Port Kembla Harbour Environment Group

Meeting No. 154
Tuesday 7 February 2023
9.00 a.m. – 11.00 a.m.

Inside Industry, BlueScope

Minutes

Attendees	
Community members Ron Hales Mark Peterlin Peter Maywald Phillip Laird **Business Representatives** Natasha Porteous – Blue Scope Brian Kiely – PK Gateway Nigel Harpley – IXOM Kate Flint – Pacific National Heath Anderson – Pacific National Rosa Thomson – AIE/Squadron Energy Alex Lovell – AIE/Squadron Energy **University of Wollongong** Amelia Hine **NSW Ports representatives** Peter Munro Bryan Beudeker **Port Authority of NSW** None present **NSW EPA** Chris Kelly	**Wollongong City Council** Karl Batshon **Dept of Agriculture** None present **Guest Presenters** Andy Davis – UoW **Apologies** Wayne Vorley – PKCT Michael Curley – PKCT Sharad Bhasin – Port Authority of NSW Paul Bollen – Morgan Cement Lana Howell – NSW Ports Jess Whittaker – Community Member Greg Newman – NSW EPA Sara Starr - AAT Lorrie Zammit - Bluescope **Chairperson & Minutes** Chris Haley – Chairperson Natalie Murphy – Minute Taker

1. **Introduction & Apologies:**

   1.1 Acknowledgment of the Dharawal people – Chris Haley
   1.2 Welcome attendees and guest presenters– Chris Haley

2. **Guest Presenter – Andy Davis– UoW - Appendix A, B & C**

- A review of the literature confirmed there were 41 publications examining the effects of anchoring on the environment. None have focussed on ocean-going vessels and their impacts on reefs.
- Recreational anchoring has dramatic effects on sea grass beds. The sea grass is very slow growing. In Jervis Bay, anchoring circles and readily apparent and the sea grass is very slow to recover.
- There is an AIS (Automated Information System) providing data on where the vessels are anchoring.
- Coastlines off Port Kembla and Newcastle could potentially be impacted from anchoring. Video from a Remotely Operated Vehicle (ROV) in anchored and anchor-free locations confirm that impacts can be dramatic.
- Designated anchorages have been adopted off Port Kembla and are a welcome management approach as they dramatically reduce the anchoring footprint.

Queries relating to:	**Responses/Updates**
Question: How close to the anchoring points are vessels adhering too?	As of October 22, I believe they are being closely adhered too. Take on notice for more accurate information.
Question: Looking from North Beach I could recently see 5 vessels off the coast. Are they being anchored?	Yes, they are all anchored.
Question: Who designated the anchorage points?	This was a state government initiative.
Question: How are vessels responding to designated anchorages?	It is legislated. Alternative anchorages can be offered.
Question? Do the anchorages have a life span?	In 2014 there was a workshop with state authorities and the shipping industry. The anchor points will likely sustain considerable damage, but we have confirmed that they are of low conservation value.
Comment: This study seems to have followed best practice.	There are environmental guidelines provided by the shipping industry (Australian Chamber of Shipping) however there is no mention of anchoring.
Comment: There were designated anchoring in Port Kembla many years ago. It was disbanded.	
Question: Has there been any testing on the sea grass at Jervis Bay? You can see the crop circles where the sea grass has not grown back.	This is correct. The damage of sea grass in this particular place seems to be effectively permanent as recovery is so slow.
Question: Do we know why the seagrass is so slow to grow?	No. This seems to be a specific species trait.

Question: Is there any interest from other Ports?	QLD. There are designated anchorages at Gladstone. There is no mapping available so I am unsure if the anchorages are in the right place.
Question: Any interest from overseas?	Yes Canada. Canada is concerned about its West Coast islands and is driven by community concerns..

3. Minutes of Meeting and Actions

3.1 Acceptance of Minutes of Meeting held 6 December 2022
3.2 Business arising from Minutes 6 December 2022

ACTIONS	TO RESPOND
Report back on Greenhouse Park remédiation plan	Karl Batshon
Obtain NSW Fisheries contact from Alex Lovell	Natalie Murphy
Invite NSW Fisheries contact to PKHEG meetings	Natalie Murphy
NSW Ports to present on community consultation process and findings	Peter Munro
Further information to be provided on the WCC motion for a memorial for seamen.	Peter Maywald

4. Round Table Reports

4.1 NSW Ports – Peter Munro /Bryan Beudeker

- Late last year, NSW Ports was part of a security emergency desktop exercise. Such exercises are regular events with port operators to prepare for various scenarios, to ensure we respond effectively and safely.
- There remains a backlog of orders for motor vehicles but this is improving as vessel visit numbers increase. Trade is strong overall, particularly grain exports
- NSW Ports has made several announcements celebrating the outcomes of our Community Grants program, which supports organisations and initiatives around Port Kembla. These announcements include our grant to Warrawong Public School, to build a yarning circle and native garden for use by students (particularly Indigenous students), and our grant to Frame Running in Wollongong, which has enabled them to purchase additional equipment to enable children with restricted mobility to move and play. I encourage you to visit the NSW Ports website to read about such achievements: https://www.nswports.com.au/latest-news
- NSW Ports will shortly call for applications for its 2023 community grants program. Please encourage local community groups and not-for-profits to apply for support.
- NSW Ports is proud to have renewed its sponsorship of the Living Classroom program, which works with seven schools in and around Port Kembla. The program supports those schools to grow and nurture permaculture gardens on their sites, to share fresh produce and to teach students about the benefits of healthy eating.
- The Manildra project proposal remains with the Department of Planning for consideration.
- It was noted to contact NSW Ports via their hotline number or the NSW Ports website to log any community environment concerns. This enables NSW Ports to contact the contractor and address the concern faster. The EPA can still be notified but in the interest of efficiency please contact NSW Ports in the first instance.

4.2 Wollongong City Council – Karl Batshon

- Renee Winsor has resigned from Wollongong City Council.
- Karl Batshon will continue to attend the meetings and represent WCC.
- Greenhouse Park remediation plan is still in review. Karl to report back any progress at next meeting

4.3 AIA/ Squadron Energy

- Pipeline works have commenced. Part owned by Jemena and AIE. Working along the coast and Springhill Road. Pipes will connect into eastern pipeline
- It was noted the pipes are approx. 450 mm diameter.
- Completion expected at the end of the year.
- Squadron Energy Community contact details: https://www.squadronenergy.com/port-kembla-energy-terminal/
- Squadron Energy 24-hour Hotline: **1800 789 177**

Queries relating to:	Responses/ Update
Question: Were there any alarming results from the soil bed testing?	There was a test prior to commencement. There were no notable large plumes or chemicals.

4.4 Pacific National

- Kate Flint and Heath Anderson joined the meeting in person today, who are based in the Port of Newcastle.

Queries relating to:	Responses/ Update
Question: How many trains coming into Newcastle Port per week?	I would have to take that on notice
Question: Is it Coal, Grain and Steel coming into Port Kembla?	Yes
Question: Is there problems with train paths into Port Kembla?	Yes, there are problems with train paths everywhere

4.5 NSW EPA

- Greg Newman is an apology today. Greg did send through the Environmental Report for the Committee to discuss.
- Chris Kelly noted the environmental incidents from October 2022 till current

4.6 IXOM

- Nigel noted that IXOM had an environmental incident on the EPA report. It was an acid spill on Foreshaw Rd. It was caused by a split hose in the loading facility. The EPA visited the site but there is yet to be a report.
- IXOM has replaced the hose, provided temporary shielding, investing in a more permanent shield, add closed circuit TV and will replace hoses more frequently.

4.7 UoW

- NSW Ports' 2022 community grants program include support for wall murals celebrating the Great Southern Reef. There is a meeting today with UoW and NSW Ports to progress this process.
- Amelia Hine has won a new contract in Germany. Chantelle Carr will attend the PKHEG meetings going forward.
- Amelia will remain on the email distribution list and receive correspondence relating to this group.

4.8 BlueScope

- BlueScope self-reported to the NSW EPA an incident. A scrap grab unloading had scrap caught in the grab which fell out and dislodged releasing some into the water.
- LINX were the operators. They were responsive and took corrective action. The NSW EPA reviewed the incident report and an advisory letter was received.

4.9 Community Members

- Ron Hales thanked the Port Kembla Operators for attending the PKHEG Meeting.
- Ron asked if a representative from NSW Fisheries could be invited to attend the PKHEG meetings. To be added as an action for the next meeting.
- Philip Laird representing Neighbourhood Forum 5 & 7 noted their ongoing interest in Manildra. They have asked Manildra to have another look at rail
- NF5 & 7 have made representations to IPART
- Peter Maywald mentioned concerns at Korrongulla Swamp at Primbee. It is alleged Mimosa have plans for that site.
- Mark Peterlin mentioned the invitation to participate in a NSW Ports community consultation survey and requested the survey results be discussed. Peter Munro (NSW Ports) will present on this process and findings.

5. General Business

5.1 Support for Motion

- Peter Maywald attended a WCC meeting online last night and was in support of a motion by Councillor Janice Kershaw relating to the erecting of a memorial structure for seamen. Peter asked that the Port Kemba Harbour Environmental Group support this motion by way of letter to WCC. Some further information was requested and will be discussed as an agenda item at the next meeting.

6. Next Meeting:

DATE: 4 April 2023

VENUE: Inside Industry, BlueScope

TIME: 9am to 11am


Dragging the Chain:
anchor scour impacts from ocean going vessels
Update for PKHEG 2023
Andy Davis
Allison Broad
University of
Wollongong

1


A talk in 3 parts
(i) Background & History
(ii) Findings in relation to Port Kembla
(iii) A good news story & the future

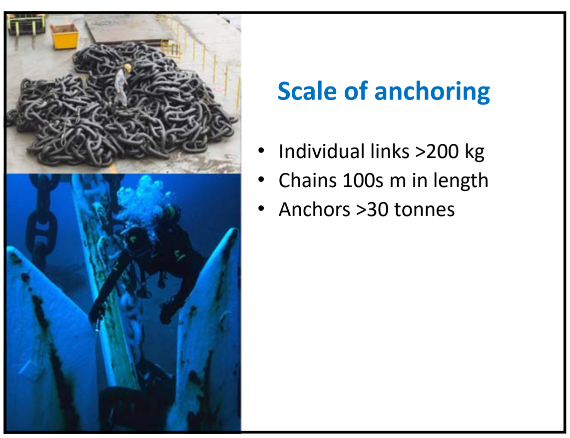
2


A talk in 3 parts
(i) Background & History
(ii) Findings in relation to Port Kembla
(iii) A good news story & the future

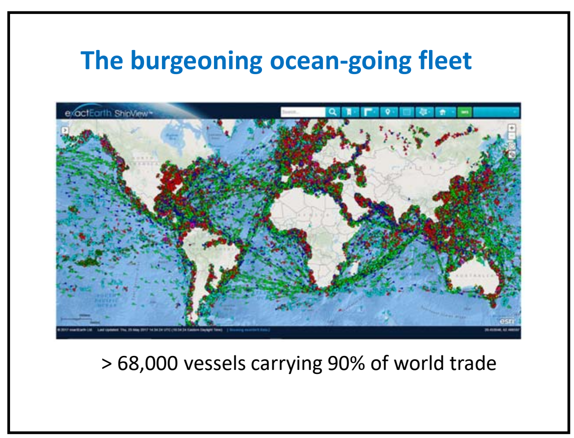
3


Anchoring a routine safety operation
Many vessels exceed 300m in length

4


Scale of anchoring
• Individual links >200 kg
• Chains 100s m in length
• Anchors >30 tonnes

5


The burgeoning ocean-going fleet
> 68,000 vessels carrying 90% of world trade

6

Anchoring – trends in the literature 2020

Contents lists available at ScienceDirect
Marine Pollution Bulletin
journal homepage: www.elsevier.com/locate/marpolbul

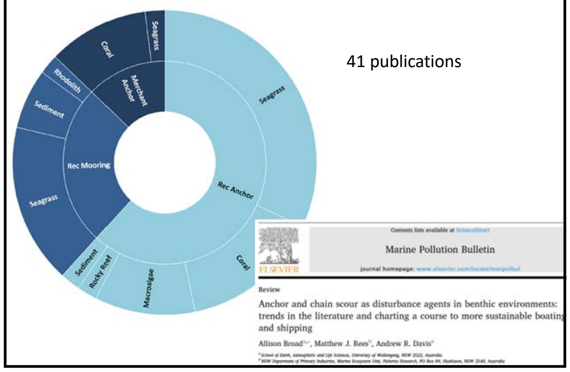
Review

Anchor and chain scour as disturbance agents in benthic environments: trends in the literature and charting a course to more sustainable boating and shipping

Allison Broad[a,*], Matthew J. Rees[b], Andrew R. Davis[a]
[a] School of Earth, Atmospheric and Life Sciences, University of Wollongong, NSW 2522, Australia
[b] NSW Department of Primary Industries, Marine Ecosystem Unit, Fisheries Research, PO Box 89, Huskisson, NSW 2540, Australia

7

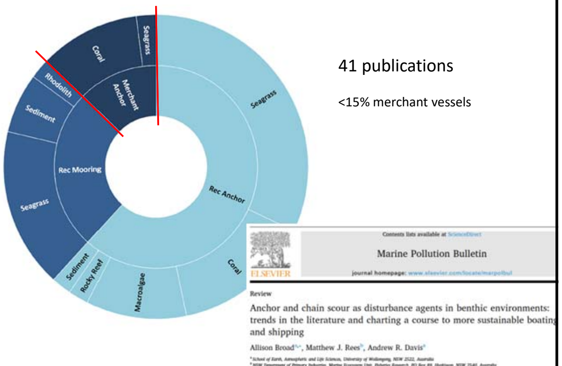
Anchoring – trends in the literature



41 publications

8

Anchoring – trends in the literature

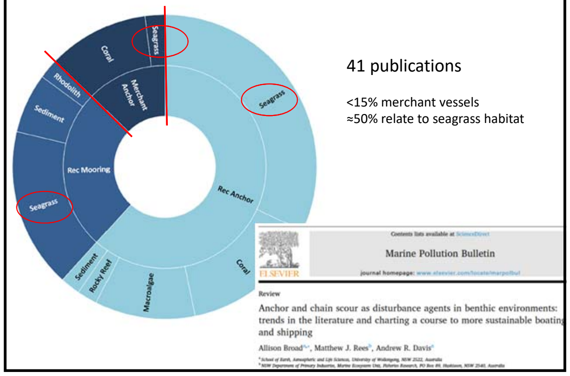


41 publications

<15% merchant vessels

9

Anchoring – trends in the literature

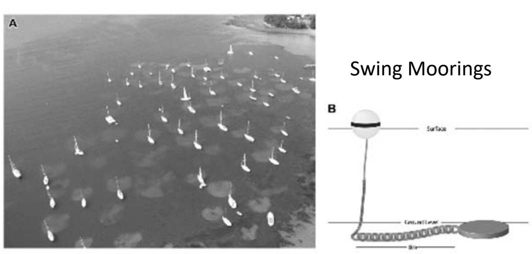


41 publications

<15% merchant vessels
≈50% relate to seagrass habitat

10

Dramatic impacts in seagrass

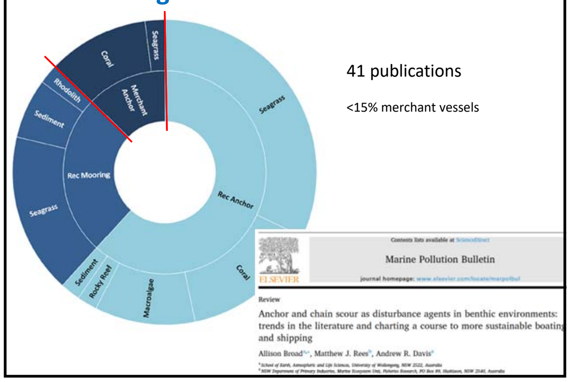


Swing Moorings

Posidonia australis meadow
Jervis Bay Marine Park, NSW Australia

11

Anchoring – trends in the literature



41 publications

<15% merchant vessels

12

Cruise ships in the Caribbean

Cruise ship threat to coral reefs 241

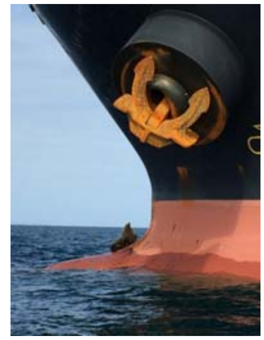
Fig. 6. Author filming deep terrace reef off George Town. Note the almost complete destruction of living reef. Depth, 22 m; chain links, 62·6 kg each.

13

Ocean-going commercial vessels

Significant unknowns surrounding potential impacts

A challenge for managers



14

Issue of global significance

15

A talk in 3 parts

(i) Background & History
(ii) Findings in relation to Port Kembla
(iii) A good news story & the future

16

Continental Shelf Research 247 (2022) 104834

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Mapping of benthic ecosystems: Key to improving the management and sustainability of anchoring practices for ocean-going vessels

Andrew R. Davis [a], Allison Broad [a], Micaela Small [b], Hazel A. Oxenford [b], Bradley Morris [c], Timothy C. Ingleton [a,c,*]

[a] Centre for Sustainable Ecosystem Solutions (CSES) and School of Earth, Atmospheric and Life Sciences, University of Wollongong, Wollongong, NSW, 2522, Australia
[b] Centre for Resource Management and Environmental Studies (CERMES), University of the West Indies, Cave Hill, Barbados
[c] Waters, Wetlands and Coasts New South Wales Department of Planning, and Environment (DPIE), Sydney, NSW, 2000, Australia

Science of the Total Environment 863 (2023) 160717

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Anchor scour from shipping and the defaunation of rocky reefs: A quantitative assessment

Allison Broad [a], Matthew Rees [b], Nathan Knott [b], Daniel Swadling [b], Matthew Hammond [b], Tim Ingleton [c], Bradley Morris [c], Andrew R. Davis [a,*]

[a] School of Earth, Atmospheric and Life Sciences, University of Wollongong, NSW 2522, Australia
[b] NSW Department of Primary Industries, Marine Ecosystem Unit, Fisheries Research, 89, Huskisson, NSW 2540, Australia

17

A focus on NSW Coast

18

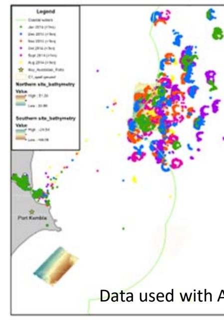
Two Busy NSW Ports

- Port of Newcastle
- Port Kembla (Wollongong)

