FRDC
FISHERIES RESEARCH & DEVELOPMENT CORPORATION

Vulnerability of commercially harvested corals to fisheries exploitation versus environmental pressures

Morgan Pratchett, Ciemon Caballes, Vanessa Messmer, Shaun Wilson, Anthony Roelofs, Shane Penny, Russell Kelley, and Stephen Newman

October 1st, 2020

FRDC Project No **2014-029**

Version 1.1 1 July 2019

ISBN [Insert ISBN/ISSN – researcher to obtain]

Vulnerability of commercially harvested corals to fisheries exploitation versus environmental pressures

2014-029

2020

Researcher Contact Details

Name:	Professor Morgan Pratchett
Address:	James Cook University
	Townsville QLD 4811
Phone:	07 4728 2519
Fax:	04 4781 6722
Email:	morgan.pratchett@jcu.edu.au

FRDC Contact Details

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

Foreword

Keeping fish for display is an ancient tradition dating back nearly 5,000 years and is now a global pastime. The aquarium hobby has been transformed over the past 20 years with the emergence of accessible, plug-and-play technologies for keeping marine life in aquaria. The technology continues to improve every year, and this has given hobbyists the confidence to move from traditional freshwater displays to the more complex marine reef systems.

The transition to marine aquariums has given rise to mini-reef displays that feature living rock adorned with vibrant corals and complemented by invertebrates and colourful fish. Keeping a mini-reef is an outstanding means of learning about marine species, their interactions with the habitat and with other marine creatures. In many cases, it is the hobby leading science when it comes to the propagation of many coral species. All of this stimulates an interest in the sea and a love for the marine environment that lends its collective weight to conservation.

However, the popularity of mini-reef systems has increased global market demand for a much broader range of marine species, including corals. Many of the countries that supply the marine aquarium trade have poorly resourced oversight of their fisheries that often operate among geographically dispersed traditional village communities where options for income generation are few. Fisheries management and enforcement can be ineffective or even absent. Provenance is veiled in opaque and complex supply chains and little is known of the losses incurred *en route* to international markets.

Australia has historically provided around 20% of the corals to the global marine aquarium market. The corals are overwhelmingly sourced from wild catch fisheries that are managed by dedicated and adequately resourced government agencies, guided by science and assessed for export eligibility against Commonwealth environmental legislation. The rigour of the process ensures licenced private commercial use of a common resource is done with minimal environmental effect.

The quality of the science is the key. The Australian coral fisheries operate in some of the most iconic reef environments on the planet, including the Great Barrier Reef. As custodians of this World Heritage Area, Australia ensures extractive activities are managed for sustainability based on the best available science.

As an association of licence holders collecting corals on the Great Barrier Reef, we strongly endorse this approach. Our members are heavily invested in the fishery through licences, infrastructure and equipment. We employ many people in regional centres along the Queensland coast and we share a love and deep respect for the ocean.

It was our pleasure to instigate this project and our members made a substantial financial contribution to it in addition to the provision of innumerable samples to researchers. The findings assert that the fisheries are low impact activities, but that environmental pressures will continue to create challenges. As an industry, we will continue to collaborate with scientists and managers to fill knowledge gaps and to adapt as new knowledge comes to light.

Lyle V. Squire
President, Pro-vision reef

Contents

Tables

Figures

Acknowledgments

This project was critically dependent on the effective and ongoing relationship between researchers and industry. In particular, there are several companies and individuals that have been instrumental in providing access to facilities, field locations, biological samples, and information (Table A.1).

Table A.1. Major organisations and individuals that contributed to this project across Queensland (Qld), Western Australia (WA) and the Northern Territory (NT).

State	Business	Individual(s)
Qld	Cairns Marine (CM)	Lyle Squire Jnr.
Qld	Ultra Coral Australia (UCA)	Nic Dos Santos
Qld	Corals Down Under (CDU)	Alex Doll
Qld	Australian Coral Exports (ACE)	Darren Brighton
Qld	GBR Marine (GBRM)	Rob Lowe
NT	Monsoon Aquatics (MA)	Daniel Kimberley
WA	Australian Coral Farms (ACF)	Wayne McKenzie-Brown
WA	Ocean Reefs Marine Aquariums (ORMA)	Simon Hawke

The conduct of this research was further aided by significant in-kind contributions from the King Abdullah University of Science and Technology (KAUST) and the National University of Singapore, which conducted genetic sequencing. A large number of researchers have contributed to the research presented, and aside from those that are listed as co-authors, we acknowledge Jilly Wheeler, who explored the reproductive biology of *Homophyllia australis*, as well as Deborah Pratchett, Cassandra Thompson and Benjamin Parry-Lemon, who helped with the conduct of experimental bleaching studies conducted at the James Cook University Marine Aquarium Research Facility (MARFU), with significant input and advice from Allison Paley, Mia Hoogenboom and Tory Chase. The following research interns also assisted in collecting data on the reproductive biology of target species: Jonathan Barton, Brianna Marshall, Nicolas Briggs, Maya Weis and Philip Kuhel. We also acknowledge significant financial and in-kind investment provided by the Department of Biodiversity, Conservation and Attractions (DBCA), Government of Western Australia through the PLUTO Offset project to support complementary research into the biodiversity and viability of coral populations in the Dampier Archipelago. This included assistance with field-work by Molly Moustaka.

