	9,874	5,769	1,394	1,039	1,799	30	1,830	18.53	10.52	14.12	1.34
5	13	3,220	1,234	340	235	0	1	1	0.03	7.29	10.55	1.45
10	6	11,536	4,845	1,605	1,189	578	3,638	3,963	34.35	10.31	13.91	1.35
6	7	22,282	8,894	2,947	2,917	2,804	3,018	5,788	25.97	13.09	13.23	1.01
11	6	13,409	7,165	1,648	1,320	55	3,717	3,717	27.72	9.85	12.29	1.25
2	7	17,476	5,138	1,406	1,020	1	620	621	3.56	5.84	8.05	1.38
2	4	22,929	9,707	2,182	1,997	381	1,420	1,801	7.85	8.71	9.52	1.09
11	19	4,550	922	738	474	1,176	2,403	2,419	53.16	10.42	16.22	1.56
2	8	27,776	11,228	2,272	1,852	52	399	451	1.62	6.67	8.18	1.23
11	22	7,603	1,005	575	299	0	2,579	2,579	33.92	3.93	7.56	1.92
8	20	16,296	4,705	1,442	1,170	5	3,208	3,209	19.70	7.18	8.85	1.23
11	21	2,344	431	255	98	8	1,367	1,367	58.35	4.19	10.90	2.60
5	15	2,656	1,186	218	218	0	20	20	0.76	8.21	8.21	1.00
11	3	8,881	4,032	900	709	1,623	3,273	3,282	36.96	7.99	10.14	1.27
5	16	1,659	608	118	118	242	13	254	15.34	7.09	7.09	1.00
1	5	20,494	4,609	1,221	1,094	16	1,831	1,841	8.98	5.34	5.96	1.12
2	3	10,164	6,336	582	578	428	0	428	4.21	5.69	5.73	1.01
7	3	5,107	3,137	298	296	202	299	446	8.72	5.80	5.84	1.01