Span the Hawkesbury Shelf Marine Bioregion

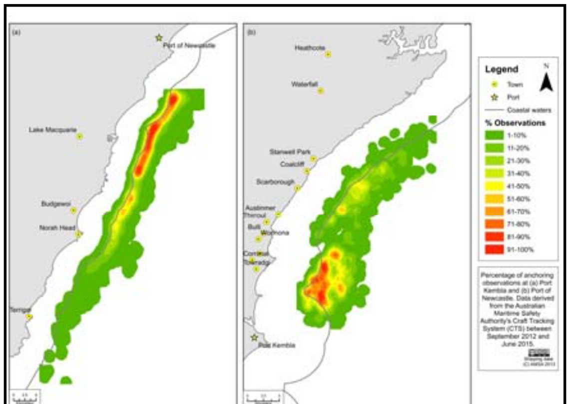
19

Craft Tracking with AIS



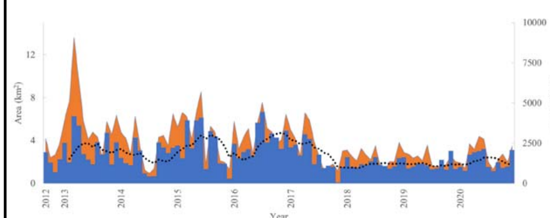
Data used with AMSA permission

20



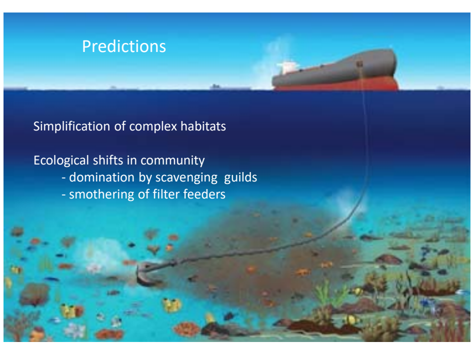
21

Port Kembla Anchoring Roadstead



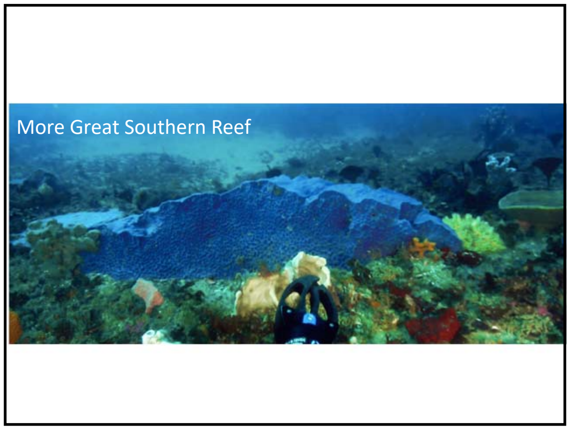
Hours, Area, Average area - dotted line (6 month moving average)

22



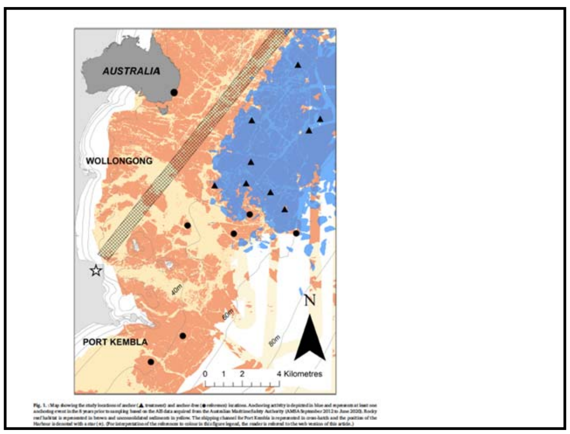
23

24

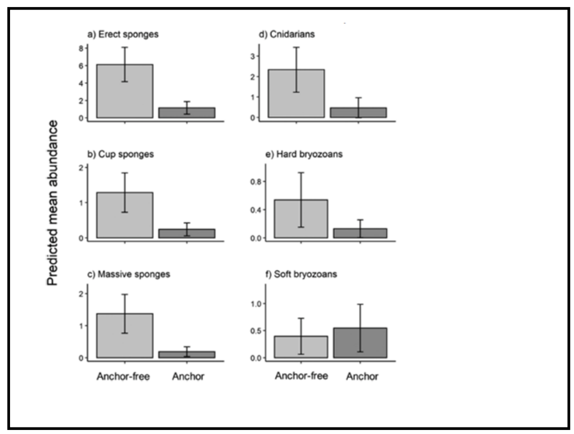


25

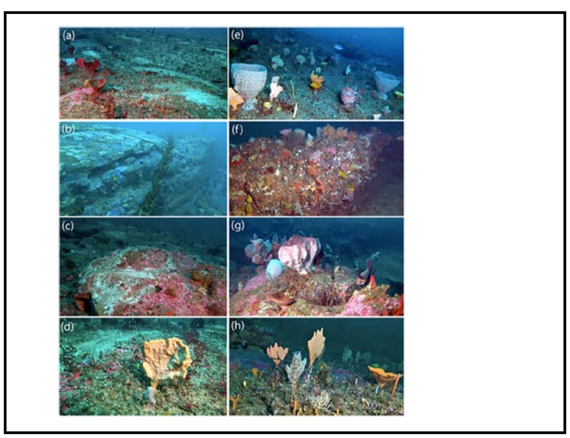
26



27

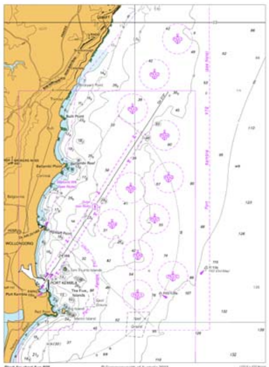


28



29

30



Designated Anchorages

>60% reduction in anchoring footprint

31

Multi-Agency Collaboration

University of Wollongong
Prof. Andy Davis
Allison Broad

NSW Dept. of Planning & Environment (DPIE)
Dr. Tim Ingleton
Dr. Brad Morris

NSW Dept. of Primary Industries (DPI)
Dr. Matt Rees
Dr. Nathan Knott

Port Authority of NSW
Sharad Bhasin

Ports NSW
Trevor Brown

32

Take home messages

- Impacts of anchoring often ignored
- Anchoring highly destructive
- Anchoring a worldwide issue
- Our focus will now shift to examining recovery

33

RE: THINK GLOBAL CHALLENGES PROGRAM UNIVERSITY OF WOLLONGONG

THE IAN POTTER FOUNDATION

NSW GOVERNMENT

NSWPorts

34

Science of the Total Environment 863 (2023) 160717

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Anchor scour from shipping and the defaunation of rocky reefs: A quantitative assessment

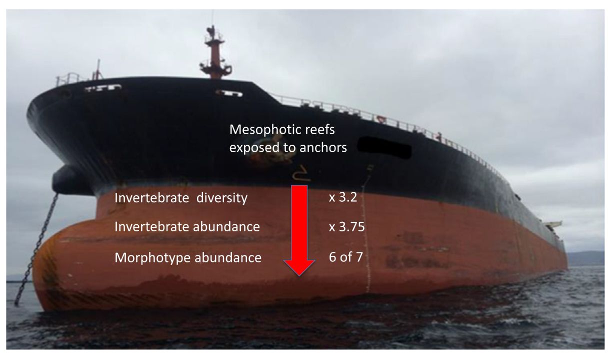
Allison Broad [a], Matthew Rees [b], Nathan Knott [b], Daniel Swadling [b], Matthew Hammond [b], Tim Ingleton [c], Bradley Morris [c], Andrew R. Davis [a,*]

[a] *School of Earth, Atmospheric and Life Sciences, University of Wollongong, NSW 2522, Australia*
[b] *NSW Department of Primary Industries, Marine Ecosystem Unit, Fisheries Research, 89, Huskisson, NSW 2540, Australia*
[c] *Waters, Wetlands and Coasts, New South Wales Department of Planning and Environment (DPE), Sydney, NSW 2000, Australia*

HIGHLIGHTS

- Assesssment of anchoring to seabed fauna from shipping is urgently needed.
- We experimentally examined how sessile biota respond to anchor scour from ships.
- Anchor scour from shipping on deep reef assemblages was highly destructive.
- Anchor scour reduced faunal richness and abundance by up to 7 fold.
- Solutions to reduce impacts exist: urgent management and legislation is warranted.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Daniel Wunderlin

Keywords:
Habitat loss
Human impacts
Anchoring
Marine invertebrates
Great Southern Reef
Disturbance

ABSTRACT

Anchor scour from shipping is increasingly recognised as a global threat to benthic marine biodiversity, yet no replicated ecological assessment exists for any seabed community. Without quantification of impacts to biota, there is substantial uncertainty for maritime stakeholders and managers of the marine estate on how these impacts can be managed or minimised. Our study focuses on a region in SE Australia with a high proportion of mesophotic reef (>30 m), where ships anchor while waiting to enter nearby ports. Temperate mesophotic rocky reefs are unique, providing a platform for a diversity of biota, including sponges, ahermatypic corals and other sessile invertebrates. They are rich in biodiversity, provide essential food resources, habitat refugia and ecosystem services for a range of economically, as well as ecologically important taxa. We examined seven representative taxa from four phyla (porifera, cnidaria, bryozoan, hydrozoa) across anchored and 'anchor-free' sites to determine which biota and which of their morphologies were most at risk. Using stereo-imagery, we assessed the richness of animal forest biota, morphology, size, and relative abundance. Our analysis revealed striking impacts to animal forests exposed to anchoring with between three and four-fold declines in morphotype richness and relative abundance. Marked compositional shifts, relative to those reefs that were anchor-free, were also apparent. Six of the seven taxonomic groups, most notably sponge morphotypes, exhibited strong negative responses to anchoring, while one morphotype, soft bryozoans, showed no difference between treatments. Our findings confirm that anchoring on reefs leads to the substantial removal of biota, with marked reductions of biodiversity and requires urgent management. The exclusion of areas of high biological value from anchorages is an important first step towards ameliorating impacts and promoting the recovery of biodiversity.

* Corresponding author.
E-mail address: adavis@uow.edu.au (A.R. Davis).

http://dx.doi.org/10.1016/j.scitotenv.2022.160717
Received 18 October 2022; Received in revised form 22 November 2022; Accepted 2 December 2022
Available online 15 December 2022

1. Introduction

Globalisation has intensified over the past century, leading to the expansion of shipping routes (Ng et al., 2018), placing marine environments under increased pressure from the inherent threats that stem from maritime activities. These threats include emissions, noise, biosecurity threats, ship strike and mechanical disturbances (Erbe et al., 2020). The maritime industry has sought to mitigate many of these impacts; in contrast anchoring from large merchant ships is a disturbance threat to marine environments that is only recently receiving attention (Davis et al., 2016; Deter et al., 2017; Metcalfe et al., 2018; Broad et al., 2020; Watson et al., 2022). Indeed, trade by ship is anticipated to double in volume by 2030, driven by population growth and globalised economies (Lloyd's Register, 2019). Consequently, the routine practice of anchoring by ships will also increase, likely placing further pressure on marine biota exposed to this disturbance (Broad et al., 2020).

Anchor disturbance, hereafter described as 'anchor scour' (Davis et al., 2016), is the act of the anchor striking the seabed, as well as abrasion of the anchor and chain over the substratum and its associated biota. Much of our understanding of the impacts of anchor scour to the seabed and its biota is drawn from recreational anchoring in shallow water (<10 m) (Broad et al., 2020). Research consistently demonstrates physical damage to habitat-forming taxa, such as seagrasses and corals, which results in either tissue damage or their complete removal (Williams, 1988; Milazzo et al., 2004; Flynn and Forrester, 2019). However, the impacts of anchor scour from ocean-going ships will undoubtedly be exponentially larger with scars from anchor drag extending hundreds of metres (Watson et al., 2020, 2022). These vessels are often hundreds of metres in length (100–450 m), deploy large anchors weighing several tonnes, as well as lengthy chain that weigh many tonnes to hold vessels fast (Davis et al., 2016). Damage to seagrass meadows from anchored ships near ports have been likened to disturbances associated with trawling (Ganteaume et al., 2005), while large cruise ships have been reported extensively damaging large areas of architecturally complex coral reef (Davis, 1977; Rogers and Garrison, 2001; Forrester et al., 2015; Small and Oxenford, 2022). In contrast, the impacts of anchor scour to rocky reef biota have never been examined in controlled studies, at any scale (Broad et al., 2020), despite their significant ecological and socio-economical value in temperate settings (Bennett et al., 2015).

Temperate reefs at mesophotic depths (30–150 m) provide a platform for animal forests, dominated by sponges, ahermatypic corals, bryozoans, hydrozoans, ascidians and other sessile fauna, to establish and grow. These animal forests provide biogenic habitats on the reefs themselves delivering valuable ecosystem services such as nutrient cycling (Bart et al., 2021), food and refuge for a diversity of associated species (Wulff, 2006; Chin et al., 2020), as well as contributing to recreational and commercial fish production (MacArthur et al., 2011; Rees et al., 2021). Compared to environments in depths able to be explored by SCUBA, mesophotic reefs, particularly those in temperate systems, are not as well understood, as they can be logistically challenging and expensive to access (James et al., 2016; Cerrano et al., 2019). Importantly, deeper ecosystems are naturally more stable environments; they experience low levels of disturbance that can make deeper-water taxa susceptible to even modest disturbances relative to their shallow water counterparts (Rocha et al., 2018; Micaroni et al., 2021). What we do know is that sessile invertebrates inhabiting deeper waters are often long-lived, with periodic, or slow growth rates and limited recruitment - all of which are indicative of extended recovery times following disturbance (Watling and Norse, 1998; Rossi et al., 2017; Prado et al., 2021). Despite the potentially dire consequences of large vessel anchoring on the biota inhabiting mesophotic reefs, these impacts have not been assessed or considered in the management of shipping activities (Davis et al., 2016; Evans et al., 2016; Watson et al., 2020; Bell et al., 2022).

In this study, we test for impacts of anchor and chain scour on temperate reefs to determine the effects to sessile animal forests. We focus on a region in SE Australia with a high proportion of reef at mesophotic depths, sustaining a diversity of fish, kelp and sessile fauna (Rees et al., 2014; Linklater et al., 2019). This system is part of the 'Great Southern Reef' (Bennett et al., 2015) and supports particularly high levels of endemism, is of great conservation significance and economic value (Van Soest et al., 2012; Evans et al., 2016; Rees et al., 2021). We predicted that mechanical disturbance from anchor and chain scour would damage, crush and remove sessile invertebrate fauna, thereby reducing their height, diversity and relative abundance. We sought to quantify the impacts of recent anchoring events and draw comparisons with nearby 'anchor-free' reference locations using a remotely operated vehicle (ROV). We deemed it unethical to direct vessels to anchor on pristine habitat and instead focused our attention on recent anchor events within an existing anchor roadstead. We used positional information for vessels (Automatic Identification System (AIS) data) to confirm that anchor-free locations had not been anchored on for at least 8 years.

2. Materials and methods

2.1. Study area and the identification of locations for assessment

This study was done along a ~30 km length of wave dominated coastline in south-eastern, Australia (Fig. 1). Ships have been shown to anchor in an area ~220 km^2 (Davis et al., 2022) in this region, in an unregulated fashion near the industrial port of Port Kembla in water depths ranging from 35 to 60 m. The seabed in this depth range is dominated by extensive rocky reef (>60 %; Linklater et al., 2019).

Shipping has had a long history of connecting industry to the world in this region. The first coal shipment left the district in 1883 and construction of the port of Port Kembla was initiated in 1900 (https://wollongong.nsw.gov.au/library/explore-our-past/your-suburb/suburbs/port-kembla accessed 20 Nov. 2022). The Port currently services the mining industry, most notably coal, represents a principal grain exporter and is the largest importer of vehicles into the state of NSW. The region is also a growing cruise ship destination. In the most recent annual reporting period, the Port hosted just over 860 visits by commercial vessels (PANSW, 2022).

To identify the anchor-roadstead and confirm the whereabouts of anchor-free reference areas we used positional information from vessels (AIS, source: Australian Maritime Safety Authority) within the GIS software ArcMap 10 (ESRI, USA). We interrogated historical AIS data within the study area (34°12′S to 34°30'S; Fig. 1) from September 2012 to June 2020 (prior data were not available). The AIS data were filtered for vessels that were identified 'at anchor' and excluded any vessels traveling at speeds >1 knot (Davis et al., 2016). This generated a series of anchoring arcs, depicting the ships movement around the anchor that were then used to estimate the area of seafloor disturbed by anchoring. The outer perimeter of the anchor arcs were concentrically reduced by one third to give a conservative estimate of the area of seabed impacted by the anchor chain (after Deter et al., 2017). The reduced arc areas were overlaid on multibeam-derived raster layers (NSW DPE, 2022) (www.seed.nsw.gov.au) allowing us to identify the historical locations of anchor activity on rocky reef and appropriate 'anchor-free' reference locations. Reference and anchored locations were at similar depths; the mean depth (±1 SE) for anchored locations was 43.39 m (±2.21) compared to 43.53 m (±2.33) for anchor-free locations, and AIS data confirmed that anchoring had not occurred in these locations for at least 8 years. Anchored locations were identified in real-time using marinetraffic.com (https://www.marinetraffic.com/en/ais/home/ accessed Nov. 2020) and the aforementioned methods to identify the area impacted on the seabed for investigation. Survey locations were characterised as 'anchor-free' if anchoring had not occurred within the previous 8 years and was categorised as 'disturbed' otherwise. To be included in our survey of seafloor disturbance, vessels had to have been at anchor for at least 24 h, and almost all of our assessments of epifauna were made within seven days of the vessel having raised anchor.

2.2. Field surveys

We recorded a total of fifty transects of 50 m length (anchored 26; 'anchor-free' 24) across 15 locations (anchored 9; 'anchor-free' 6;

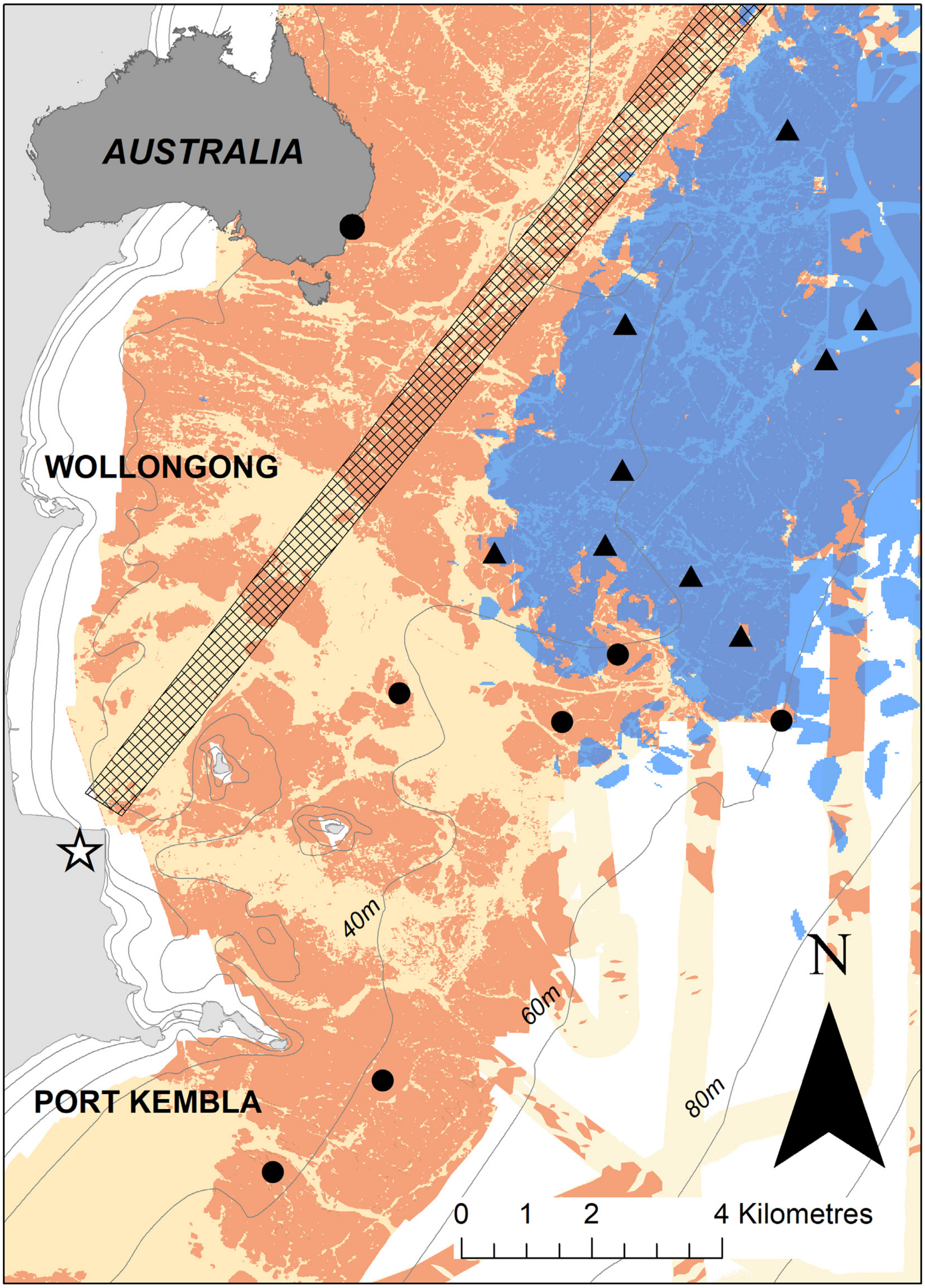


Fig. 1. : Map showing the study locations of anchor (▲ treatment) and anchor-free (● reference) locations. Anchoring activity is depicted in blue and represents at least one anchoring event in the 8 years prior to sampling based on the AIS data acquired from the Australian Maritime Safety Authority (AMSA September 2012 to June 2020). Rocky reef habitat is represented in brown and unconsolidated sediments in yellow. The shipping channel for Port Kembla is represented in cross-hatch and the position of the Harbour is denoted with a star (☆). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 1; see Supplemental Table S1). Field investigations were done in the austral Spring of 2020 using a Remotely Operated Vehicle (BlueRobotics BlueROV2) equipped with stereo cameras (see Supplemental Fig. S1). Transects were recorded by manoeuvring the ROV system ~0.5 m above the reef. Continuous footage at each location was split into 50 m transects with a minimum separation of 30 m between transects. For anchored locations, the position of the transects was determined using the AIS data to ensure all transects fell within the predicted anchoring footprint of each vessel assessed. Where possible, transects were positioned in the middle of the predicted anchoring footprint to increase the likelihood of surveying recently scoured seafloor. As the size of the anchoring footprint varied, between 2 and 6 transects were completed per anchored location. In ArcMap, transect distance was calculated by plotting the tracks of the surface vessel as the ROV was piloted directly beneath this vessel. Transects are depicted within ‘anchoring events’ in supplemental data (Supplemental Fig. S2).