Region	Assemblage	Area(km²)	Cells trawled	Total swept	Footprint	Trawl closed	Reserve closed	Total closed	%Closed	% Trawled	% Swept	Intensity
1	1	17,078	8,457	965	965	0	64	64	0.38	5.65	5.65	1.00
5	3	3,491	1,079	148	119	0	0	0	0.00	3.41	4.23	1.24
9	1	7,501	1,284	1,462	637	5,917	1,956	5,919	78.92	8.49	19.49	2.30
8	9	7,403	2,333	875	547	4,399	99	4,399	59.42	7.39	11.82	1.60
8	23	3,965	2,221	481	454	2,188	317	2,229	56.22	11.45	12.14	1.06
5	17	2,084	763	140	140	704	68	726	34.81	6.72	6.72	1.00
1	7	27,674	11,614	986	986	1	2,025	2,026	7.32	3.56	3.56	1.00
1	4	30,138	9,605	1,003	1,003	0	1,101	1,101	3.65	3.33	3.33	1.00
7	2	8,478	3,973	387	371	1,046	1,418	2,062	24.32	4.37	4.56	1.04
6	17	10,167	1,340	292	279	0	19	19	0.18	2.74	2.87	1.05
2	12	50,310	4,177	613	478	1	3,866	3,867	7.69	0.95	1.22	1.28
4	6	14,281	4,625	473	473	0	1,909	1,909	13.37	3.31	3.31	1.00
2	5	30,607	11,464	926	922	2,149	1,319	3,468	11.33	3.01	3.03	1.00
7	20	18,644	1,925	413	342	4	3,498	3,502	18.78	1.83	2.21	1.21
8	5	8,965	4,552	375	352	2,589	229	2,810	31.35	3.93	4.19	1.07
9	8	4,701	181	13	9	993	34	1,025	21.81	0.19	0.27	1.39
1	15	36,813	4,093	496	420	0	7,226	7,226	19.63	1.14	1.35	1.18
1	11	30,576	4,803	611	554	1,284	5,815	6,488	21.22	1.81	2.00	1.10
6	13	10,157	915	149	149	0	29	29	0.29	1.47	1.47	1.00
2	15	32,667	3,713	322	322	0	0	0	0.00	0.99	0.99	1.00
1	3	19,422	1,902	165	163	285	1,038	1,268	6.53	0.84	0.85	1.01
9	13	6,085	1,189	88	87	578	860	1,103	18.12	1.42	1.45	1.02
2	14	38,629	2,757	167	161	0	0	0	0.00	0.42	0.43	1.03
2	13	34,472	1,271	81	81	0	0	0	0.00	0.23	0.23	1.00
2	11	51,674	2,044	121	121	1	1,015	1,016	1.97	0.23	0.23	1.00
9	16	9,436	851	123	118	313	1,904	2,183	23.14	1.25	1.30	1.04
1	22	24,523	470	32	32	0	644	644	2.62	0.13	0.13	1.00
7	27	20,362	24	9	6	2,888	4,200	6,471	31.78	0.03	0.04	1.38
7	6	17,474	606	46	46	96	1,529	1,570	8.98	0.27	0.27	1.00
4	10	14,837	1	0	0	0	310	310	2.09	0.00	0.00	1.00
9	17	5,727	596	13	13	25	585	585	10.22	0.23	0.23	1.00
6	14	10,463	8	0	0	462	78	540	5.16	0.00	0.00	1.00
4	16	19,120	92	1	1	0	1,037	1,037	5.42	0.01	0.01	1.00
7	22	14,301	2,336	95	95	1,103	1,652	2,514	17.58	0.66	0.66	1.00
6	16	5,604	43	1	1	111	273	384	6.85	0.01	0.01	1.00
4	14	20,475	12	0	0	0	1,520	1,520	7.42	0.00	0.00	1.00
6	2	1,843	54	1	1	31	167	167	9.08	0.06	0.06	1.00
2	10	17,944	188	6	6	0	1,573	1,573	8.77	0.04	0.04	1.00
4	1	5,741	54	2	2	0	634	634	11.04	0.03	0.03	1.00
1	21	35,005	289	26	26	3,967	232	4,199	11.99	0.07	0.07	1.00
1	8	21,333	955	72	72	0	3,403	3,403	15.95	0.34	0.34	1.00
4	7	22,835	300	10	10	0	3,288	3,288	14.40	0.04	0.04	1.02
11	24	6,155	40	0	0	0	749	749	12.17	0.01	0.01	1.00
4	3	11,254	16	0	0	0	1,436	1,436	12.76	0.00	0.00	1.00
6	6	12,736	17	0	0	31	1,725	1,756	13.79	0.00	0.00	1.00
4	15	28,837	1	0	0	0	4,063	4,063	14.09	0.00	0.00	1.00
7	5	8,197	272	15	15	704	924	1,377	16.80	0.19	0.19	1.00
4	2	8,245	37	1	1	0	1,224	1,224	14.85	0.02	0.02	1.00
1	6	19,179	3,327	360	350	14	6,163	6,178	32.21	1.82	1.88	1.03
7	19	10,033	101	2	2	633	1,255	1,518	15.13	0.02	0.02	1.00
6	12	13,907	3,365	596	596	6,047	32	6,079	43.71	4.28	4.29	1.00
4	9	17,660	59	1	1	0	2,860	2,860	16.19	0.00	0.00	1.00
7	12	16,197	183	4	4	29	2,667	2,690	16.61	0.03	0.03	1.00
7	23	8,198	1,105	62	62	1,726	489	2,022	24.66	0.75	0.75	1.00
3	7	8,300	25	0	0	0	1,611	1,611	19.41	0.00	0.00	1.00

Region	Assemblage	Area(km²)	Cells trawled	Total swept	Footprint	Trawl closed	Reserve closed	Total closed	%Closed	% Trawled	% Swept	Intensity
1	19	16,529	34	1	1	59	3,328	3,387	20.49	0.00	0.00	1.00
1	17	41,458	4,667	477	477	1,063	12,149	12,469	30.08	1.15	1.15	1.00
7	18	10,039	16	0	0	387	1,939	2,235	22.26	0.00	0.00	1.00
6	4	10,639	1,002	87	87	2,483	1,655	3,093	29.07	0.82	0.82	1.00
1	9	28,551	619	24	24	32	6,710	6,742	23.62	0.08	0.08	1.00
8	6	6,114	2,882	358	347	2,714	567	3,281	53.66	5.67	5.86	1.03
7	11	20,722	752	59	59	0	5,512	5,512	26.60	0.29	0.29	1.00
4	8	9,917	4	0	0	0	2,443	2,443	24.63	0.00	0.00	1.00
2	1	8,003	509	28	25	2,603	0	2,603	32.52	0.31	0.34	1.11
4	4	13,330	56	1	1	0	3,306	3,306	24.80	0.00	0.00	1.00
1	18	61,161	593	18	18	4,475	11,373	15,781	25.80	0.03	0.03	1.00
8	2	14,599	2,667	117	116	4,323	551	4,727	32.38	0.80	0.80	1.00
8	25	4,929	1,263	90	89	1,900	1,640	1,911	38.77	1.80	1.82	1.01
3	1	32,820	176	15	15	0	9,115	9,115	27.77	0.04	0.04	1.00
10	4	6,643	24	1	1	1,161	1,320	1,858	27.97	0.01	0.01	1.00
7	7	13,279	244	19	19	0	3,918	3,918	29.50	0.14	0.14	1.00
5	19	4,321	270	54	54	1,531	376	1,564	36.19	1.24	1.24	1.00
7	13	10,068	46	1	1	89	2,830	2,913	28.93	0.01	0.01	1.00
1	14	22,749	16	3	3	0	7,263	7,263	31.93	0.01	0.01	1.00
7	15	21,100	793	236	175	302	10,357	10,475	49.64	0.83	1.12	1.34
7	26	16,580	160	4	4	3,551	2,395	5,751	34.68	0.03	0.03	1.00
10	2	13,924	1,142	707	335	2,384	10,329	10,330	74.19	2.41	5.08	2.11
6	18	9,507	596	34	34	0	3,602	3,602	37.89	0.36	0.36	1.00
2	9	17,050	768	128	123	2	7,156	7,158	41.99	0.72	0.75	1.04
7	4	10,124	1,775	128	128	1,929	3,562	4,420	43.66	1.26	1.26	1.00
6	11	9,104	152	2	2	3,395	1,031	3,420	37.57	0.03	0.03	1.00
2	2	6,195	376	19	19	2,306	141	2,446	39.49	0.31	0.31	1.00
9	7	3,424	98	1	1	662	824	1,305	38.10	0.02	0.02	1.00
4	11	20,465	3	2	2	0	7,943	7,943	38.82	0.01	0.01	1.00
6	15	6,203	2	0	0	2,336	80	2,416	38.96	0.00	0.00	1.00
7	10	20,812	25	2	2	6,719	4,034	8,219	39.49	0.01	0.01	1.00
11	25	7,441	111	1	1	1,498	3,086	3,086	41.47	0.01	0.01	1.00
8	3	18,850	2,197	63	62	8,124	170	8,287	43.96	0.33	0.33	1.03
11	11	13,733	3,804	408	392	2,543	7,590	7,590	55.27	2.86	2.97	1.04
1	10	25,964	2,340	182	160	947	12,116	12,839	49.45	0.62	0.70	1.14
9	6	10,009	51	0	0	2,192	3,122	4,455	44.51	0.00	0.00	1.00
7	25	13,967	265	14	14	5,397	1,538	6,351	45.47	0.10	0.10	1.00
7	24	4,741	37	3	3	1,664	985	2,196	46.33	0.06	0.06	1.00
10	5	13,073	96	2	2	4,054	5,902	6,228	47.64	0.02	0.02	1.00
9	12	11,192	119	2	2	4,858	1,633	5,378	48.05	0.02	0.02	1.00
7	9	22,869	10	3	3	423	10,976	10,987	48.04	0.01	0.01	1.00
7	14	20,622	83	26	24	0	10,500	10,500	50.92	0.12	0.12	1.07
8	24	8,150	2,814	167	165	4,673	1,252	4,718	57.89	2.02	2.05	1.02
11	7	20,013	1,703	220	193	2,873	11,501	11,501	57.47	0.97	1.10	1.14
9	4	5,883	538	119	113	3,398	367	3,521	59.85	1.92	2.02	1.05
11	10	17,990	3,730	949	766	7,781	13,034	13,036	72.47	4.26	5.27	1.24
1	20	13,129	116	6	6	4,934	3,134	6,915	52.67	0.04	0.04	1.00
10	11	13,740	1	0	0	4,630	2,770	7,400	53.86	0.00	0.00	1.00
9	11	13,259	217	29	29	3,573	4,293	7,394	55.76	0.22	0.22	1.00
8	1	7,443	473	15	15	4,191	307	4,199	56.42	0.20	0.20	1.02
9	14	11,017	301	66	62	2,362	6,448	6,503	59.03	0.56	0.60	1.06
4	18	6,830	0	0	0	0	0	0	0.00	0.00	0.00	0.00
4	13	14,666	0	0	0	0	92	92	0.63	0.00	0.00	0.00
10	8	5,778	102	4	4	3,265	68	3,327	57.58	0.07	0.07	1.00
9	5	9,392	506	55	55	4,265	2,966	5,690	60.58	0.59	0.59	1.00