2.3. Invertebrate classification and analysis of stereo imagery

As taxa could not be reliably identified from imagery, we used the CATAMI classification scheme (Collaborative and Automated Tools for Analysis of Marine Imagery) (Althaus et al., 2015; Schönberg, 2021). Taxa were classified based on their phylum as well as their shape or growth forms (see Supplemental Table S2; Fig. S3).

The use of two forward-facing cameras (Sony x3000) in stereo format allowed us to confirm the height of the ROV above the seafloor, standardise a field of view (FOV) for estimates of relative abundance (the total number of individuals of all morphotypes observed for each frame), as well as determine the height of observed taxa. The stereo cameras were calibrated using the software CAL (Seagis Pty www.seagis.com.au) prior to fieldwork commencing and again upon completion. Stereo-video imagery was annotated using ‘EventMeasure’ ® software (www.seagis.com.au/event.htm) in conjunction with the CATAMI classification scheme (see Supplemental Table S2; Fig. S3). Sessile invertebrate abundance and diversity were quantified from a series of still video frames, with biota beyond 1.5 m from the cameras excluded from counts (see Supplemental Fig. S4). We aimed to examine 20 equally spaced frames per transect, with all biota within each still frame analysed. In circumstances where the frame was compromised (*i.e.* the elevation of the ROV above the seabed was too high; issues with illumination of the bottom; or the presence of patches of sand), we then moved to the next appropriate frame. In some transects the annotation of 20 evenly spaced frames was not achievable and, in these circumstances, a reduced number of frames were examined. In sampling from the 50 transects we analysed a total of 889 images, 464 from reefs exposed to anchoring and 425 from anchor-free reefs (see Supplemental Table S1). A blinded procedure was used for image processing, where the treatment group of each frame was unknown to the annotator.

Size estimates were drawn from both cameras and only erect sessile taxa >5 cm (height or width) were quantified. Encrusting fauna were too difficult to distinguish with the forward-facing cameras and were not assessed. Resolution of the stereo-system allowed measurement of dimensions with a 5 % error (Garner et al., 2021).

2.4. Statistical analyses

To test for change in animal forests between the anchored and anchor-free treatments we used generalised linear mixed-effects models (GLMMs, link = “log”; Bolker et al., 2009) implemented with the package “glmmTMB” (Brooks et al., 2017) in R. Models were fitted for (i) overall relative abundance (total number of individuals of all morphotypes observed for each frame); (ii) morphotype richness (total number of morphotypes observed for each frame); (iii) morphotype abundance of common phyla (>7 % occurrence across all frames). To determine the most appropriate distribution, model residuals were assessed visually. The Poisson distribution provided a good fit to the total morphotype richness. A negative binomial distribution provided a good fit to the total relative abundance and relative abundance of common morphotypes. The survey ‘Location’ and ‘Transect’ were included as random effects in each model, where ‘Transect’ was nested within ‘Location’. We plotted model coefficients and 95 % confidence intervals to determine important treatment effects (anchored/anchor-free) which were determined if the limits of the model coefficients did not cross zero. Positive values with no intersection with zero support a significant positive effect and similarly, negative values with no intersection demonstrate detrimental effects from treatments. Magnitude of decline was calculated by dividing the ‘anchor-free’ predicted mean abundance by the ‘anchored’ predicted mean abundance for each response measure.

Further exploration of multivariate data was done using joint statistical modeling and Latent Variable Models using the ‘boral’ package (Hui, 2016) in R. As random effects are not possible in this analysis, data were aggregated by sites where abundances for each morphotype was summed. Using a Latent Variable Model (LVM) we created a Bayesian ordination to visualise the overarching trends between anchored and anchor-free transects, with regard to morphotype composition of the invertebrate assemblage. To account for differences in sampling effort between transects, the log number of frames processed was included as an offset. A negative binomial distribution was used, and row effects were set to fixed. The role of the latent variables in LVMs is to account for unknown or unmeasured variables, and, by inducing correlations between taxa, enable an unconstrained ordination for visualising transects and species patterns (Parsons et al., 2016).

Kernel density estimates (KDE) were constructed for the length-frequency data for each sessile invertebrate morphotype group in anchored and anchor-free reefs following Langlois et al. (2012). The statistical test between the pairs of length-frequency distributions collected by anchor and anchor-free treatments, for each species, was based on a null model of no difference and a permutation test. To construct the test, the geometric mean between the bandwidths were calculated for each morphospecies or phyla. This avoids the effect of differences in sample size. The mean bandwidths for each sessile invertebrate morphotype or phyla were then used to construct KDE for both anchored and anchor-free reefs. If the length frequency of sessile taxa on anchored and anchor-free reefs represent the same distribution, the KDE should only differ in minor ways due to within population variance and sampling effects. Finally, we report our statistical outcomes using

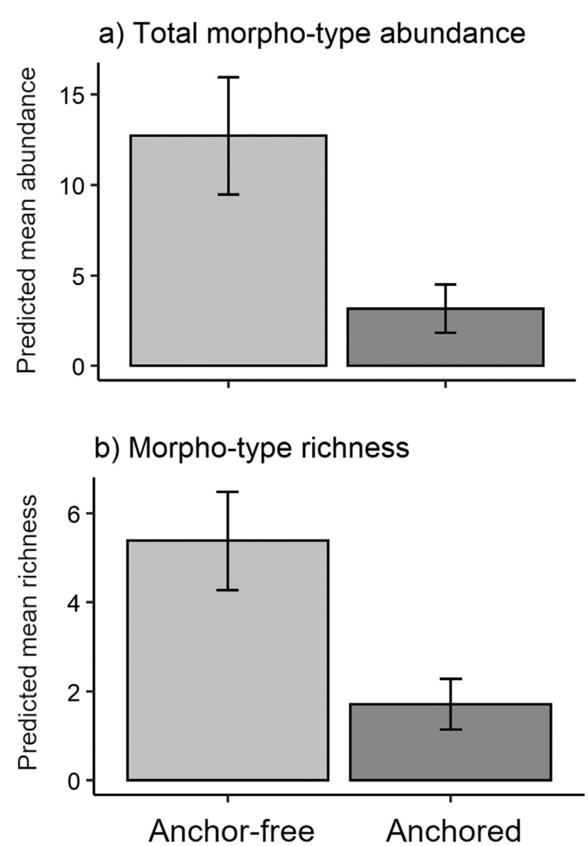


Fig. 2. Mean predictions of the total relative abundances of key sessile invertebrate morphotypes (taxa occurring on >7 % of frames analysed and based on the CATAMI Classification scheme) and morphotype richness per still video frame in anchor-free (light grey) and anchored (dark grey) locations from Generalised Linear Mixed Models (GLMMs). Error bars $\pm 2 \times$ estimated SE, as reported from the GLMMs.

evidence-based language associated with *P*-value ranges as described in Muff et al. (2022). All statistical analyses were done in the statistical computing program 'R' (R Core Team, 2020) and plots created using the ggplot2 package (Wickham, 2016).

3. Results

We detected marked changes in the biota on reefs exposed to anchoring. The combined relative abundance and morphotype richness estimates of all erect sessile taxa were 3.75 and 3.2 times lower on anchored reefs relative to 'anchor-free' (control) reefs respectively ($P < 0.0001$; Fig. 2; also see Supplemental Table S3), We also observed substantial shifts in the overall assemblage on reefs exposed to anchor scour, as depicted in multivariate space (Fig. 3).

Of the 7 morphotypes examined, 3 phyla consisting of 6 morphotypes responded negatively to anchor disturbance. These included sponges (massive, erect and cup-like), cnidarians (octocorals and stony corals combined) and hard bryozoans (Fig. 4; see Supplemental Table S3; Fig. S3). There was very strong evidence that sponges, the most abundant sessile fauna in the study area, exhibited the largest declines in relative abundance in response to anchor disturbance. Among morphotypes in this phylum, massive sponges were impacted the most by anchor scour (7.4-fold decrease; $P < 0.0001$), followed by erect sponges (5.75-fold decrease; $P < 0.0001$) and cup-like morphotypes (4.75-fold decrease; $P < 0.001$) (Fig. 5 (a-c); see Supplemental Fig. S3 (c-e)). Similarly, hard bryozoans showed strong evidence of impacts (4-fold reductions, $P < 0.001$), whilst cnidarians also had large, 5-fold declines relative to anchor-free locations. We emphasise though that for cnidarians their abundance was highly variable and resulted in weak evidence ($P = 0.055$) of their response to anchor scour (Figs. 4, 5 (d-e); see Supplemental Table 3S (f)). Not all erect sessile taxa responded negatively to anchor scour. Soft bodied bryozoans (dendroid and foliaceous morphotypes combined) provided no evidence of decline in the presence of anchors ($P = 0.312$) (Figs. 4, 5 (f); see Supplemental Table S3 (h)). Hydroids and ascidians (3 morphotypes) could not properly be examined as they were observed in low abundance and were patchily distributed (occurring in <7 % of transect frames). They were excluded from our analysis.

There was no evidence of decreases in the predicted length-frequency distributions of any of the seven morphotypes on exposure to anchoring, as their size distributions were variable across transects. However, when all sponge morphotypes were combined, the frequency of sponge fauna in the 9-18 cm range showed some evidence of being moderately taller in anchor-free locations (Fig. 6; $P = 0.046$). Sponge sizes ranged from 5 to 55 cm in height. Importantly, even quite large erect sponges (>18 cm in height) were apparent on the reefs exposed to anchoring.

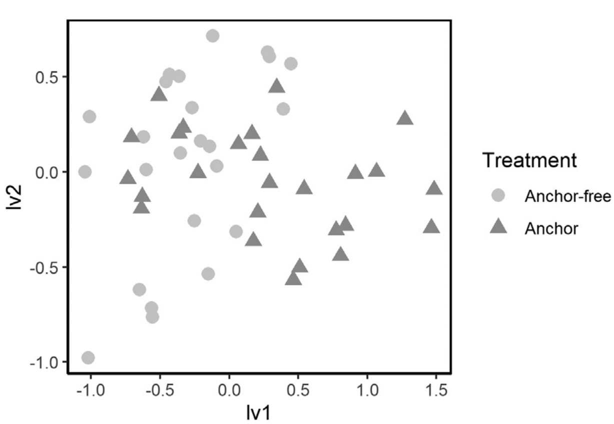


Fig. 3. Biplot showing the Latent Variable Model (LVM) unconstrained ordination of transects on reefs exposed to anchoring (triangles) and those that were 'anchor-free' (circles).

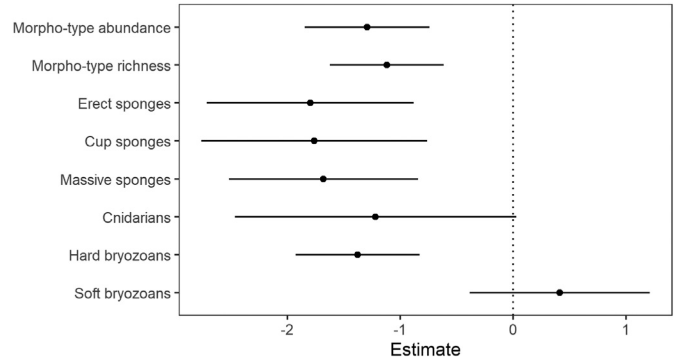


Fig. 4. Coefficients from model outputs for the fixed effect of "Treatment" (anchoring) for sessile invertebrate taxa. Groupings were based on morphotypes according to the CATAMI classification scheme examining (i) overall morphotype relative abundance (all morphotypes combined); (ii) (morphotype richness) and (iii) the relative abundance of specified morphotypes found to respond to treatments on 'anchored' and 'anchor-free' reefs. Data are means ±95 % confidence intervals around the predictions. Coefficients from the model outputs for the random nested factors are plotted with significance. A significant effect of anchoring was supported when the 95 % confidence limits of model coefficients did not cross zero, which are also supported by *p*-values presented in model output summary results (see Supplemental Table S3). Negative values indicate that the anchor treatment had a negative effect on relative abundance, while positive values support a positive effect.

4. Discussion

We observed unequivocal, direct effects of anchor damage to key animal forest taxa resulting in the defaunation of these assemblages on temperate rocky reefs over large spatial scales (10's km; Supplemental Fig. S2, see also Davis et al., 2022). Anchoring appears to remove the majority of erect fauna it comes into contact with, directly affecting the biodiversity of sponges, corals and bryozoans, notwithstanding the indirect effects to the vagile species that rely upon them as essential habitat. The architecture of the reef also suffered significant damage; we observed fractured rock and rubble in locations where anchors had been dropped and white marks on the reef indicative of anchor and chain scour (Fig. 7a-d; also see Supplemental Fig. S5). Most strikingly, these areas were visually largely denuded of large epibiota. Every morphotype of the sessile fauna we examined, with the exception of soft bryozoans, were reduced in abundance on anchored reefs. Sponges, the dominant fauna on these reefs, were dramatically impacted with reductions in abundance of up-to 7-fold. The abundances of hard-bodied bryozoans were reduced by 4-fold on anchored reefs, while 5-fold declines across cnidarian taxa were also observed. In contrast, soft bryozoans were the only group that showed no apparent response to anchoring. There was little evidence of differences in the height of sessile fauna between reefs exposed to anchoring and those that were anchor-free. This is consistent with the removal of entire animals by anchor scour rather than the simple reduction of their height. We also frequently observed dislodged sponges in anchored locations. The complete removal of animals will hinder recovery, as this will require recruitment of new individuals, that is often slow or episodic (Knott et al., 2004), rather than regrowth.

Mechanical damage as a result of anchor scour has been commonly observed on tropical reefs; the rigidity of stony corals renders them particularly vulnerable to anchoring activity (Davis, 1977; Smith, 1988). Though we know of no other controlled examinations of anchoring impacts to temperate reef communities, our findings mirror effects observed on tropical reefs where 7-fold (Rogers and Garrison, 2001) and ~2-fold (Forrester et al., 2015) decreases in coral cover have been reported. We anticipate that recovery from disturbances to mesophotic habitats will be slow owing to sporadic recruitment (Dayton et al., 2013; Rossi et al., 2017)

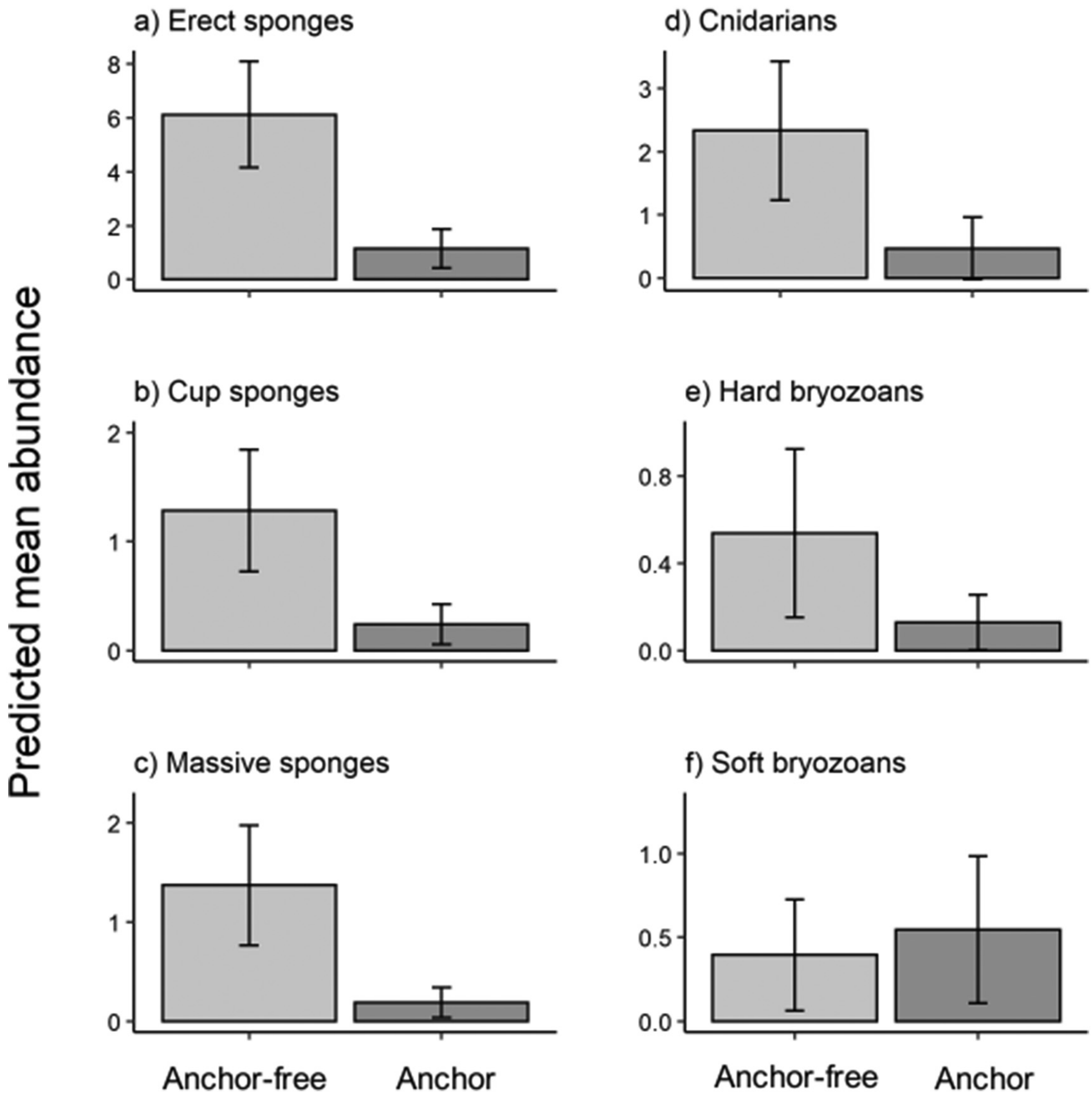


Fig. 5. Mean predictions of the relative abundances of key sessile invertebrate morphotypes in anchor-free (light grey) and anchored (dark grey) locations (based on the CATAMI Classification scheme) per still video frame from Generalised Linear Mixed Models (GLMMs) (note the differences in scale on y axes). Error bars are $\pm 2 \times$ estimated SE from GLMMs.

and the life-history traits of many habitat forming taxa (Dayton, 1979; Leys and Lauzon, 1998; McMurray et al., 2008; Benedetti et al., 2016). A lack of rigidity may explain why soft bryozoans appear unaffected by anchor scour and may render this morphotype resilient to mechanical disturbances, although higher rates of recruitment cannot be ruled out (Keough, 1984). Previous research examining benthic fishing effects on temperate reef epibiota have shown that flexible taxa appear to be resilient to trawling (Van Dolah et al., 1987; Freese et al., 1999).