Region	Assemblage	Area(km²)	Cells trawled	Total swept	Footprint	Trawl closed	Reserve closed	Total closed	%Closed	% Trawled	% Swept	Intensity
11	20	9,995	161	3	3	63	5,928	5,928	59.31	0.03	0.03	1.00
6	8	15,428	40	1	1	7,577	2,249	9,230	59.82	0.01	0.01	1.00
3	8	13,088	0	0	0	443	3,163	3,163	24.17	0.00	0.00	0.00
11	14	5,435	102	21	8	1,796	4,713	4,713	86.72	0.15	0.39	2.58
8	4	11,849	429	21	20	6,362	1,292	7,613	64.25	0.17	0.18	1.08
1	16	33,370	537	30	30	30	20,783	20,813	62.37	0.09	0.09	1.00
9	3	6,783	318	100	79	4,958	1,373	4,958	73.11	1.16	1.48	1.27
11	15	6,943	542	16	14	2,788	4,671	4,691	67.57	0.21	0.23	1.12
4	17	8,195	1	1	1	0	5,282	5,282	64.46	0.01	0.01	1.00
10	12	8,320	0	0	0	2,718	0	2,718	32.67	0.00	0.00	0.00
4	5	6,643	0	0	0	0	2,388	2,388	35.95	0.00	0.00	0.00
8	7	9,904	315	11	11	6,694	561	6,740	68.05	0.11	0.11	1.04
11	12	15,230	2,003	325	250	8,870	11,813	11,827	77.66	1.64	2.13	1.30
10	10	6,158	194	7	4	152	4,848	4,878	79.22	0.07	0.11	1.63
3	3	14,604	0	0	0	0	5,862	5,862	40.14	0.00	0.00	0.00
10	9	6,865	6	1	1	4,728	0	4,728	68.87	0.01	0.01	1.00
7	17	12,162	91	4	4	7,270	2,444	8,432	69.33	0.04	0.04	1.00
8	8	12,146	1,386	9	9	7,170	1,906	8,804	72.48	0.07	0.07	1.00
8	26	7,829	1,815	108	105	5,932	537	6,061	77.41	1.35	1.38	1.03
10	3	8,526	354	32	18	2,882	7,599	7,602	89.15	0.21	0.37	1.80
9	15	9,281	0	0	0	1,683	4,395	4,956	53.40	0.00	0.00	0.00
11	16	5,916	478	16	16	3,909	4,613	4,658	78.73	0.26	0.26	1.00
11	9	16,121	1,715	195	141	3,150	14,090	14,090	87.40	0.87	1.21	1.38
11	26	4,829	76	1	1	1,106	3,812	3,812	78.93	0.02	0.02	1.00
1	2	10,055	322	10	10	6,266	2,709	8,153	81.09	0.10	0.10	1.00
7	16	18,523	40	2	2	14,302	3,842	15,257	82.37	0.01	0.01	1.00
10	14	3,899	0	0	0	1,860	2,450	2,450	62.83	0.00	0.00	0.00
5	18	2,301	277	13	13	1,975	248	1,975	85.83	0.56	0.56	1.01
7	8	21,700	2	0	0	14,646	15,371	18,365	84.63	0.00	0.00	1.00
6	9	16,060	1,007	249	226	14,283	190	14,459	90.03	1.41	1.55	1.10
8	10	5,808	196	5	5	5,180	6	5,180	89.18	0.08	0.08	1.00
11	2	6,475	84	20	20	4,963	5,843	5,843	90.24	0.30	0.30	1.00
4	12	8,075	0	0	0	0	5,696	5,696	70.53	0.00	0.00	0.00
9	10	9,060	18	5	5	8,550	6,154	8,556	94.44	0.05	0.05	1.00
6	5	14,298	0	0	0	8,972	7,694	10,997	76.92	0.00	0.00	0.00
1	12	37,991	435	32	32	34,492	26,655	36,919	97.18	0.08	0.08	1.00
3	2	10,144	9	0	0	0	9,853	9,853	97.13	0.00	0.00	1.00
1	13	32,379	1	1	1	31,215	21,705	32,107	99.16	0.00	0.00	1.05
3	4	17,845	4	0	0	0	17,591	17,591	98.58	0.00	0.00	1.00
8	12	7,791	24	11	11	7,731	33	7,756	99.54	0.14	0.14	1.00
11	13	11,954	30	1	1	12	11,927	11,927	99.78	0.01	0.01	1.00
3	12	64,958	1	0	0	1,597	64,926	64,926	99.95	0.00	0.00	1.00
10	13	2,139	0	0	0	1,617	1,794	1,797	84.01	0.00	0.00	0.00
3	9	5,736	0	0	0	2,638	5,201	5,201	90.68	0.00	0.00	0.00
3	11	35,095	0	0	0	63	34,123	34,123	97.23	0.00	0.00	0.00
3	6	40,527	0	0	0	2,330	39,712	39,712	97.99	0.00	0.00	0.00
3	5	22,993	0	0	0	1,207	22,550	22,552	98.08	0.00	0.00	0.00
9	18	1,014	0	0	0	566	996	998	98.33	0.00	0.00	0.00
3	13	15,948	0	0	0	7,764	15,875	15,875	99.54	0.00	0.00	0.00
8	11	3,653	0	0	0	3,642	0	3,642	99.72	0.00	0.00	0.00
9	9	6,887	0	0	0	6,695	1,078	6,886	99.99	0.00	0.00	0.00
3	10	21,275	0	0	0	3,131	21,275	21,275	100.00	0.00	0.00	0.00
3	14	10,408	0	0	0	37	10,408	10,408	100.00	0.00	0.00	0.00
ALL	**ALL**	**2,923,734**	**408,338**	**154,216**	**100,190**	**458,209**	**838,351**	**1,108,855**	**37.93**	**3.43**	**5.27**	**1.54**