Damage stemming from one-off anchoring 'events' by large, ocean-going vessels can occur over formidable spatial scales on benthic habitat (Rogers and Garrison, 2001; Forrester et al., 2015; Watson et al., 2022). For example, on tropical Caribbean reefs, Davis (1977) reported that a single 'event' resulted in the destruction of ~10,000m^2 of coral reef. Large-scale disturbance has also been observed in temperate waters across a range of habitats including seagrass in the Mediterranean (Ganteaume et al., 2005; Boudouresque et al., 2009) as well as unconsolidated sediments in Australia (Davis et al., 2016) and New Zealand (Watson et al., 2020, 2022). At our study location, long-term AIS data reveals that anchoring disturbance can occur along stretches of reef many 10's of km in length (Fig. 1). The scale of disturbance associated with anchoring ocean-going ships is only now beginning to be appreciated (Davis et al., 2022; Watson et al., 2022).

Removal of large, complex, three-dimensional animal forests may have far reaching implications for reef-associated taxa (Alvarez-Filip et al., 2009; Rossi, 2013; Maldonado et al., 2017). The ecosystem functions that invertebrates provide sustain reef-associated fauna. The simplification or loss of sponges will result in the direct loss of food resources for these taxa such gastropods, nudibranchs, spiny lobsters (MacArthur et al., 2011) as well as fish that feed directly on sponge tissue (Wulff, 2006). Beyond food, animal forests provide important habitat to a raft of biota (Rossi et al., 2017; Bell et al., 2020). Reductions in animal forest fauna will inevitably flow-on to the reduction of small vagile invertebrates that dwell on their surfaces and within their tissues (Poore et al., 2000; Wulff, 2006). Abundances of these small invertebrate taxa have been found to be several orders of magnitude greater on a number of sponges when compared to the surrounding substrata, with many species specific to their host sponge (Chin et al., 2020). Moreover, research examining the loss or simplification of erect sessile fauna has demonstrated significant declines in fish diversity, as well as the relative abundance of fish (Chong-Seng et al., 2012; Forrester et al., 2015; Flynn and Forrester, 2019). On the positive side of the ledger,

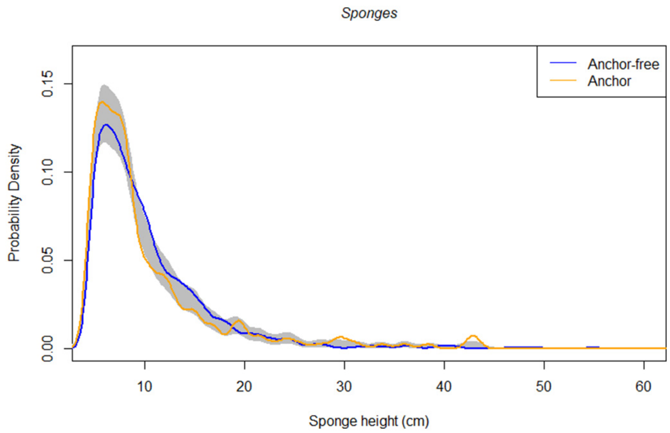


Fig. 6. Height-frequency distribution for all sponges sampled using stereo-ROV ($P < 0.05$). Orange and blue lines represent the kernel density estimate (KDE) probability density functions of "anchor" and "anchor-free" length-frequency data, respectively. The grey band represents a range of ± one standard error around the null model of no difference between the two KDEs. Areas where the lines do not intersect the grey band indicate where significant differences in the length-frequency distribution are likely. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the continued presence of large sponges in anchored locations in our study may serve enhance subsequent recovery.

Impacts on biota aside, we also observed significant damage to the architecture of the reef. When we viewed an anchor *in-situ,* we observed broken reef, damaged rock ledges, along with, overturned, cleaved or crushed boulders (see Supplemental Fig. S5). Duffy (2009) argues that a combination of biodiversity loss as well as abiotic habitat alteration will often have greater impacts to overall ecological processes than species loss alone. The breakdown and simplification of rocky reef structure not only poses an issue for epifauna that are more abundant on rugose reefs (Rees et al., 2014) but reef-associated taxa as well. Several fish species show elevated population sizes (Krieger, 1993; Rees et al., 2018) or improved survivorship and growth on rugose reefs (Tupper and Boutilier, 1995). Recovery experiments in the Caribbean examining the survival of coral fragments and recruits after an anchoring event reported low survival and limited recovery attributed to the instability of the broken substratum (Rogers and Garrison, 2001). There is evidence of widespread loss of reef complexity on tropical Caribbean reefs (Alvarez-Filip et al., 2009), and there is building evidence, albeit anecdotal, of the break-down of rocky reef substrata in both tropical settings and temperate reefs (see supporting material in Broad et al., 2020).

Currently, anchor disturbance is largely unmanaged, hence, there is an urgent need for action from stakeholders associated with maritime industries (Davis et al., 2016). As a precursor to the successful management of anchoring, a detailed understanding of the nature of the seabed is required and should ensure the identification of habitats of significant conservation value (Broad et al., 2020; Davis et al., 2022). Well-planned, designated anchorages can be used to identify good 'holding ground' for vessels near ports and position ships away from sensitive reef, or other ecologically sensitive habitat. As an example of reducing the anchoring footprint, the footprint in our study currently spans ~88 km^2, yet with the introduction of designated anchorages the area of direct anchor damage could be substantially reduced. Another important element of reducing anchoring impacts is ensuring that marine managers are supported by policies that regulate this activity with greater consideration of seabed environments generally. This will require cooperation and collaboration between stakeholders, including the shipping Industry, international agencies (such as the International Maritime Organisation) and all levels of Government. Decision makers need to strike a balance between, social, economic and environmental considerations and determine what level of impact to biologically valuable seabeds, if any, is acceptable.

5. Conclusion

Globally, the structure and function of mesophotic rocky reef communities exposed to ongoing mechanical disturbances from marine industries are deteriorating (Aburto-Oropeza et al., 2015; Evans et al., 2016; Enrichetti et al., 2019; Bell et al., 2022). The pervasive impacts of anchor scour have largely been overlooked when considering the impacts of shipping to marine fauna (Erbe et al., 2020), resulting in this disturbance being poorly characterised (Broad et al., 2020). In this study we demonstrate that anchor scour from large ships has deleterious impacts to sessile biota on temperate mesophotic reefs. We provide evidence that anchor scour dramatically reduces the relative abundance and diversity of almost all of the erect animal taxa examined (6/7 morphotypes). Drastic reductions of sessile biota are likely to have long lasting impacts on reefs owing to the life-history traits of these habitat forming taxa, as well as the loss of three-dimensional biogenic habitat for associated taxa (Alvarez-Filip et al., 2009; Rossi, 2013). Failure to manage the impacts stemming from anchoring activities will result in a reduction of biodiversity, ecosystem services and compromise valuable fisheries resources. The defaunation of these valuable seabed environments, over large spatial scales (McCauley et al., 2015; Davis et al., 2022) emphasises that management, further investigation and monitoring is paramount (Frid, 2003).

CRediT authorship contribution statement

AB, MR, NK and ARD conceived the ideas and designed the methodology. AB, MR, DS and MH collected the data. MR, TI and BM analysed the data. All authors contributed critically to the drafts and gave final approval for publication.

Data availability

Data will be made available on request.

Declaration of competing interest

None of the authors have interests to declare.

Acknowledgements

We thank the Ian Potter Foundation and the Global Challenges Program, University of Wollongong (UOW) for supporting our 'anchor scour' research from its inception. AB has been supported by an Australian Government Research Training Program (AGRTP) scholarship and wishes to thank the Max Day Environmental Science Fellowship Award (Australian Academy of Science) and the Paddy Pallin Research Grant (Royal Zoological Society of New South Wales) for financial support. This research was further funded by the NSW Government under the Marine Estate Management Strategy. The ten-year Strategy was developed by the NSW Marine Estate Management Authority to coordinate the management of the marine estate. We are grateful to Merrick Ekins, Phil Aldersade and Jan Watson for classification guidance for porifera, cnidarian and hydroid morphotypes based on imagery. Representatives from Transport NSW and the Port Authority of NSW provided comments on a late draft. Finally, we thank Jason Delamont for assistance with video annotation and Rachel Przeslawski for reviewing a draft of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.160717.

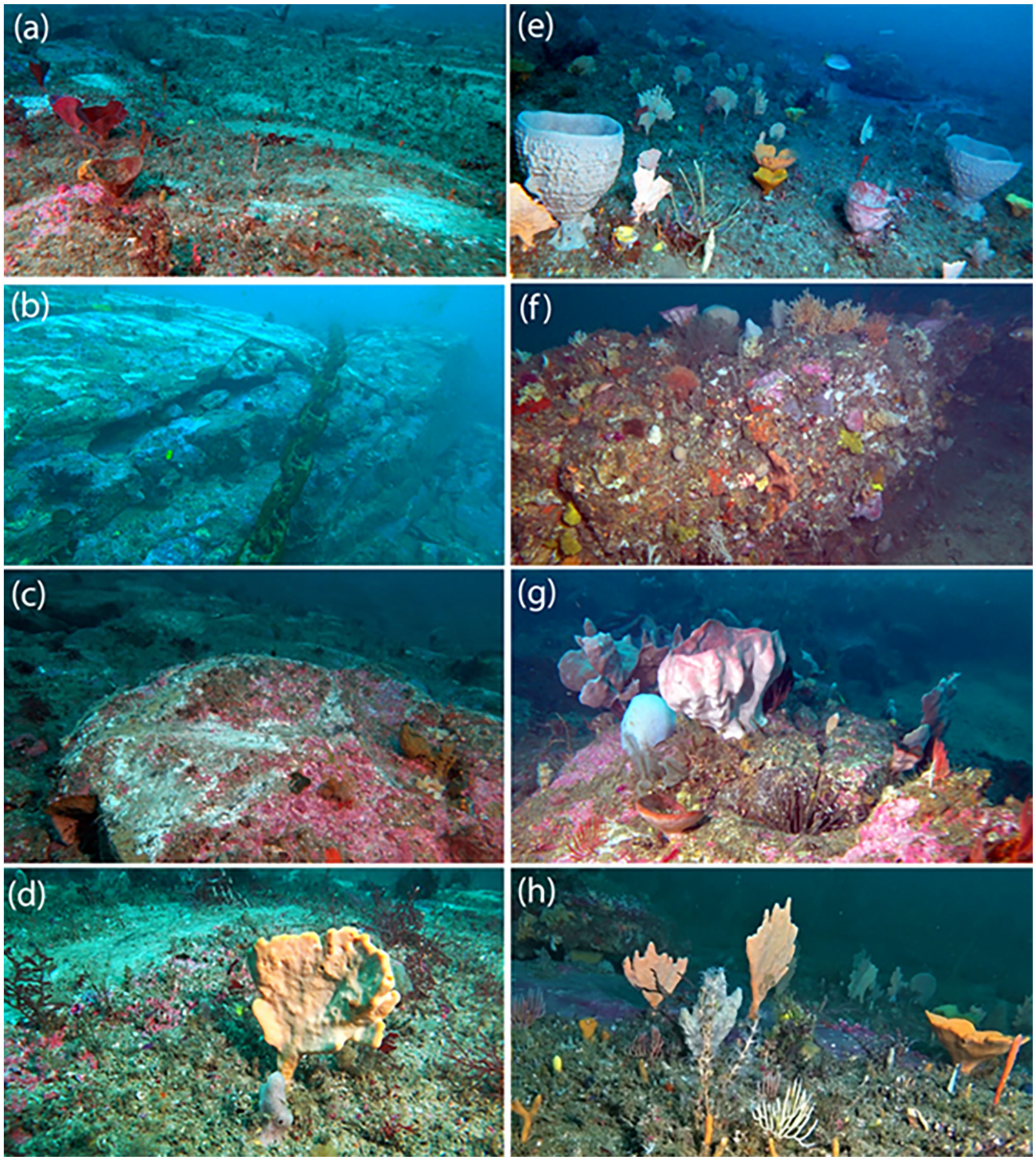


Fig. 7. ROV imagery of deep-water (35-55 m) rocky reef offshore of Wollongong; **(a-d)** Imagery taken from areas scoured by anchoring and evidence of chain scour tracks (white marks) on the rocky substratum (note the anchor chain on the substratum in **(b)**; **(e-h)** 'anchor-free' reference locations of similar topography depicting similar habitat in undisturbed areas.

References

Aburto-Oropeza, O., Ezcurra, E., Moxley, J., Sánchez-Rodríguez, A., Mascareñas-Osorio, I., Sánchez-Ortiz, C., Erisman, B., Ricketts, T., 2015. A framework to assess the health of rocky reefs linking geomorphology, community assemblage, and fish biomass. Ecol. Indic. 52, 353–361. https://doi.org/10.1016/j.ecolind.2014.12.006.

Althaus, F., Hill, N., Ferrari Legorreta, R., Edwards, L., Przeslawski, R., Schoenberg, C., Stuart-Smith, R., Barrett, N., Edgar, G., Colquhoun, J., Tran, M., Jordan, A., Rees, T., Gowlett-Holmes, K., 2015. A standardised vocabulary for identifying benthic biota and substrata from underwater imagery: the CATAMI classification scheme. PLoS ONE 10, e0141039. https://doi.org/10.1371/journal.pone.0141039 doi:10.e0141039.

Alvarez-Filip, L., Dulvy, N.K., Gill, J.A., Côté, I.M., Watkinson, A.R., 2009. Flattening of Caribbean coral reefs: region-wide declines in architectural complexity. Proc. R. Soc. B Biol. Sci. 276, 3019–3025. http://www.jstor.org/stable/30244103.

Bart, M.C., Hudspith, M., Rapp, H.T., Verdonschot, P.F.M., de Goeij, J.M., 2021. A deep-sea sponge loop? Sponges transfer dissolved and particulate organic carbon and nitrogen to associated fauna. Front. Mar. Sci. 8, 604879. https://doi.org/10.3389/fmars.2021.604879.

Bell, J.J., McGrath, E., Kandler, N.M., Marlow, J., Beepat, S.S., Bachtiar, R., Shaffer, M.R., Mortimer, C., Micaroni, V., Mobilia, V., Rovellini, A., Harris, B., Farnham, E., Strano, F., Carballo, J.L., 2020. Interocean patterns in shallow water sponge assemblage structure and function. Biol. Rev. 95, 1720–1758. https://doi.org/10.1111/brv.12637.

Bell, J.J., Micaroni, V., Harris, B., Strano, F., Broadribb, M., Rogers, A., 2022. Global status, impacts, and management of rocky temperate mesophotic ecosystems. Conserv. Biol. e13945. https://doi.org/10.1111/cobi.13945.

Benedetti, M.C., Priori, C., Erra, F., Santangelo, G., 2016. Growth patterns in mesophotic octocorals: timing the branching process in the highly-valuable Mediterranean Corallium rubrum. Estuar. Coast. Shelf Sci. 171, 106–110. https://doi.org/10.1016/j.ecss.2015.12.026.

Bennett, S., Wernberg, T., Connell, S.D., Hobday, A.J., Johnson, C.R., Poloczanska, E.S., 2015. The 'Great southern Reef': social, ecological and economic value of Australia's neglected kelp forests. Mar. Freshw. Res. 67, 47–56. https://doi.org/10.1071/MF15232.

Bolker, B.M., Brooks, M.E., Clark, C.J., Geange, S., Poulsen, J.R., Stevens, M.H., White, J., 2009. Generalized linear mixed models: a practical guide for ecology and evolution. Trends Ecol. Evol. 24, 127–135. https://doi.org/10.1016/j.tree.2008.10.008.

Boudouresque, C.F., Bernard, G., Pergent, G., Shili, A., Verlaque, M., 2009. Regression of Mediterranean seagrasses caused by natural processes and anthropogenic disturbances and stress, a critical review. Bot. Mar. 52, 395–418. https://doi.org/10.1515/BOT.2009.057.

Broad, A., Rees, M.J., Davis, A.R., 2020. Anchor and chain scour as disturbance agents in benthic environments: trends in the literature and charting a course to more sustainable ting and shipping. Mar. Poll. Bull. 161, 111683. https://doi.org/10.1016/j.marpolbul.2020.111683.

Brooks, M.E., Kristensen, K., van Benthem, K.J., Magnusson, A., Berg, C.W., Nielsen, A., Skaug, H.J., Maechler, M., Bolker, B.M., 2017. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. R J. 9, 378–400. https://journal.r-project.org/archive/2017/RJ-2017-066/index.html.

Cerrano, C., Bastari, A., Calcinai, B., Di Camillo, C., Pica, D., Puce, S., Valisano, L., Torsani, F., 2019. Temperate mesophotic ecosystems: gaps and perspectives of an emerging conservation challenge for the Mediterranean Sea. Eur. Zool. J. 86, 370–388. https://10.1080/24750263.2019.1677790.

Chin, Y.Y., Prince, J., Kendrick, G., Wahab, M.A.A., 2020. Sponges in shallow tropical and temperate reefs are important habitats for marine invertebrate biodiversity. Mar. Biol. 167, 164. https://doi.org/10.1007/s00227-020-03771-1.

Chong-Seng, K.M., Mannering, T.D., Pratchett, M.S., Bellwood, D.R., Graham, N.A.J., 2012. The influence of coral reef benthic condition on associated fish assemblages. PLoS ONE 7, e42167. https://doi.org/10.1371/journal.pone.0042167.

Davis, A.R., Broad, A., Gullett, W., Reveley, J., Steele, C., Schofield, C., 2016. Anchors away? The impacts of anchor scour by ocean-going vessels and potential response options. Mar. Pol. 73, 1–7. https://doi.org/10.1016/j.marpol.2016.07.021.

Davis, A.R., Broad, A., Small, S., Oxenford, H.A., Morris, B., Ingleton, T.C., 2022. Mapping of benthic ecosystems: key to improving the management and sustainability of anchoring practices for ocean-going vessels. Cont. Shelf Res. 247, 104834. https://doi.org/10.1016/j.csr.2022.104834.