7.8 Appendix 8: Preliminary relative benthic status assessment

This appendix summarises, for the assemblages mapped herein, preliminary 'relative benthic status' (RBS) assessment results for Australia from the related international Trawl Best Practice (TBP) Project. While these results are preliminary they are relevant to the question of what is the actual risk in the more exposed assemblages — in this case for the estimated overall status of unconsolidated sedimentary habitats (mud, sand, gravel), based on the average sensitivity to trawling of the typical benthic invertebrate faunal community common in such habitats. The RBS method can also be applied to sensitive habitat-forming benthos; however, such application requires distribution information for these biota that is lacking for most trawled assemblages (see section 4.4.1). Thus, these RBS results do not address the status of sensitive habitats, so are not a substitute for the recommended future research needs to address this lack of data.

RBS provides an estimate of the long-term equilibrium status of the benthos with current trawling effort, relative to that with no trawling. The details of the RBS method are published in Pitcher et al (2017). The parameters needed for RBS are grid-cell trawl swept-area ratio, per trawl depletion rate *d* and logistic recovery rate *r*, and sediment grain size (% mud, % sand, % gravel: Figure 29). The *d* and *r* values were estimated by the TBP meta-analysis (Hiddink et al 2017) and represent the average *d* and *r* for the typical common benthos compositions in mud, sand and gravel habitats. Depletion *d* differs by gear type (in Australia, this is mostly otter trawl) and also varies with sediment because the depth of penetration *P* of gear into the sediment depends on the sediment composition and *d* is related to *P* (see Fig. 2 in Hiddink et al 2017). The relationship between *P* and sediment grain size composition is still in development — hence, the current results are preliminary, but closely indicative.

As part of the TBP Project, RBS is being implemented for sedimentary habitats assessment for Australia and ~20 other regions overseas. For TBP, the RBS results will be summarised at the scale of large marine regions (five for Australia) and for shelf and slope areas within each region. Here, preliminary grid-cell RBS results for Australia are summarised for each assemblage (Figure 33). In this case, the upper confidence interval (CI) for *d* and the lower CI for *r* have been used, so the assemblage mean RBS estimates are the lower CI to be conservative / precautionary.

RBS directly uses the grid-cell trawl swept-area ratios, and thus takes into account both trawl footprint and trawl intensity. Hence, unsurprisingly the RBS results reflect both the footprint map (Figure 19) and the swept area map (Figure 20) in section 4.3. Nevertheless, there are differences because RBS also takes into account the sediment habitat types, which have varying *P* and thus *d*, and also *r*. Table 5 (below) lists regional assemblages that have the lowest average RBS values (with threshold at RBS < 0.95). The same assemblages are towards the top of this list as in Appendix 7.7, although in a slightly different order (refer to the regional maps Figure 8 to Figure 18 for the location of each assemblage).

Table 5 also provides additional RBS statistics including: prop100=the proportion of the assemblage by area that is at 100% status; prop80=the proportion of the assemblage that is >80% status; prop50=proportion >50% status; and prop0=proportion at 0% status. These statistics for benthic status can be used in various ways to support definitions of risk. For example, the EU MSFD aims to achieve good environmental status (GES) by 2020; for "Sea-floor Integrity" implementation, this could mean that >80% of each habitat should be in >80% status. The Marine

Stewardship Council has applied a similar 80% criterion and have been investigating implementation of RBS for their assessments. A number of assemblages in the east (region#5), southeast (#8) and northeast (#11) would not meet this 80% criterion even for these relatively resilient sedimentary benthic habitats.