Davis, G.E., 1977. Anchor damage to a coral reef on the coast of Florida. Biol. Conserv. 11, 29–34. https://doi.org/10.1016/0006-3207(77)90024-6.

Dayton, P.K., 1979. Observations of growth, dispersal and population dynamics of some sponges in McMurdo Sound, Antarctica. Colloq. Int. du CNRS 291, 271–282.

Dayton, P.K., Kim, S., Jarrell, S.C., Oliver, J.S., Hammerstrom, K., Fisher, J.L., O'Connor, K., Barber, J.S., Robilliard, G., Barry, J., Thurber, A.R., Conlan, K., 2013. Recruitment, Growth and Mortality of an Antarctic Hexactinellid Sponge, Anoxycalyx joubini. PLoS ONE 8, e56939. https://doi.org/10.1371/journal.pone.0056939.

Deter, J., Lozupone, X., Inacio, A., Boissery, P., Holon, F., 2017. Boat anchoring pressure on coastal seabed, quantification and bias estimation using AIS data. Mar. Poll. Bull. 123, 175–181. https://doi.org/10.1016/j.marpolbul.2017.08.065.

Duffy, J.E., 2009. Why biodiversity is important to the functioning of real-world ecosystems. Front. Ecol. Environ. 7, 437–444. https://doi.org/10.1890/070195.

Enrichetti, F., Dominguez-Carrió, C., Toma, M., Bavestrello, G., Betti, F., Canese, S., 2019. Megabenthic communities of the Ligurian deep continental shelf and shelf break (NW Mediterranean Sea). PLoS ONE 14, e0223949. https://doi.org/10.1371/journal.pone.0223949.

Erbe, C., Smith, J.N., Redfern, J.V., Peel, D., 2020. Editorial: impacts of shipping on marine fauna. Front. Mar. Sci. 7, 637. https://doi.org/10.3389/fmars.2020.00637.

Evans, K., Bax, N.J., Smith, D.C., 2016. Marine environment. In: Australia state of the environment 2016, Australian Government Department of the Environment and Energy, Canberra. https://soe.environment.gov.au/theme/marine-environment https://doi.org/10.4226/94/58b657ea7c296.

Flynn, R.L., Forrester, G.E., 2019. Boat anchoring contributes substantially to coral reef degradation in the British Virgin Islands. Peer J. 23, e7010. https://doi.org/10.7717/peerj.7010.

Forrester, G.E., Flynn, R.L., Forrester, L.M., Jarecki, L.L., 2015. Episodic disturbance from boat anchoring is a major contributor to, but does not alter the trajectory of long-term coral reef decline. PLoS ONE 10, e0144498. https://doi.org/10.1371/journal., pone.0144498.

Freese, L., Auster, P.J., Heifetz, J., Wing, B.L., 1999. Effects of trawling on seafloor habitat and associated invertebrate taxa in the Gulf of Alaska. Mar. Ecol. Prog. Ser. 182, 119–126. http://www.jstor.org/stable/24852124.

Frid, C.L.J., 2003. Managing the health of the seafloor. Front. Ecol. Environ. 8, 429–436. https://doi.org/10.2307/3868140.

Ganteaume, A., Bonhomme, P., Emery, E., Herve, G., Boudouresque, C.F., 2005. Impact sur la prairie a` Posidonia oceanica de l'amarrage des bateaux de croisie` re, au large du port de Porquerolles (Provence, France, Me´ diterrane´ e). Sci. Reports. Port-Cros Natl. Park 21, 163–173.

Garner, S.B., Olsen, A.M., Caillouet, R., Campbell, M.D., Patterson III, W.F., 2021. Estimating reef fish size distributions with a mini remotely operated vehicle-integrated stereo camera system. PLoS One 16, e0247985. https://doi.org/10.1371/journal.pone.0247985.

Hui, F.K., 2016. boral–Bayesian ordination and regression analysis of multivariate abundance data in R. Methods Ecol. Evol. 7, 744–750. https://doi.org/10.1111/2041-210X.12514.

James, L., Marzloff, M., Barrett, N., Friedman, A., Johnson, C., 2016. Changes in deep reef benthic community composition across a latitudinal and environmental gradient in temperate eastern Australia. Mar. Ecol. Prog. Ser. 565, 35–52. https://doi.org/10.3354/meps11989.

Keough, Michael J., 1984. Dynamics of the epifauna of the bivalve Pinna bicolor: interactions among recruitment, predation, and competition. Ecology 65, 678–688. https://doi.org/10.2307/1938040.

Knott, N.A., Underwood, A.J., Chapman, M.G., Glasby, T.M., 2004. Epibiota on vertical and on horizontal surfaces on natural reefs and on artificial structures. J. Mar. Biol. Assoc. UK 84, 1117–1130.

Krieger, K., 1993. Distribution and abundance of rockfish determined from a submersible and by bottom trawling. Fish. Bull. 91, 87–96.

Langlois, T.J., Fitzpatrick, B.R., Fairclough, D.V., Wakefield, C.B., Hesp, S.A., McLean, D.L., Harvey, E.S., Meeuwig, J.J., 2012. Similarities between line fishing and baited stereo-video estimations of length-frequency: novel application of kernel density estimates. PLoS One 7, e45973. https://doi.org/10.1371/journal.pone.0045973.

Leys, S.P., Lauzon, N.R.J., 1998. Hexactinellid sponge ecology: growth rates and seasonality in deep water sponges. J. Exp. Mar. Bio. Ecol. 230, 111–129. https://doi.org/10.1016/S0022-0981(98)00088-4.

Linklater, M., Ingleton, T.C., Kinsela, M.A., Morris, B.D., Allen, K.M., Sutherland, M.D., Hanslow, D.J., 2019. Techniques for classifying morphology and composition on subtropical-temperate continental shelf. Geosci. 9, 141. https://doi.org/10.3390/geosciences9030141.

Lloyd's Register, 2019. Global marine trends 2030. www.lr.org/en/latest-news/gmt-2030 (Accessed 17 July 2019).

MacArthur, L.D., Phillips, D.L., Hyndes, G.A., Hanson, C.E., Vanderklift, M.A., 2011. Habitat surrounding patch reefs influences the diet and nutrition of the western rock lobster. Mar. Ecol. Prog. Ser. 436, 191–205. https://doi.org/10.3354/meps09256.

Maldonado, M., Aguilar, R., Bannister, R., Bell, J., Conway, J., Dayton, P., Díaz, C., Gutt, J., Kelly, M., Kenchington, E., Leys, S., Pomponi, S., Tore Rapp, H., Rützler, K., Tendal, O., Vacelet, J., Young, C., 2017. Sponge grounds as key marine habitats: A synthetic review of types, structure, functional roles, and conservation concerns. In: Rossi, S., Bramanti, L., Gori, A., Orejas, C. (Eds.), Marine Animal Forests: The Ecology of Benthic Biodiversity Hotspots. Springer International Publishing, Switzerland, pp. 145–183.

McCauley, D.J., Pinsky, M.L., Palumbi, S.R., Estes, J.A., Joyce, F.H., Warner, R.R., 2015. Marine defaunation: animal loss in the global ocean. Science 347, 6219. https://doi.org/10.1126/science.1255641.

McMurray, S.E., Blum, J.E., Pawlik, J.R., 2008. Redwood of the reef: growth and age of the giant barrel sponge Xestospongia muta in the Florida keys. Mar. Biol. 155, 159–171. https://doi.org/10.1007/s00227-008-1014-z.

Metcalfe, K., Bréheret, N., Chauvet, E., Collins, T., Curran, B.K., Parnell, R.J., Turner, R.A., Witt, M.J., Godley, B.J., 2018. Using satellite AIS to improve our understanding of shipping and fill gaps in ocean observation data to support marine spatial planning. J. Appl. Ecol. 55, 1834–1845. https://doi.org/10.1111/1365-2664.13139.

Micaroni, V., McAllen, R., Turner, J., Strano, F., Morrow, C., Picton, B., Harman, L., Bell, J.J., 2021. Vulnerability of temperate mesophotic ecosystems (TMEs) to environmental impacts: rapid ecosystem changes at Lough Hyne Marine Nature Reserve, Ireland. Sci. Total Environ. 789, 147708. https://doi.org/10.1016/j.scitotenv.2021.147708.

Milazzo, M., Badalamenti, F., Ceccherelli, G., Chemello, R., 2004. Boat anchoring on Posidonia oceanica beds in a marine protected area (Italy, western Mediterranean), effect of anchor types in different anchoring stages. J. Exp. Mar. Biol. Ecol. 299, 51–62. https://doi.org/10.1016/j.jembe.2003.09.003.

Muff, S., Nilson, E.B., O'Hara, R.B., Nater, C.R., 2022. Rewriting results sections in the language of evidence. Trends Ecol. Evol. 37, 203–210. https://doi.org/10.1016/j.tree.2021.10.009.

Ng, A.K.Y., Andrews, J., Babb, D., Lin, Y., Becker, A., 2018. Implications of climate change for shipping, opening the Arctic seas. WIREs Clim. Chang. 9, e507. https://doi.org/10.1002/wcc.507.

NSW DPE, 2022. New South Wales Department of Planning and Environment - Sharing and Enabling Environmental Data portal – GIS shapefiles. downloaded for Wollongong https://datasets.seed.nsw.gov.au/dataset/wollongong-seabed-landforms-derived-from-mbes-data-2022 (Accessed 18 July 2022).

PANSW, 2022. Port Authority of NSW, Annual Report 2021/22. https://www.portauthoritynsw.com.au/news-and-publications/reports-publications/annual-reports-1/ (Accessed 21 Nov. 2022).

Parsons, D.F., Suthers, I.M., Cruz, D.O., Smith, J.A., 2016. Effects of habitat on fish abundance and species composition on temperate rocky reefs. Mar. Ecol. Prog. Ser. 561, 155–171. https://doi.org/10.3354/meps11927.

Poore, A., Huggett, M., de Nys, R., Lowry, J.K., Steinberg, P., 2000. Patterns of host use in alga- and sponge-associated amphipods. Mar. Ecol. Prog. Ser. 208, 183–196. https://doi.org/10.3354/meps208183.

Prado, E., Cristobo, J., Rodríguez-Basalo, A., Ríos, P., Rodríguez-Cabello, C., Sánchez, F., 2021. In situ growth rate assessment of the hexactinellid sponge asconema setubalense using 3D photogrammetric reconstruction. Front. Mar. Sci. 8, 612613. https://doi.org/10.3389/fmars.2021.612613.

R Core Team, 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Rees, M.J., Price, O., Jordan, A., Coleman, M., Davis, A.R., 2014. Habitat complexity as a surrogate for temperate rocky reef biodiversity, implications for marine protected areas. Divers. Distrib. 20, 284–296. https://doi.org/10.1111/ddi.12134.

Rees, M.J., Knott, N.A., Neilson, J., Linklater, M., Osterloh, I., Jordan, A., Davis, A.R., 2018. Accounting for habitat structural complexity improves the assessment of performance in no-take marine reserves. Biol. Conserv. 224, 100–110.

Rees, M.J., Knott, N.A., Hing, M.L., Hammond, M., Williams, J., Neilson, J., Swadling, D.S., Jordan, A., 2021. Habitat and humans predict the distribution of juvenile and adult snapper (Sparidae: Chrysophrys auratus) along Australia's most populated coastline. Estuar. Coast. Shelf Sci. 257, 107397. https://doi.org/10.1016/j.ecss.2021.107397.

Rocha, L.A., Pinheiro, H.T., Shepherd, B., Papastamatiou, Y.P., Luiz, O.J., Pyle, R.L., Bongaerts, P., 2018. Mesophotic coral ecosystems are threatened and ecologically distinct from shallow water reefs. Science 361, 281–284.

Rogers, C.S., Garrison, V.H., 2001. Ten years after the crime, lasting effects of damage from a cruise ship anchor on a coral reef in St. John, U.S. Virgin Islands. Bull. Mar. Sci. 69, 793–803.

Rossi, S., 2013. The destruction of the 'animal forests' in the oceans: towards an over-simplification of the benthic ecosystems. Ocean Coast. Manage. 84, 77–85. https://doi.org/10.1016/j.ocecoaman.2013.07.004.

Rossi, S., Bramanti, L., Gori, A., Orejas, C., 2017. Animal forests of the world, an overview. In: Rossi, S., Bramanti, L., Gori, A., Orejas, C. (Eds.), Marine Animal Forests. Springer, Switzerland, pp. 1–28.

Schönberg, C.H.L., 2021. No taxonomy needed: sponge functional morphologies inform about environmental conditions. Ecol. Indic. 129, 107806. https://doi.org/10.1016/j.ecolind.2021.107806.

Small, M., Oxenford, H.A., 2022. Impacts of cruise ship anchoring during COVID-19: management failures and lessons learnt. Ocean Coast. Manag. 229, 106332. https://doi.org/10.1016/j.ocecoaman.2022.106332.

Smith, S.H., 1988. Cruise ships: a serious threat to coral reefs and associated organisms. Ocean Shoreline Manag. 11, 231–248.

Tupper, M., Boutilier, R.G., 1995. Effects of conspecific density on settlement, growth and post-settlement survival of a temperate reef fish. J. Exp. Mar. Biol. Ecol. 191, 209–222. https://doi.org/10.1016/0022-0981(95)00058-Y.

Van Dolah, R.F., Wendt, P.H., Nicholson, N., 1987. Effects of a research trawl on a hard-bottom assemblage of sponges and corals. Fish. Res. 5, 39–54. https://doi.org/10.1016/0165-7836(87)90014-2.

Van Soest, R.W.M., Boury-Esnault, N., Vacelet, J., Dohrmann, M., Erpenbeck, D., De Voogd, N.J., Santodomingo, N., Vanhoorne, B., Kelly, M., Hooper, J.N.A., 2012. Global diversity

of sponges (Porifera). PLoS ONE 7, e35105. https://doi.org/10.1371/journal.pone.0035105.
Watling, L.E., Norse, E.A., 1998. Disturbance of the seabed by Mobile fishing gear: a comparison to Forest clearcutting. Conserv. Biol. 12, 1180–1197. https://doi.org/10.1046/j.1523-1739.1998.0120061180.x.
Watson, S.J., Neil, H., Ribó, M., Lamarche, G., Strachan, L.J., MacKay, K., Wilcox, S., Kane, T., Orpin, A., Nodder, S., Pallentin, A., Steinmetz, T., 2020. What we do in the shallows: natural and anthropogenic seafloor geomorphologies in a Drowned River Valley, New Zealand. Front. Mar. Sci. 7, 772. https://doi.org/10.3389/fmars.2020.579626.
Watson, S.J., Ribó, M., Seabrook, S., Strachan, L.J., Hale, R., Lamarche, G., 2022. The footprint of ship anchoring on the seafloor. Sci. Rep. 12, 7500. https://doi.org/10.1038/s41598-022-11627-5.
Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. 224. Springer.
Williams, S.L., 1988. Thalassia testudinum productivity and grazing by green turtles in a highly disturbed seagrass bed. Mar. Biol. 98, 447–455. https://doi.org/10.1007/BF00391121.
Wulff, J.L., 2006. Ecological interactions of marine sponges. Can. J. Zool. 84, 146–166. https://doi.org/10.1139/z06-019.

Continental Shelf Research 247 (2022) 104834

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Mapping of benthic ecosystems: Key to improving the management and sustainability of anchoring practices for ocean-going vessels

Andrew R. Davis [a], Allison Broad [a], Micaela Small [b], Hazel A. Oxenford [b], Bradley Morris [c], Timothy C. Ingleton [a,c,*]

[a] Centre for Sustainable Ecosystem Solutions (CSES) and School of Earth, Atmospheric and Life Sciences, University of Wollongong, Wollongong, NSW, 2522, Australia
[b] Centre for Resource Management and Environmental Studies (CERMES), University of the West Indies, Cave Hill, Barbados
[c] Waters. Wetlands and Coasts New South Wales Department of Planning, and Environment (DPIE), Sydney, NSW, 2000, Australia

ARTICLE INFO

Keywords:
AIS
Anchor scour
Ecologically sensitive habitats
Habitat mapping
Marine LiDAR
Multibeam echosounder

ABSTRACT

A global fleet of more than 48,000 vessels conveys >80% of world trade by volume. Anchor damage to benthic habitats by these vessels, along with the burgeoning cruise ship industry, represents a key threat to benthic biodiversity and ecosystem function. Here, we use vessel positional information (Automated Identification System (AIS) data) to map anchoring activity. We then focus on the important role that high resolution habitat mapping will play in understanding the distribution of habitat types which may be impacted by anchoring activities. Many international ports have high-intensity anchor areas that remain unmapped and thus risks to benthic biodiversity are poorly understood and inadequately managed. We use case studies from an anchorage in south-eastern Australia, major trade routes in the Middle East and the anchoring of cruise vessels in the Caribbean to highlight the important role of habitat mapping in reducing anchoring impacts. We contend that mapping represents an important safeguard against anchoring impacts from unexpected events such as the COVID-related redirection of cruise vessels to anchorages and the blocking of the Suez Canal by the *Ever Given* grounding. With increasing maritime trade expected over coming decades there is a need to transition toward sustainable anchorage management practices and provide public confidence in stewardship of marine ecosystems by the maritime industry into the future.

1. Introduction and background

World trade is heavily reliant on the ocean-going fleet. More than 48,000 merchant vessels convey more than 80% of the world's goods by volume (UNCTAD, 2019). Importantly, trade volumes have risen more than 4-fold since 1970 as the number of commercial vessels and their sizes continue to increase (UNCTAD, 2018). Further, trade volumes are growing at around 4% per annum and are expected to double by 2030 (Llyod's Register, 2019). Likewise, the cruise industry is growing rapidly, with a 7.4% increase annually over the last 20 years (Jean-Marie, 2020). Cruise ships, currently number more than 320 and are among the world's largest vessels. Cruise passengers have burgeoned from around 3.5 million a year in the early 1990s to more than 29.5 million in 2019 (Cruise Lines International Assoc, 2021; Cruise Market Watch, 2021). Many of these commercial vessels spend periods of time at anchor as they await an opportunity to berth, or when taking cruise passengers to remote locations with no berthing facilities. The scale of these activities is formidable. Many vessels approach 300 m in length, drop anchors weighing more than 25 tonnes and pay out hundreds of meters of anchor chain with individual links that may exceed 100 kg (House, 2002; Sotra 2021). These mega-vessels may be stacked high with containers or with up to 15 passenger decks and present a huge area of windage. Given this, and their typical shallow draft, lack of keel and deployment of a single anchor from one side of the vessel, means that they continuously tack back and forth at anchor, even in a steady wind, dragging the anchor chain across the seafloor – a process termed 'anchor scour' (Davis et al., 2016). This movement is further exacerbated by changing winds, tides, and currents. Evidence is mounting that this process is highly destructive, with the removal of biota, simplification of benthic ecosystems and structural damage to reefs and soft sediment (Smith, 1988; Broad et al., 2020; Watson et al., 2022).

Here we highlight some of the environmental issues associated with

Abbreviations: AIS, Automated Identification System; LiDAR, Light Detection And Ranging.

* Corresponding author. Department of Planning and Environment, 480 Weeroona Road, Lidcombe, NSW 2141, Australia.
E-mail address: Tim.Ingleton@environment.nsw.gov.au (T.C. Ingleton).

https://doi.org/10.1016/j.csr.2022.104834
Received 6 February 2022; Received in revised form 8 August 2022; Accepted 19 August 2022
Available online 27 August 2022

anchoring and the utility of marrying positional information for ocean-going vessels to benthic habitat maps. The pairing of spatial information for vessel locations with habitat maps will generate a better understanding of how anchors and anchor scour interact with benthic environments, particularly critical for ecologically sensitive habitats. Much of our understanding of anchor impacts is derived from small recreational vessels in shallow water – particularly coral and seagrass habitats (Davis, 1977; Dinsdale and Harriott, 2004; Demers et al., 2013; Flynn and Forrester, 2019; Broad et al., 2020). In contrast, large ocean-going merchant ships and passenger vessels (cruise ships) have the potential to be much more destructive. In this contribution, we seek to assist in moving shipping to a more sustainable footing and advance the UN sustainable development goals, particularly SDG14 - *conserve and sustainably use the oceans, seas, and marine resources for sustainable development* and SDG17 – *developing partnerships to achieve the goals* (UNDP, 2019). We use three unpublished case studies to illustrate the value of access to benthic habitat mapping to reduce anchoring impacts; – the first in SE Australia to highlight how benthic habitat maps and positional information for vessels can be used to understand the spatial scale of anchoring and reduce the anchoring footprint on ecologically sensitive (reefal) habitats. The second concerns the surprising lack of readily available habitat maps on major trade routes, with a particular focus on the recent unexpected blockage of a key maritime chokepoint, the Suez Canal. The obstruction forced many large vessels to queue at anchor at the approaches to this trade arterial. Finally, we consider evidence of COVID-related anchoring damage stemming from unprecedented anchoring of 'out-of-work' cruise ships in Barbados. Here, significant reef damage occurred despite the existence of detailed habitat mapping. We conclude by considering options for increasing the sustainability of anchoring with emphasis on a role for habitat mapping.

2. Marrying positional information to habitat maps: the utility of AIS

The International Maritime Organisation (IMO) is the United Nations Agency charged with the safety and security of international shipping along with the prevention of shipping-related marine and atmospheric pollution. In a move to ensure navigational safety and collision avoidance the IMO made a positional system (AIS - Automated Identification System) for ocean-going vessels mandatory in 2000. AIS transponders provide the identity of a vessel, its dimensions, intentions, as well as dynamic navigational data, including speed, past track, and position. Information is provided in real time (every 10 s or less) to shore-based or coastal receivers, while satellites provide near-global coverage, although these latter data are often time delayed (Robards et al., 2016). Whilst not developed as a research tool, the research community has embraced the opportunity to explore applications for these data and AIS has been the focus of several thematic reviews (Robards et al., 2016; Svanberg et al., 2019). Indeed, AIS has proven a rich source of data for applications as diverse as the detection of nefarious fishing activity (Park et al., 2020), the avoidance of ship-strike with megafauna (Greig et al., 2020), informing Marine Spatial Planning (Metcalfe et al., 2018) along with conservation decisions (Almunia et al., 2021). It is also clear that the United Nations Conference on Trade and Development (UNCTAD) sees an important future role for the analysis of AIS data, which extends beyond supply chain applications into the research realm (UNCTAD, 2018). Here, we emphasise the benefits of marrying the spatial information provided by AIS overlaid on benthic habitat maps to improve our understanding of the scale of anchoring and to help with better management of anchoring to minimise impacts on the benthos, particularly for sensitive ecosystems.

The use of high-resolution imagery (aerial, satellite) and/or bathymetric data, and its derivatives, to interpret seabed morphology, geomorphology and sedimentology has become commonplace (Harris and Baker, 2020). In turn, these data have been used as a surrogate for biota. Combined with ground-validating surveys, remotely sensed data can be used to infer sediment typology, landform, as well as benthic habitat (at the community level) over large scales. This is all at relatively low cost and/or greater spatial coverage than that captured from underwater imagery, dive, or sediment surveys alone. Currently, high (horizontal and vertical) resolution bathymetric data are predominantly acquired using multi-beam echosounders (MBES) across a range of depths. While in shallow water (<25–30 m) with low turbidity, sound, or airborne laser bathymetry ((ALB) also referred to as marine LiDAR (Light Detection And Ranging)) can be used to generate bathymetric information. Processed data can then be modelled to produce digital elevation surfaces (bathymetry) and backscatter (termed reflectance for LiDAR) values (returned value for each sounding) 'mosaicked' over a surveyed area for exploration in GIS-type applications (Finkl and Makowski, 2014; Linklater et al., 2019). A range of analysis techniques can then be applied to segment layers into a series of seabed classes (Evans, 2012; Lecours et al., 2016). While early iterations applied simple manual interpretation, more recent techniques have moved away from subjective approaches and facilitate more robust semi-supervised or unsupervised classification. Geomorphometric approaches utilise a terrain analysis to classify surface forms and features (Pike, 2000) and are based on statistical measures of the bathymetric layer (slope, rugosity, curvature) (Evans, 2012). More recent techniques assess the variability of seabed geomorphometry at multiple spatial scales (Wilson et al., 2007). In the first case study we consider the value of combining habitat maps with positional information derived from vessel AIS.

3. Case study I – anchoring on Australia's 'Great Southern Reef'

Australia's temperate seaboard is now recognised as hosting a poorly appreciated, yet extensive set of interconnected reefs spanning more than 8100 km of coastline. Dubbed the 'Great Southern Reef', much of this system remains to be mapped at high resolution (Lucieer et al., 2019) and the biota that it supports are inadequately known (Bennett et al., 2016). Stretching along Australia's most populous coast, this reefal ecosystem represents a biodiversity hotspot for at least nine phyla, enjoys high levels of endemism and contributes billions of dollars to the Australian economy (Bennet et al., 2016). The economic benefits, stemming largely from fishery resources and tourism, don't include the contribution of ecosystem services[1]; Australia-wide these services may exceed $25 billion annually (Deloitte Access Economics, 2021). In the east, ports have been established along the coast near the city of Sydney, including Wollongong's Industrial Port of Port Kembla, which receives ~ 750 ships annually (Port Authority NSW, 2020). Reefs in the vicinity of Wollongong form the anchoring roadstead for this port and include extensive areas of reefal habitat (Figs. 1 and 2) extending to a depth of at least 90 m (AHO, 2006; Linklater et al., 2019).

In this region, the anchoring of bulk carriers is standard practice while awaiting an opportunity to berth. While there is no national (Federal) management plan for managing the anchoring of ships, some states provide designated anchor zones while others leave anchoring to the discretion of the Ship's Master. Near Port Kembla, Ship Masters are encouraged to anchor outside of the 3 nm line that constitutes the intersection of State and Federal jurisdictions and most of the anchor activity thus falls beyond this line (Davis et al., 2016, Fig. 2a). Anchoring on this wave-dominated coastline is restricted to offshore waters shallower than 70 m as anchors and chains are too heavy to recover when weighing anchor beyond this depth. Consequently, most anchoring occurs in a 35–70 m depth range, and the anchorage (roadstead) appears as a relatively narrow linear feature extending >40 km to the north of the Port (Fig. 2A). On average, vessels lay at anchor for 4.2 days, although the maximum elapsed time at anchor can exceed a month (Davis et al., 2016). The first high-resolution bathymetric surveys offshore of

[1] Ecosystem services – the extensive benefits to humans provided by healthy natural ecosystems.

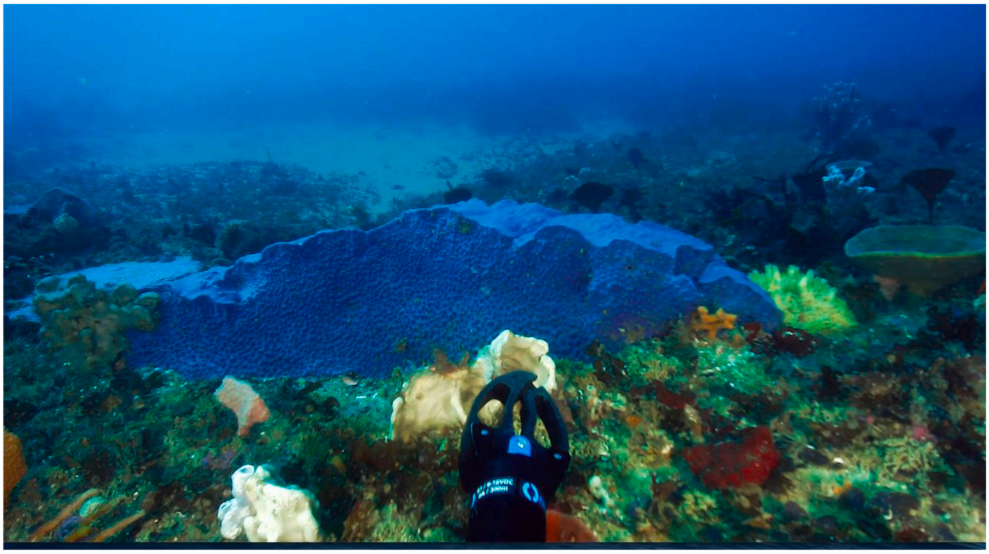


Fig. 1. Invertebrate assemblages on an undisturbed section of Australia's 'Great Southern Reef' near Wollongong (46m depth). Image from a Remotely Operated Vehicle (ROV), depicting a diversity of sponges including a blue mound sponge that dominates this picture. The collecting arm (5.8 cm at its widest point when closed) is visible in the foreground of this image and provides some measure of scale. *Photo Credit*: David Rowland and Allison Broad.

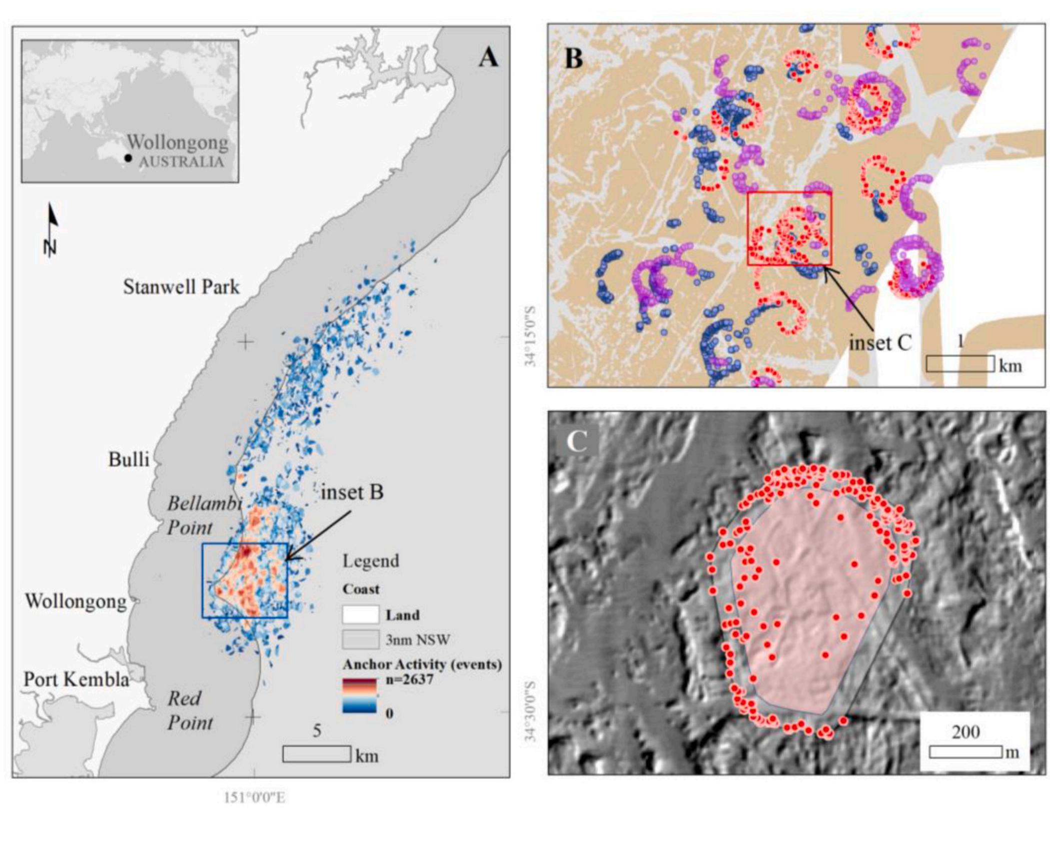


Fig. 2. Anchoring on the 'Great Southern Reef' near Wollongong. A) heat map of anchor activity (blue, red) in the Port Kembla anchor roadstead which extends over 40 km along the NSW coast. Warmer colours indicate elevated anchor activity. The line offshore is at 3 nm and represents the intersection of New South Wales State and Federal waters. B) detail of the anchor roadstead with vessel positions (coloured arcs) overlaying a habitat map for 3 months during 2020. Note the extensive area of reef (brown tones) interspersed with sediments (light grey) while some areas remain unmapped (white). Different shades in anchoring arcs allow vessels to be distinguished. C) hill-shaded relief (5m gridded bathymetry) with positions of a single vessel at anchor, based on AIS (red points), with evidence of a broad anchoring arc and depiction of an anchoring polygon (pink) used to calculate the area impacted.

Wollongong were completed in 2006 (AHO, 2006) with subsequent seabed mapping based on multibeam surveys completed in 2015–2018 (https://portal.aodn.org.au, accessed Nov. 19, 2021). Of the ~220 km^2 of seabed used for anchoring, ~ 50% of the total area has been mapped with the most intensely anchored southern zone mapped to ~85% coverage. A 5 × 5 m gridded bathymetry was used to classify habitat by applying a semi-automated geomorphometric technique (Linklater et al., 2019) using ArcMap (ESRI, USA). Mapping has confirmed that >60% of this area is rocky reef.

We interrogated monthly AIS data (hourly ships position) offshore of Wollongong (Oct 2012–Dec 2020) to assess the spatial and temporal extent of anchor activity and overlaid this information on habitat maps derived from multibeam echosounder surveys (Fig. 2B&C). AIS data (hourly data) were acquired from the Australian Maritime Safety Authority (www.amsa.gov.au: monthly data accessed January 15, 2021) and imported to ArcMap. Data were treated using the approach of Deter et al. (2017) applying a range of filters including vessel speed, type, and residence time (≥6 h) to determine those vessels laying at anchor. Filtered GPS points were then used to define a polygon ('convex-hull' function in ArcMap) per vessel and per anchor event per month. The length of chain in contact with the seabed while a vessel is at anchor is unknown, as is the exact location of the anchor itself (not recorded in AIS), although we assumed that the position of the anchor was within the anchor 'polygon'. The location of the vessel's GPS beacon is also uncertain and, for the purposes of this approach, it is assumed to be located near the helm, i.e., at the stern. To accommodate these unknowns and not over-estimate the extent of anchor scour, the area of the defined polygon was then systematically reduced, in a concentric manner, by 1/3 in keeping with the approach of Deter et al. (2017). Polygons for the total 'time' period were then summarised to identify the total number of anchor events per month (averaging 45 ± 3 per month (±sem[2])) as well as the total number of anchored hours (mean of 2499 ± 140 h per month (±sem)) to produce anchoring heat maps (Fig. 2A). Monthly totals of anchor events and polygon area (km^2) were then plotted to examine trends offshore of Wollongong across the eight-year period (Fig. 3). The total summed area for monthly anchoring events reached a mean of 2.64 ± 0.14 km^2 and peaked at a maximum annual total event area of 47.8 km^2 in 2016. Following the removal of overlapping anchor events, we estimate that a total area of 87.8 km^2 has been anchored upon off Wollongong during the eight years 2012–2020. We also emphasise that the AIS information allows anchor-free reference locations to be identified with a high degree of confidence. As a footnote, designated anchorages are likely to be implemented on the Wollongong anchor roadstead to minimise the anchoring footprint (pers. comm. Sharad Bhasin, Port Authority of NSW).

4. Case study II – unexpected events underscore the need for more comprehensive habitat mapping

In March 2020, the grounding of the 399 m container vessel, *Ever Given,* brought shipping in the Suez Canal to a standstill (Fig. 4) and highlighted the fragility of the World's supply chains. The Suez Canal is a 193 km trade arterial that connects the Mediterranean Sea and the Red Sea, carrying around 13% of global trade, it supports more than 19,000 vessel transits annually with a net annual tonnage of almost 1.2 billion tonnes (Lee and Wong, 2021). The blockage forced more than 370 vessels to queue at anchor at either end of the canal (Fig. 5A), while others rerouted to make the 10,000 km voyage around the southern tip of Africa. Open-source information of digital bathymetry for the approaches to the Canal (International Hydrographic Organization Data Centre for Digital Bathymetry https://www.ncei.noaa.gov/maps/iho_dcdb/) revealed a paucity of available information (Fig. 5B&C). Given the importance of this trade route, the scant availability of mapping information for these waters is remarkable. Open-source marine habitat maps may be expected to be inadequate almost everywhere, but we note that this is not always the case (Supplemental Fig. 1). It should also be acknowledged that other global mapping efforts are progressing (Ocean Data Viewer, https://data.unep-wcmc.org/; Allen Coral Atlas, https://allencoralatlas.org/atlas/#10.32/29.7941/32.6230), although at low resolution and are likely inadequate for the purposes of managing anchoring or assessing potential impacts.

Our estimate of the scale of the anchoring disturbance due to the blockage is considerable. If we conservatively assume that each ocean-going anchored vessel directly disturbed a hectare of seabed as they swung at anchor, this equates to direct impacts to more than 3.5 km^2 of seabed as a direct result of the blockage. Anchoring extended >50 km into the Gulf of Suez (the southern entrance to the canal), likely disturbing habitats not previously exposed to anchor scour (Fig. 5C). Attempts to understand the impacts to the benthos were hindered by the lack of accessible habitat maps for this critical trade route (Fig. 5A&B).

This has not been the first unexpected event to dramatically affect the shipping Industry; the Global Financial Crisis of 2008 saw large numbers of vessels lay at anchor during its peak. Many of these vessels anchored in the ports or along the coast of South East Asia; Singapore alone hosted more than 700 vessels and many laid at anchor for months (Floerl and Coutts, 2009). Concerns were raised about the spread of Introduced Marine Pests (Floerl and Coutts, 2009), but impacts of anchoring on seafloor assemblages were probably pervasive, but not considered. More recently, the COVID pandemic has impacted global supply chains with dramatic bottlenecks of container vessels laying at anchor on the US Pacific coast (Murray, 2021). Significant increases in time at anchor have also been reported for May 2021 compared with two years previous. In North American ports, time at anchor was up more than 4-fold to 33 h, while it more than doubled in Northern European ports to 30 h and was up by half to 15 h in East Asian ports (Hellenic Shipping News, 2021). Although the economic impact of increases in the number of vessels at anchor and their time at anchor is dire, the environmental costs have scarcely been considered. If anchoring activities particularly in the face of unexpected circumstances, are to move to a more sustainable footing, then detailed habitat maps near key ports on International trade routes are an important first step. Although, as we state in the next case study, detailed benthic habitat maps and positional information for vessels do not guarantee sustainable anchoring outcomes.