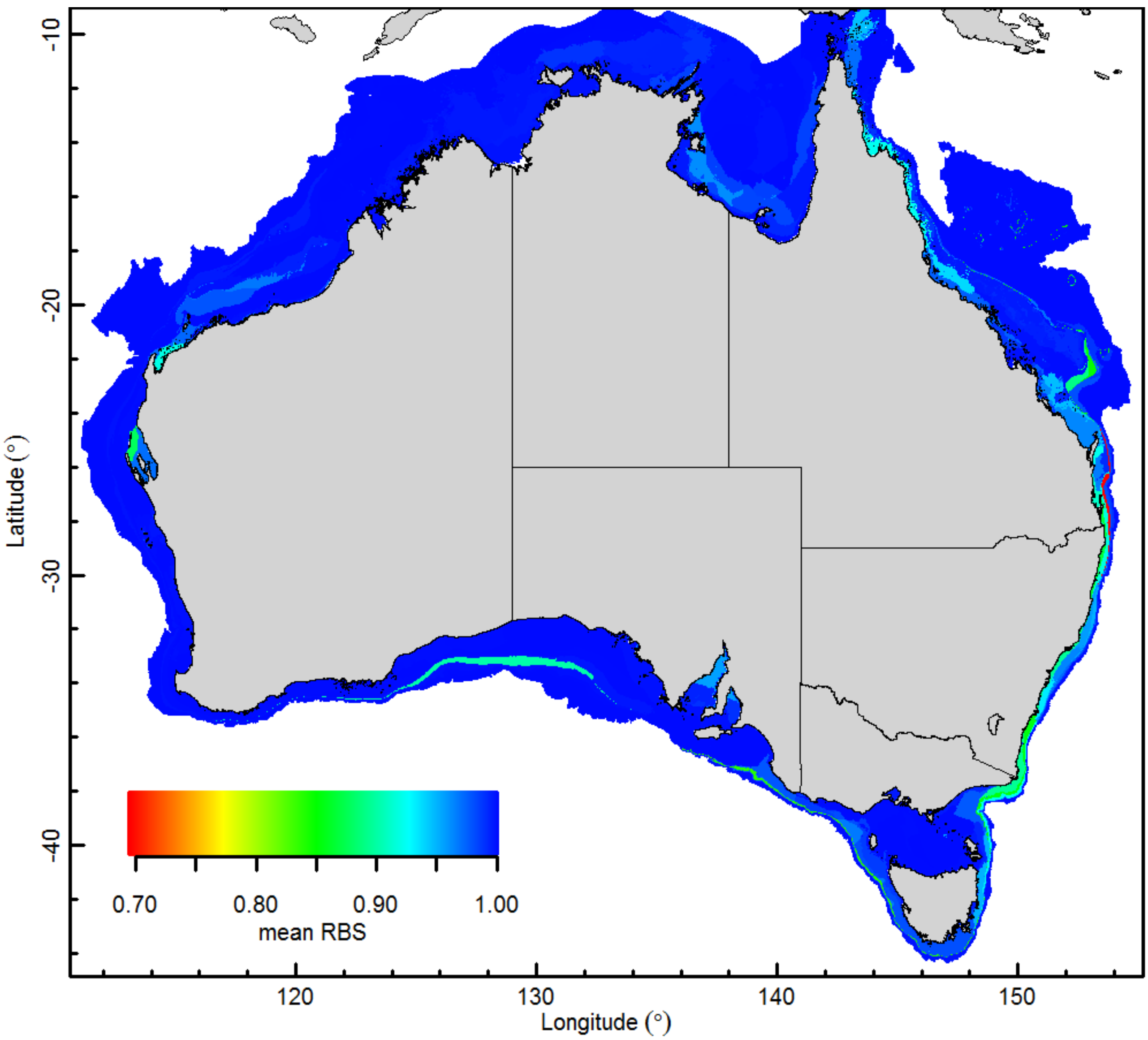

Figure 33 Preliminary mean relative benthic status (RBS) of sedimentary habitats for each assemblage; average of the lower confidence interval (CI) of RBS estimates for grid cells in each assemblage, calculated using the upper confidence interval (CI) for depletion (*d*) and the lower CI for recovery (*r*).