5. Case study III – COVID, cruise ships and Caribbean reefs

The appearance of COVID-19 in early 2020 saw wholesale change in the shipping industry worldwide (March et al., 2021). These reductions in marine traffic had some demonstrable environmental benefits. The absence or slowing of recreational and commercial vessels produced dramatic declines in the levels of anthropogenic noise, with corresponding increases in communication ranges for cetaceans and fishes (e.g., Dunn et al., 2021; Pine et al., 2021). On the other side of the ledger, the cruise ship industry was virtually shut down overnight, with vessels forced to seek safe harbour. This meant laying up at anchor in many locations (e.g., Webster, 2021). The Caribbean nation of Barbados provided incentives to the cruise industry early in the pandemic, including discounted port rates. A total of 43 cruise vessels, some more than 300 m in length, sought shelter and port facilities in this small Caribbean nation, and 28 chose to anchor in the nearshore waters, performing a total of 132 anchoring events from March to September 2020 (Fig. 6A) (the first 6 months of the pandemic). This was the first time cruise vessels had been permitted to anchor in these waters. Unfortunately, there appear to have been policy failures with inadequate oversight of the anchoring process by environmental managers, despite detailed habitat maps being available for the island's nearshore waters (Baldwin et al., 2016). These maps confirmed the locations of sensitive reefal habitat. Ironically, other island nations in the Caribbean provided the

[2] sem - standard error of the mean.

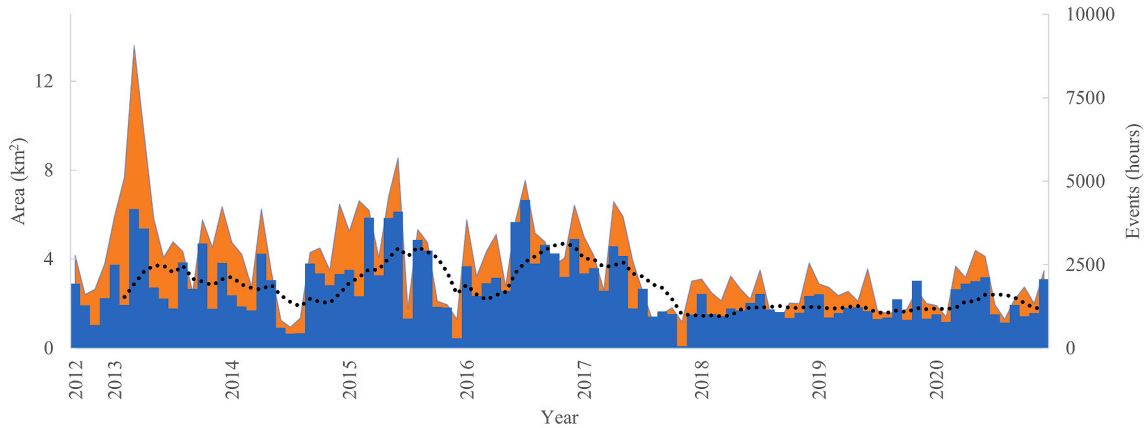


Fig. 3. Estimates of hours (orange) at anchor and area (km^2) (blue) affected directly by anchor scour for the Port Kembla anchoring roadstead from Oct 2012 to Dec 2020. Dotted line represents a 6-month moving average of area anchored.

Fig. 4. The grounding of the *Ever Given* container vessel blocked the Suez Canal and saw frenzied attempts to refloat the ship in March 2020. *Photo Credit*: Shutterstock.

first tangible evidence for the destructive effects of anchor scour by ocean-going vessels (again cruise ships) over 30 years earlier, disturbingly in one instance, within a United Nations Biosphere Reserve (Smith, 1988; Allen, 1992). Unfortunately, the same mistakes have been repeated, adding to the extensive loss of reefal architecture that has been chronicled right across the Caribbean due to a range of anthropogenic activities (Alvarez-Filip et al., 2009).

In Barbados, an assessment of AIS data tracking the movement of cruise ships swinging at anchor over 132 anchoring events and direct ecological assessments with SCUBA of 6 anchoring events confirmed the prevalence of anchor scour and the destruction of significant areas of coral reef as reported by Small and Oxenford (2021). Accounting for overlap between these anchor events, we calculate that as much as 1.2 km^2 of seabed habitat was subsequently disturbed or destroyed. The extensive damage reported for Barbados is particularly concerning given that an estimated 30% of their GDP is reliant on the Blue Economy – predominantly marine-based tourism. As highlighted by Small and Oxenford (2021), the charter of the cruise industry seeks to minimise environmental impact, but it appears that the industry remains ignorant of the pervasive effects of their vessel anchors. Indeed, the shipping industry more generally fails to acknowledge the impacts of anchoring on the environment (International Chamber of Shipping, 2008).

Policy failures including a resistance to sharing detailed spatial habitat data among management authorities and the industry, contributed to the serious damage to coral reefs in Barbados over this unprecedented period.

6. Habitat mapping and sustainable anchoring – charting a way forward

There is clear evidence that ocean-going vessels can have significant negative impacts when anchoring on sensitive habitats. Dramatic imagery chronicles the destruction of seagrass habitat in Malta, including damaging the structure of the underlying reef (see supplementary material in Broad et al., 2020). Multibeam imagery confirms marked anchor scouring in sedimentary habitat (Watson et al., 2022) while coral reefs in the Caribbean have sustained significant damage because of anchoring (Smith, 1988; Allen, 1992; Small and Oxenford, 2021). Most reports of habitat damage from ocean-going vessels in the Caribbean are from cruise ships, which might be expected given that a reported 70% of cruises take place in sensitive biodiversity hotspots (Clegg et al., 2020a). In contrast, impacts on reefal habitat at temperate latitudes are unstudied and although rates of habitat recovery have been estimated, they have not been quantitatively investigated anywhere (Broad et al., 2020). Small and Oxenford (2021) estimate that as a direct result of recent anchor activity by cruise ships, Caribbean coral reefs will take 100's of years to recover and where the architecture of the reef has been damaged, recovery may never occur. Given the additional stressors associated with climate change, including rising sea temperatures, more intense storms, rising sea levels and ocean acidification, recovery will likely be further inhibited (Perry et al., 2013; Oxenford and Monnereau, 2017). Acknowledging that anchor scour is destructive and requires attention is the first step in tackling this hidden issue.

Anchor damage to pristine habitat is of particular concern (Davis and Broad, 2016) and given the uncertainty and expense of restoration intervention (Bayraktarov et al., 2016), impacts are best avoided in the first place. In a move to ensure that sea areas of exceptional ecological, scientific or socio-economic value are afforded protection from shipping, the IMO has implemented two categories of protection: 'Particularly Sensitive Sea Areas' (PSSAs) (https://www.imo.org/en/OurWork/Environment/Pages/PSSAs.aspx Accessed Oct. 20, 2021) as well as 'Areas To Be Avoided' (ATBAs) (Huntington et al., 2019). Globally, the IMO has designated 17 areas as PSSAs. In general, protection stems from the routing of shipping, but several of these locations include explicit bans on anchoring and vessels ignoring these regulations are at risk of prosecution as highlighted recently on the Caribbean's Saba bank (https://safety4sea.com/vessels-violating-saba-bank-environmental-regulations-to-be-prosecuted/?_cf_chl_jschl_tk_=pmd_c93CxwOAFZCGZcqIlUi0craHaVtca349hotuo6gYXj8-1634020072-0-gqNtZGzNAlCjcnBszQfl Accessed Oct. 20, 2021).

There is growing recognition of the impacts of recreational vessels anchoring in coral reef environments. The Great Barrier Reef Marine Park Authority has designated public moorings and anchor free zones within the Park (https://www.gbrmpa.gov.au/access-and-use/mooring

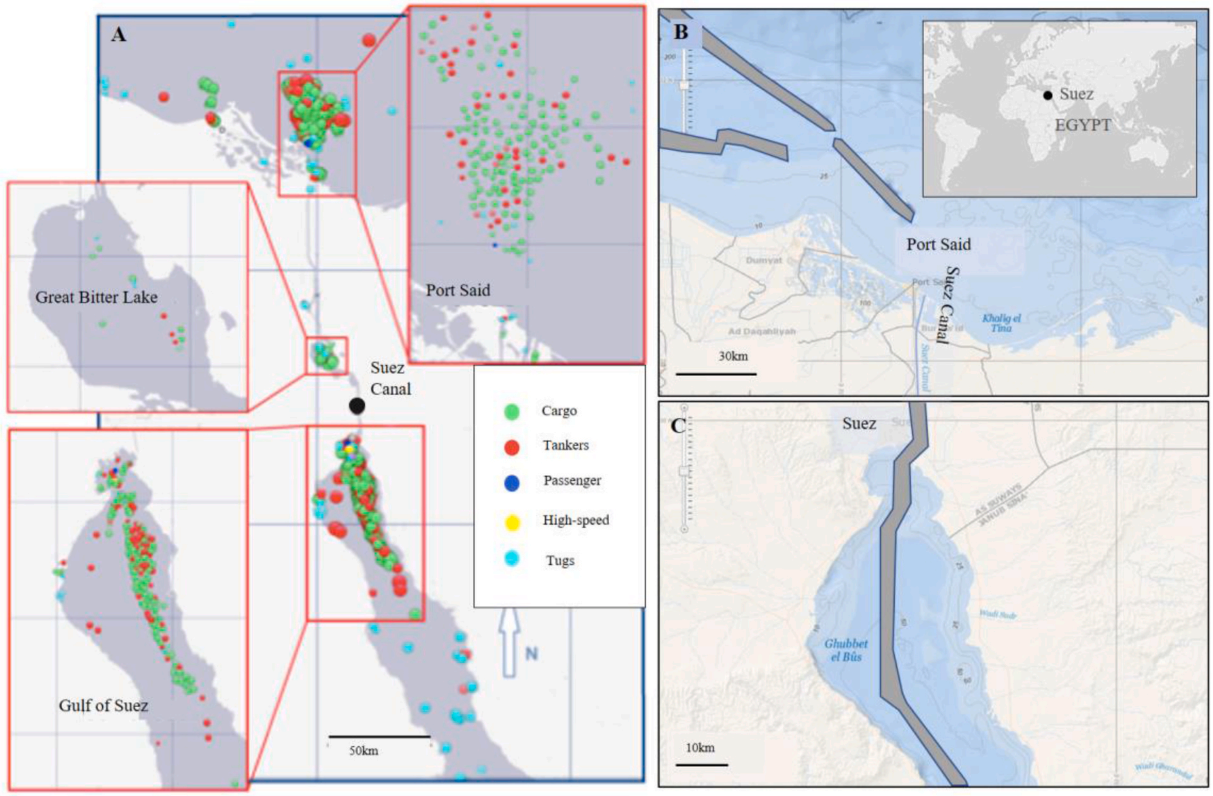


Fig. 5. The Suez Canal, a major shipping arterial in the Middle East, highlights the fragility of international supply chains and the scant availability of habitat mapping information following the grounding of the *Ever Given* container vessel. A) Queued vessels (coloured dots) at anchor March 30, 2020, a few hours after the refloating of the *Ever Given* at the northern and southern approaches of the Suez Canal (positional information from Marine Traffic). The limited extent of publicly accessible multibeam data (grey-shaded polygons) at B) the northern approach to the Canal (offshore of Port Said) and C) Port Suez, the southern entry point to the Canal. Multibeam coverage adapted from the IHO Data Centre for Digital Bathymetry (ESRI Ocean Basemap; GEBCO, 2021 bathymetric contours).
Source: https://www/ncei/noaa.gov/maps/iho_dcdb/accessed Nov 17, 2021.

s Accessed Oct. 20, 2021). Similarly, the British Virgin Islands (Caribbean) have installed more than 200 moorings for the large number of recreational and charter yachts within its waters (Forrester et al., 2015). The effectiveness of seabed friendly moorings in sensitive habitats is well demonstrated (Demers et al., 2013), but unfortunately these moorings are not an option for large ocean-going vessels in wave-swept environments. What then are the options for reducing anchoring impacts in the marine environment? The simplest approach is not to anchor at all, but drifting vessels or those holding position present a different suite of challenges with increased likelihood of collision and greenhouse gas emissions associated with continuous motoring. Heaver (2021) outlines the benefits of a vessel arrival system (VAS) developed for the Port of Newcastle, Australia – the world's largest coal exporting port. Vessels now join the loading queue while still at sea and up to 15 days before their estimated time of arrival. Although originally established in response to safety concerns following a "near black swan event" (a rare event which fortunately did not have dire consequences) – the grounding of the *Pasha Bulker* – the VAS has had tangible commercial benefits for all stakeholders in the supply chain and the environment as a by-product (Heaver 2021). Prior to the introduction of VAS, waiting times at anchor were more than 11 days, post VAS this fell to just 3 days and 64% of vessels did not anchor at all (Heaver, 2021). It should be highlighted though that a VAS is challenging to establish for multi-commodity ports (pers. comm. Sharad Bhasin, Port Authority of NSW). Designated anchorages have also been suggested as a means of reducing the anchoring footprint near port facilities (Davis et al., 2016). They ensure that only a small number of locations are exposed to repeated anchoring activities – a press disturbance – while large sections of an anchor roadstead remain undisturbed. Unfortunately, there is evidence that once designated anchorages are full, anchoring spills over in an unregulated fashion, compromising the benefits of designated sites (Steele et al., 2017). As international trade builds, spill over from designated anchorages will likely increase in frequency. Furthermore, as the size of ships and the length of anchor chain they require continues to increase, the space required to safely anchor these mega-vessels far exceeds most long-established anchorages, especially near small islands with limited shallow water.

In relation to anchoring, we now have the capacity to map marine habitat and overlay the positions of vessels at anchor. The challenge though is identifying the real scale of the anchoring footprint and the extent of sensitive habitat. The anchoring footprint, that is the area of seafloor directly impacted by physical disturbance from anchor scour, may underestimate the total area impacted. Indirect impacts associated with anchoring include noise generation and the mobilisation of sediment. Noise generated by anchors and chains on the seafloor will extend well beyond the areas that are directly affected and anthropogenically-generated sound in marine systems may be much more pervasive than ever imagined (Solé et al., 2021). Watson et al. (2022) reported that an astounding 2700 cubic meters of sediment may be displaced in a single anchoring event by a 'high tonnage' vessel and suggest that this may equate to >1 billion cubic meters of sediment disturbance globally each year. The mobilisation of sediment during the process of anchor scour or anchor retrieval may be far reaching, shading habitat and interfering with, or smothering, suspension-feeding animals such as corals, sponges, ascidians, and a host of others. Sediments in suspension are particularly damaging to coral reef communities (reviews in Weber et al., 2012; Tuttle et al., 2020), and have been implicated in the shift of benthic assemblages in temperate reefal habitat from sponge to

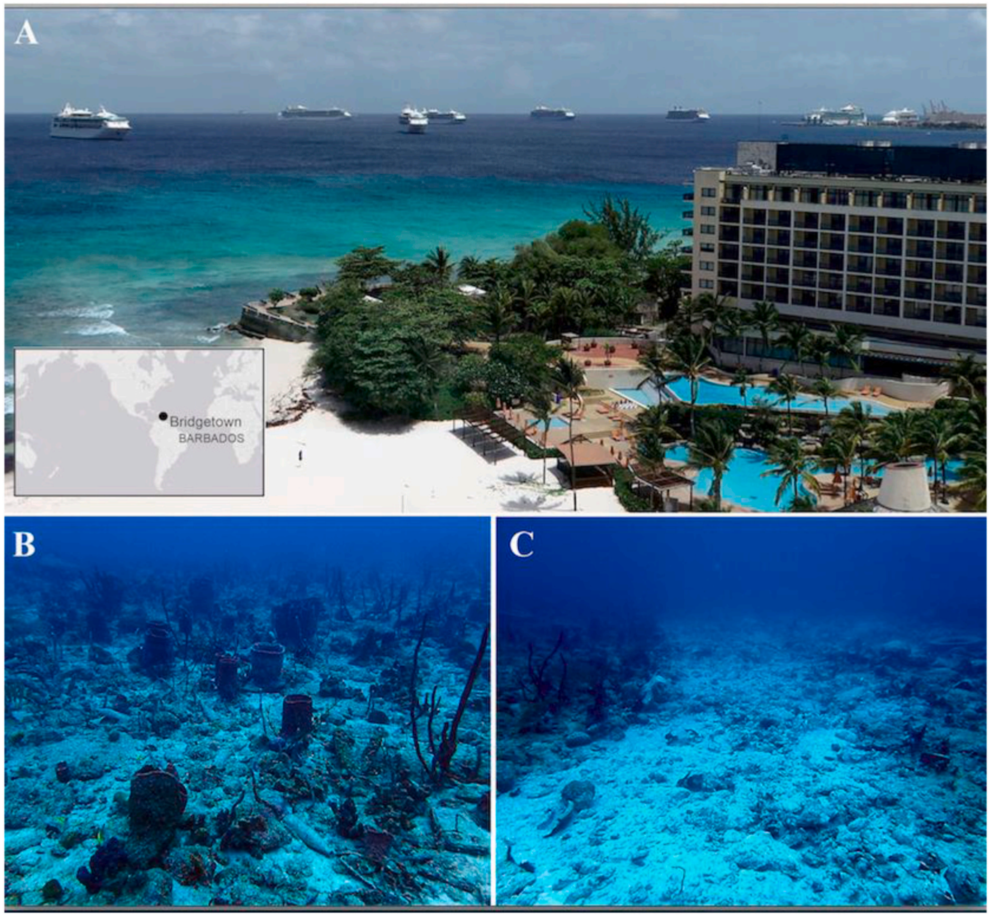


Fig. 6. Cruise ship impacts in the Caribbean during COVID. A) Cruise ships anchored off Bridgetown (Carlisle Bay), Barbados July 9, 2020. B) Carlisle Reef, Barbados (24 m) July 12, 2020 showing the reef condition immediately adjacent to anchor scour. C) Anchor scour on Carlisle Reef, Barbados (24 m) July 12, 2020. *Photo Credit*: Annabel Cox, Hazel Oxenford and Joseph Weekes.

ascidian-dominated (Roberts et al., 1998), with marked effects on individual taxa (Roberts et al., 2006).

We contend that places where ships routinely anchor should be assessed and managed in the same way that transport infrastructure on land are administered and governed. In terrestrial settings, Environmental Impact Assessments (EIA) are routine appraisals that consider impacts to biota, their life histories, and habitats. The main objective of an EIA is to identify impacts and propose ways to ameliorate them ahead of time to limit disturbance. Unfortunately for marine systems, rarely have EIA's been done ahead of marine operations. In regions near ports, we suggest that anchorages should be considered shipping infrastructure and that high-resolution seabed mapping be used to ensure that anchoring is not occurring on habitat of high conservation value, such as reef. Detailed habitat maps would also assist in ensuring that shipping does not impact other marine industries such as recreational and commercial fisheries. Indeed, Marine Spatial Planning (MSP) that utilises detailed seabed mapping and promotes knowledge sharing between mariners, scientists and marine estate managers is essential if we are to work towards sustainable anchoring practices for generations to come.

There is increasing recognition of the value and importance of a sustainable Blue Economy (https://www.worldbank.org/en/topic/oceans-fisheries-and-coastal-economies#1, accessed Oct. 12, 2021). Nowhere is the Blue Economy of more critical importance than in Small Island Developing States (SIDS) (Patil et al., 2016; Clegg et al., 2020b). Environmental stewardship is now often an explicit aim of stakeholders in the marine environment (Voyer et al., 2018). Unfortunately, though there is often a disconnect between 'green' credentials stated by corporate entities and the environmental reality (Small and Oxenford, 2021). As stakeholders strive to be good corporate citizens there is still a long path to achieve the UN's Sustainable Development Goals (Wan et al., 2016). In reflecting on shipping over the last 50 years and considering what the future may hold, the secretariat for the United Nations Conference on Trade and Development (UNCTAD) identified sustainability as one of three upcoming key objectives, yet unfortunately there continues to be no recognition of anchoring as a threatening process (UNCTAD 2018).

7. Conclusions

Evidence is mounting that anchor scour, particularly by ocean-going vessels, can be highly destructive. Habitat mapping along major trade routes and near Ports is central to developing a sustainable 'Blue Economy'. Benthic habitat mapping is an important precursor to identifying habitat of high conservation value – such as reefal habitat. Anchoring near sensitive habitats must be avoided and anchoring on pristine habitat prevented; restoration is expensive and unproven. Importantly, habitat maps and vessel positional information alone are not sufficient to ensure sustainable outcomes. Political will, management oversight and accessibility to habitat mapping by managers and industry stakeholders are critical to achieving sustainable outcomes for both routine anchoring as well as anchoring that occurs because of unexpected or unprecedented events as we have witnessed in the Suez Canal and Barbados case studies. The development of multi-stakeholder partnerships is key to achieving these outcomes. Options to reduce the anchoring footprint include holding position using a dynamic positioning system; drifting; use of a Vessel Arrival System (VAS) to reduce waiting times; and designated anchorages and no-anchor zones in areas of particularly sensitive habitat. As shipping charts a more sustainable path and embraces the UN sustainable development goals, important knowledge gaps remain; key among these are rates of ecosystem recovery following disturbance by anchor scour.

Competing interests statement

The authors have no conflicts of interest to declare.

Author contributions

Andy Davis: Conceptualisation, Writing – original draft, Supervision, Project administration, Funding acquisition Allison Broad: Conceptualisation, Writing - review and editing, Visualization, Funding acquisition Micaela Small: Data Curation, Writing - review and editing Hazel Oxenford: Conceptualisation, Writing - review and editing, Supervision, Funding acquisition Brad Morris: Software, Data Curation, Writing - review and editing Tim Ingleton: Conceptualisation, Data Curation, Writing - review and editing, Visualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Allison Broad reports financial support was provided by Ian Potter Foundation. Allison Broad reports financial support was provided by Australian Academy of Science. Allison Broad reports financial support was provided by Royal Zoological Society of New South Wales. Micaela Small reports administrative support was provided by Marine Traffic.

Acknowledgements

We thank the Ian Potter Foundation and the Global Challenges Program, University of Wollongong (UOW) for supporting our 'anchor scour' research from its inception. One of us (AB) has been supported by an Australian Government Research Training Program (AGRTP) scholarship and wishes to thank the Max Day Environmental Science Fellowship Award (Australian Academy of Science) and the Paddy Pallin Research Grant (Royal Zoological Society of New South Wales) for financial support. The Barbados case study was supported in part by a student research grant (to MS) from the Centre for Resource Management and Environmental Studies, University of the West Indies, and by MarineTraffic through access to their global ship tracking intelligence data. Comments by Christine McComb improved a draft.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csr.2022.104834.

References

AHO, 2006. Australian Hydrographic Office HMAS Leewin Survey © Commonwealth of Australia. Survey HI 416_J - Port Kembla Approaches provided by Hydro licensing@defence.nsw.gov.au, 15 Nov. 2021.

Allen, W.H., 1992. Increased dangers to Caribbean marine ecosystems: cruise ship anchors and intensified tourism threaten reefs. Bioscience 42, 330–335.

Almunia, J., Delponti, P., Rosa, F., 2021. Using Automatic Identification System (AIS) data to estimate whale watching effort. Front. Mar. Sci. 8, 635568 https://doi.org/10.3389/fmars.2021.635568.

Alvarez-Filip, L., Dulvy, N.K., Gill, J.A., Côté, I.M., Watkinson, A.R., 2009. Flattening of Caribbean coral reefs: region-wide declines in architectural complexity. Proc. Biol. Sci. 276 (1669), 3019–3025.

Baldwin, K., Oxenford, H.A., Purkis, S., Knowles, L., 2016. Developing a Benthic Habitat Classification Scheme and Island-wide Map Based on Remote Sensing and Comprehensive Ground-Truthing. Centre for Resource Management and Environmental Studies, The University of the West Indies, Barbados. CERMES Technical Report No. 94: 48pp. https://www.cavehill.uwi.edu/cermes/docs/technical_reports/baldwin_et_al_2019_benthic_habitat_classification_.aspx.

Bayraktarov, E., Saunders, M.I., Abdullah, S., Mills, M., Beher, J., Possingham, H.P., Mumby, P.J., Lovelock, C.E., 2016. The cost and feasibility of marine coastal restoration. Ecol. Appl. 26, 1055–1074.

Bennett, S., Wernberg, T., Connell, S.D., Hobday, A.J., Johnson, C.R., Poloczanska, E.S., 2016. The 'Great Southern Reef': social, ecological and economic value of Australia's neglected kelp forests. Mar. Freshw. Res. 67, 47–56. https://doi.org/10.1071/MF15232.

Broad, A., Rees, M.J., Davis, A.R., 2020. Anchor and chain scour as disturbance agents in benthic environments: trends in the literature and charting a course to more sustainable boating and shipping. Mar. Pollut. Bull. 161, 111683 https://doi.org/10.1016/j.marpolbul.2020.111683.

Clegg, P., Cumberbatch, J., Degia, K., 2020a. Chapter 11; Tourism in the Caribbean and the blue economy: can the two be aligned? In: Clegg, P., Mahon, R., McConney, P., Oxenford, H.A. (Eds.), The Caribbean Blue Economy. Europa Regional Perspectives. Routledge Taylor Francis Group, London, pp. 131–142.

Clegg, P., Mahon, R., McConney, P., Oxenford, H.A., 2020b. The Caribbean Blue Economy. Europa Regional Perspectives. Routledge Taylor Francis Group, London.

Cruise Lines International Assoc, 2021. State of the Cruise Industry Outlook, p. 29. https://cruising.org/-/media/research-updates/research/2021-state-of-the-cruise-industry_optimized.ashx. (Accessed 15 November 2021).

Davis, G.E., 1977. Anchor damage to a coral reef on the coast of Florida. Biol. Conserv. 11, 29–34.

Davis, A.R., Broad, A., 2016. Environment: curb anchor scour for green shipping. Nature 533, 36. https://doi.org/10.1038/533036a.

Davis, A.R., Broad, A., Gullett, W., Reveley, J., Steele, C., Schofield, C., 2016. Anchors away? The impacts of anchor scour by ocean-going vessels and potential response options. Mar. Pol. 73, 1–7.

Deloitte Access Economics, 2021. The Value of Australian Seabed Mapping Data to the Blue Economy. Report Commissioned by Geoscience Australia, p. 58. https://www2.deloitte.com/au/en/pages/economics/articles/value-of-australian-seabed-mapping-data-to-blue-economy.html.

Demers, M.-C.A., Davis, A.R., Knott, N.A., 2013. A comparison of the impact of 'seagrass-friendly' boat mooring systems on *Posidonia australis*. Mar. Environ. Res. 83, 54–62.

Deter, J., Lozupone, X., Inacio, A., Boissery, P., Holon, F., 2017. Boat anchoring pressure on coastal seabed: quantification and bias estimation using AIS data. Mar. Pollut. Bull. 123, 175–181.

Dinsdale, E., Harriott, V., 2004. Assessing anchor damage on coral reefs: a case study in selection of environmental indicators. Environ. Manag. 33, 126–139. https://doi.org/10.1007/s00267-003-3056-9.

Dunn, C., Theriault, J., Hickmott, L., Claridge, D., 2021. Slower ship speed in the Bahamas due to COVID-19 produces a dramatic reduction in ocean sound levels. Front. Mar. Sci. 8, 673565 https://doi.org/10.3389/fmars.2021.673565.

Evans, I.S., 2012. Geomorphometry and landform mapping: what is a landform? Geomorphology 137, 94–106. https://doi.org/10.1016/j.geomorph.2010.09.029.

Finkl, C.W., Makowski, 2014. Autoclassification versus cognitive interpretation of digital bathymetry data in terms of geomorphological features of seafloor characterisation. J. Coast Res. 31 (1), 1–16. https://doi.org/10.2112/JCOASTRES-D-14A-00006.1.

Floerl, O., Coutts, A., 2009. Potential ramifications of the global economic crisis on human-mediated dispersal of marine non-indigenous species. Mar. Pollut. Bull. 58, 1595–1598.

Flynn, R.L., Forrester, G.E., 2019. Boat anchoring contributes substantially to coral reef degradation in the British Virgin Islands. PeerJ 7, e7010. https://doi.org/10.7717/peerj.7010.

Forrester, G.E., Flynn, R.L., Forrester, L.M., Jarecki, L.L., 2015. Episodic disturbance from boat anchoring is a major contributor to, but does not alter the trajectory of, long-term coral reef decline. PLoS One 10 (12), e0144498. https://doi.org/10.1371/journal.pone.0144498.

17/11/2021 GEBCO, The General Bathymteric Chart of the Oceans, 2021. GEBCO Compilation Group (2021) GEBCO 2021 Grid (doi:10.5285/c6612cbe-50b3-0cff-e053-6c86abc09f8f). https://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_2021/. (Accessed 17 November 2021).

Greig, N.C., Hines, E.M., Cope, S., Liu, X., 2020. Using satellite AIS to analyze vessel speeds off the coast of Washington state, U.S., as a risk analysis for cetacean-vessel collisions. Front. Mar. Sci. 7, 109–122. https://doi.org/10.3389/fmars.2020.00109.

Harris, P.T., Baker, E.K., 2020. Chapter 60 – geohab Atlas of seafloor geomorphic features and benthic habitats – synthesis and lessons learned. In: Harris, P.T., Baker, E.K. (Eds.), Seafloor Geomorphology as a Benthic Habitat, second ed. Elsevier, Amsterdam, pp. 969–990. https://doi.org/10.1016/B978-0-12-814960-7.00060-9.

Heaver, T.D., 2021. Reducing anchorage in ports: changing technologies, opportunities and challenges. Frontiers in Future Transportation 2, 709762. https://doi.org/10.3389/ffutr.2021.709762.

Hellenic Shipping News, 2021. Surge in Container Ships Needing to Anchor at Port Waiting for Berths. https://www.hellenicshippingnews.com/surge-in-container-ships-needing-to-anchor-at-port-waiting-for-berths/. (Accessed 14 September 2021).

House, D.J., 2002. Anchor Practice, A Guide for Industry, first ed. Witherby and Co. Ltd, London, p. 200.

Huntington, H.P., Bobbe, S., Hartsig, A., Knight, E.J., Knizhnikov, A., Moiseev, A., Romanenko, O., Smith, M.A., Sullender, B.K., 2019. The role of areas to be avoided in the governance of shipping in the greater Bering Strait region. Mar. Pol. 110, 103564 https://doi.org/10.1016/j.marpol.2019.103564.

International Chamber of Shipping, 2008. Shipping and the Environment: A Code of Practice, fourth ed.

Jean-Marie, D., 2020. The role of shipping and marine transport in developing blue economies, Chapter 12. In: Clegg, P., Mahon, R., McConney, P., Oxenford, H.A.

(Eds.), The Caribbean Blue Economy. Europa Regional Perspectives. Routledge Taylor Francis Group, London, pp. 143–155.
Lecours, V., Dolan, M.F., Micallef, A., Lucieer, V.L., 2016. A review of marine geomorphometry, the quantitative study of the seafloor. Hydrological and Earth Systems Science 20, 3207–3244. https://doi.org/10.5194/hess-20-3207-2016.
Lee, J.M., Wong, E.Y., 2021. Suez Canal blockage: an analysis of legal impact, risks and liabilities to the global supply chain. MATEC Web of Conferences 339, 01019. https://doi.org/10.1051/matecconf/202133901019.
Linklater, M., Ingleton, T.C., Kinsela, M.A., Morris, B.D., Allen, K.M., Sutherland, M.D., Hanslow, D.J., 2019. Techniques for classifying seabed morphology and composition on a subtropical-temperate continental shelf. Geosciences 9, 141–179.
Lloyd's Register, 2019. Global Marine Trends 2030. www.lr.org/en/latest-news/gmt-2030. (Accessed 17 October 2021).
Lucieer, V., Barrett, N., Butler, C., Flukes, E., Ierodiaconou, D., Ingleton, T., Jordan, A., Monk, J., Meeuwig, J., Porter-Smith, R., Smit, N., 2019. A seafloor habitat map for the Australian continental shelf. Sci. Data 6, 1–7.
March, D., Metcalfe, K., Tintoré, J., Godley, B.J., 2021. Tracking the global reduction of marine traffic during the COVID-19 pandemic. Nat. Commun. 12, 1–12.
Market Watch, Cruise, 2021. Growth of the Ocean Cruise Line Industry. https://cruisemarketwatch.com/growth/. (Accessed 15 November 2021).
Metcalfe, K., Bréheret, N., Chauvet, E., Collins, T., Curran, B.K., Parnell, R.J., Turner, R.A., Witt, M.J., Godley, B.J., 2018. Using satellite AIS to improve our understanding of shipping and fill gaps in ocean observation data to support marine spatial planning. J. Appl. Ecol. 55, 1834–1845.
Murray, B., 2021. Economics: U.S. Container-Ship Bottleneck Lurches Near its February Record. Bloomberg. https://www.bloomberg.com/news/articles/2021-08-16/u-s-container-ship-bottleneck-lurches-near-its-february-record. (Accessed 14 September 2021).
Oxenford, H.A., Monnereau, I., 2017. Impacts of climate change on fish and shellfish in the coastal and marine environments of Caribbean small island developing states (SIDS). Caribbean Marine Climate Change Report Card: Sci. Rev. 83–114, 2017.
Park, J., Lee, J., Seto, K., Hochberg, T., Wong, B.A., Miller, N.A., Takasaki, K., Kubota, H., Oozeki, Y., Doshi, S., Midzik, M., Hanich, Q., Sullivan, B., Woods, P., Kroodsma, D.A., 2020. Illuminating dark fishing fleets in North Korea. Sci. Adv. 6, eabb1197.
Patil, P.G., Virdin, J., Diez, S.M., Roberts, J., Singh, A., 2016. Toward a Blue Economy: A Promise for Sustainable Growth in the Caribbean - an Overview. The World Bank, Washington D.C.
Perry, C.T., Murphy, G.N., Kench, P.S., Smithers, S.G., Edinger, E.N., Steneck, R.S., Mumby, P.J., 2013. Caribbean-wide decline in carbonate production threatens coral reef growth. Nat. Commun. 4, 1402.
Pike, R.J., 2000. Geomorphometry-diversity in quantitative surface analysis. Prog. Phys. Geogr.: Earth Environ. 24, 1–20. https://doi.org/10.1177/030913330002400101.
Pine, M.K., Wilson, L., Jeffs, A.G., McWhinnie, L., Juanes, F., Scuderi, A., Radford, C.A., 2021. A Gulf in lockdown: how an enforced ban on recreational vessels increased dolphin and fish communication ranges. Global Change Biol. 27, 4839–4848. https://doi.org/10.1111/gcb.15798.
Port Authority NSW, 2020. Port Authority of New South Wales. Annual Report 2019/20. https://www.portauthoritynsw.com.au/media/4802/pa_073_ar_20_wcag_v1.pdf. (Accessed 13 December 2021).
Robards, M.D., Silber, G.K., Adams, J.D., Arroyo, J., Lorenzini, D., Schwehr, K., Amos, J., 2016. Conservation science and policy applications of the marine vessel Automatic Identification System (AIS)—a review. Bull. Mar. Sci. 92, 75–103.
Roberts, D.E., Smith, A., Ajani, P., Davis, A.R., 1998. Rapid changes in encrusting marine assemblages exposed to anthropogenic point-source pollution: a 'Beyond BACI' approach. Mar. Ecol. Prog. Ser. 163, 213–224.
Roberts, D.E., Davis, A.R., Cummins, S.P., 2006. Experimental manipulation of shade, silt, nutrients and salinity on the temperate reef sponge *Cymbastela concentrica*. Mar. Ecol. Prog. Ser. 307, 143–154.
Small, M., Oxenford, H.A., 2021. Assessing Anchoring Impacts of Cruise Ships in Barbados during the COVID-19 Pandemic of 2020. Centre for Resource Management and Environmental Studies, The University of the West Indies, Cave Hill Campus, Barbados. CERMES Technical Report No.101, 69 pp. https://www.cavehill.uwi.edu/cermes/docs/technical_reports/small_oxenford_2021_cruise_ship_anchor-damage_in-b.aspx. (Accessed 25 August 2021).
Smith, S.H., 1988. Cruise ships: a serious threat to coral reefs and associated organisms. Ocean Shorel. Manag. 11, 231–248.
Solé, M., Lenoir, M., Durfort, M., Fortuño, J.M., van der Schaar, M., De Vreese, S., André, M., 2021. Seagrass *Posidonia* is impaired by human-generated noise. Commun Biol. 4, 743–754. https://doi.org/10.1038/s42003-021-02165-3.
Sotra, 2021. Anchor and Chain Handbook, eighth ed., p. 237 https://www.sotra.net/wp-content/uploads/2021/08/Catalogue-8.pdf. (Accessed 15 November 2021).
Steele, C., Broad, A., Ingelton, T., Davis, A.R., 2017. Anchors Aweigh? The visible and invisible effects of anchored ocean-going vessels. In: Proceedings of the Coasts and Ports Conference 2017, p. 6pp. Cairns Australia.
Svanberg, M., Santén, V., Hörteborn, A., Holm, H., Finnsgård, C., 2019. AIS in maritime research. Mar. Pol. 106, 103520.
Tuttle, L.J., Johnson, C., Kolinski, S., Minton, D., Donahue, M.J., 2020. How does sediment exposure affect corals? A systematic review protocol. Environ. Evid. 9, 1–7.
UNCTAD, 2018. 50 Years of Review of Maritime Transport, 1968–2018-Reflecting on the Past, Exploring the Future. https://unctad.org/system/files/official-document/dtl2018d1_en.pdf.
UNCTAD, 2019. Review of Maritime Transport. United Nations Conference on Trade and Development, Geneva. https://unctadstat.unctad.org/EN/BulkDownload.html. (Accessed 19 November 2020).
UNDP, 2019. United Nations Development Programme, Sustainable Development Goals. Goal 14, Life below Water. www.undp.org/content/undp/en/home/sustainabledevelopment- goals/goal-14-life-below-water.html. (Accessed 10 June 2021).
Voyer, M., Quirk, G., McIlgorm, A., Azmi, K., 2018. Shades of blue: what do competing interpretations of the Blue Economy mean for oceans governance? J. Environ. Pol. Plann. 20, 595–616.
Wan, Z., Zhu, M., Chen, S., Sperling, D., 2016. Three steps to a green shipping industry. Nature 530, 275–277.
Watson, S.J., Ribó, M., Seabrook, S., Strachan, L.J., Hale, R., Lamarche, G., 2022. The footprint of ship anchoring on the seafloor. Sci. Rep. 12, 7500. https://doi.org/10.1038/s41598-022-11627-5.
Weber, M., De Beer, D., Lott, C., Polerecky, L., Kohls, K., Abed, R.M., Ferdelman, T.G., Fabricius, K.E., 2012. Mechanisms of damage to corals exposed to sedimentation. Proc. Natl. Acad. Sci. USA 109, E1558–E1567.
Webster, B., 2021. Luxury Liners Blamed for Scarring of Protected Dorset Seabed. The Times. https://www.thetimes.co.uk/article/luxury-liners-blamed-for-scarring-of-protected-dorset-seabed-dt28f5cfg. (Accessed 18 November 2021).
Wilson, M.F.J., O'Connell, B., Brown, C., Guinan, J.C., Grehan, A.J., 2007. Multiscale terrain analysis of multibeam bathymetry data for habitat mapping on the continental slope. Mar. Geodes. 30, 3–35. https://doi.org/10.1080/01490410701295962.