RBS was not calculated here for sensitive benthic habitats because they tend to have more specialised restricted distributions, which may or not overlap with trawling. Hence the recommendation that distribution information for any sensitive habitat types is a priority in trawl exposed assemblages. Had RBS been calculated for sensitive habitat types in a general way without distribution information, their preliminary estimated status would have been substantively lower than for sedimentary habitats, as a grid-cell swept-area ratio of only ~0.35 would extirpate such sensitive habitats, and grid-cell swept ratios <0.065 are necessary to maintain sensitive habitats at >80%.

RBS can be used to implement quantitative (level 3) ecological risk assessments (ERA) for habitats, contingent on the availability of suitable habitat distribution information. Further, if such risk assessments indicate that risk management is necessary, then a range of management interventions may be possible and RBS can be used to evaluate the benefits for habitats of alternative interventions.

Table 5 Preliminary mean sedimentary habitat RBS estimates for assemblages (average of the lower confidence interval RBS estimate for each grid-cell), listed for assemblages with mean RBS < 0.95 only. Also including: prop100=the proportion of the assemblage by area that is at 100% status; prop80=the proportion of the assemblage that is >80% status; prop50=proportion >50% status; and prop0=proportion at 0% status.

Region	Assemblage	meanRBS	prop100	prop80	prop50	prop0
5	7	0.694	0.109	0.646	0.717	0.202
8	22	0.837	0.204	0.740	0.899	0.027
11	18	0.847	0.386	0.716	0.905	0.013
8	17	0.853	0.020	0.749	0.945	0.008
5	4	0.866	0.012	0.837	0.944	0.004
9	2	0.877	0.303	0.767	0.940	0.000
5	5	0.886	0.092	0.805	0.978	0.003
11	17	0.889	0.302	0.806	0.933	0.009
8	16	0.894	0.009	0.882	0.996	0.001
5	8	0.895	0.032	0.845	0.995	0.000
7	21	0.900	0.330	0.829	0.963	0.009
5	1	0.909	0.234	0.839	0.952	0.006
5	6	0.916	0.009	0.900	0.968	0.002
6	1	0.918	0.507	0.856	0.956	0.005
11	8	0.920	0.102	0.874	0.981	0.001
10	1	0.921	0.500	0.882	0.947	0.022
8	21	0.922	0.210	0.881	0.971	0.006
5	9	0.932	0.126	0.883	0.993	0.000
11	5	0.937	0.181	0.904	0.990	0.000
10	7	0.945	0.675	0.900	0.970	0.004
11	4	0.945	0.251	0.931	0.994	0.002
8	19	0.949	0.386	0.939	0.982	0.007
5	12	0.949	0.297	0.960	0.988	0.004

7.9 Appendix 9: List of researchers and project staff

Roland Pitcher, CSIRO

Wayne Rochester, CSIRO

Malcolm Dunning, CSIRO

Tony Courtney, DAF Qld

Matt Broadhurst, DPI NSW

Craig Noell, Jason Tanner, SARDI

Mervi Kangas, Stephen Newman, DPIRD WA

Jayson Semmens, IMAS

Cassandra Rigby, JCU

Thor Saunders, Julie Martin, DPIR NT

Bill Lussier, VFA

7.10 Appendix 10: Intellectual Property

Published, widely disseminated and promoted, and/or training and extension provided. Related products and/or services developed. Relates mainly to outputs that will largely be available in the public domain, but components may be commercialised or intellectual property protected.

Data collated by the project are existing IP and most have associated data agreements that do not permit provision of data to third parties. In particular, fishing effort data are confidential and maps of fishing effort cannot be made publicly available at the fine scale and detail used in this project.

All derived products produced by the project are expected to be unrestricted and thus made available in the public domain.

FOR FURTHER INFORMATION

CSIRO Oceans & Atmosphere
Dr C. Roland Pitcher
Senior Principal Research Scientist
t +61 7 3833 5954
e roland.pitcher@csiro.au
w www.csiro.au