Abbreviations

AFMA	Australian Fisheries Management Authority, Australian Government
AIMS	Australian Institute of Marine Science
CITES	Convention for the International Trade in Endangered Species
CSMP	Coral Sea Marine Park
DAWE	Department of Agriculture, Water and the Environment, Australian Government
DBCA	Department of Biodiversity, Conservation and Attractions, Government of Western Australia
DOF	Department of Fisheries, Government of Western Australia
DEEDI	Department of Employment, Economic Development and Innovation, Queensland Government
DPIRD	Department of Primary Industries and Regional Development, Government of Western Australia
DPIR	Department Primary Industry and Resources, Northern Territory Government
EPBC Act	Environment Protection and Biodiversity Conservation Act (1999)
ERA	Ecological (or Environmental) Risk Assessment
GBR	Great Barrier Reef
GBRMP	Great Barrier Reef Marine Park
JCU	James Cook University
LTMP	Long Term Monitoring Program, AIMS
MSFR	Minimum Size at First Reproduction
NDF	Non-Detriment Findings (as pertaining to CITES export approvals)
NTAF	Northern Territory Aquarium Fishery
QCF	Queensland Coral Fishery
QDAF	Queensland Department of Agriculture and Fisheries
TACC	Total Allowable Commercial Catch
VMS	Vessel Monitoring System
MAFMF	Marine Aquarium Fish Managed Fishery, Western Australia
WTO	Wildlife Trade Operation

Executive Summary

Australia's aquarium fisheries are high value (>$20 million), small-scale fisheries, which are critically reliant on continued exports of *CITES*-listed corals. However, widespread and accelerating degradation of coral reef ecosystems is leading to considerable public and political scrutiny regarding the sustainability of ongoing coral harvesting. The purpose of this study, conducted by coral reef researchers working in close collaboration with fisheries managers and Australian coral fisheries licensees, was to provide unprecedented information on the stock size and structure for select high value and critically important coral species across northern Australia (in Western Australia, Northern Territory and Queensland). This project greatly improved knowledge regarding the vulnerabilities of commonly harvested corals to fisheries exploitation versus environmental pressures, with relevant information being rapidly incorporated into harvest strategies that will help to ensure the sustainability and viability of Australia's aquarium coral fisheries.

The objectives and outcomes of this project were:
1) To establish the distribution and abundance of commercially important coral species in areas of concentrated fishing across northern Australia;
2) Improve the accuracy of species identifications across the industry through extensive genotyping of major harvest corals, both to refine species-level taxonomy and explore genetic structure among widely distributed coral;
3) Establish abundance and turnover of representative commercially important inter-reefal corals, which is fundamental to establishing baselines and sustainable harvest levels;
4) Establish a cost-effective industry based long-term monitoring program; and
5) Contribute Environmental Risk Assessments (ERA) in NT and WA to establish vulnerability of major target species.

This project represented an effective collaboration between coral reef scientists and Australian coral fisheries licensees and mangers across Western Australia, Northern Territory and Queensland. A total of 246 video transects (50m^2) were completed during the course of this study, providing unprecedented information on the stock size and structure of harvested coral species across a broad range of fishery habitats. Moreover, a large number of corals (>1,400) were provided by Australian coral fisheries for important and timely research on the reproductive biology among major harvest coral species, as well as genetic structure and vulnerability to environmental change. This research centred mainly on six focal study species (*Duncanopsammia axifuga*, *Catalaphyllia jardinei*, *Euphyllia glabrescens*, *Micromussa lordhowensis*, *Homophyllia australis*, and *Trachyphyllia geoffroyi*, considered to be particularly important to the viability of Australian coral fisheries.

Our results show that the current standing biomass of select coral species in areas with highly concentrated and sustained fisheries pressure, and also in the aftermath of very significant extrinsic pressures (most notably widespread coral bleaching and cyclones) is substantial, especially compared to current limits and reported harvest levels. Simply comparing the total biomass of harvested species versus standing biomass in major fishing areas does not, however, accurately represent potential fisheries impacts, nor the harvestable biomass of aquarium corals. Importantly, harvesting of most species is extremely selective, either taking only certain colours, size or shapes of corals. This selectivity for specific morphs may reduce risk of over-exploitation or localised depletion of species, but the consequences of selective targeting on the population structure is unknown. Moreover, fishery reliance on particular coral types means that *in situ* surveys of species abundance may greatly overestimate harvestable biomass, and will ultimately need to be constrained to just those morphs that are actually harvested.

Genetic sequencing of major focal species confirmed that *C. jardinei*, *D. axifuga*, and *T. geoffroyi* each represent single, widespread species, albeit with strong genetic structure at the largest scales examined (e.g., between Queensland and Western Australia). There is however, considerable uncertainty regarding

the taxonomy of corals within the family Lobophyllidae (including, *H. australis* and *M. lordhowensis*), which are among the most important Australian aquarium corals. Though reportedly harvested from a wide range of locations, there is increasing evidence that *H. australis* and *M. lordhowensis* are mainly (if not exclusively) harvested from the southern GBR, while similar corals harvested in outer jurisdictions may represent new and undescribed species.

The foremost contribution of this study to Australian coral fisheries is to provide new and unprecedented data on the distribution, abundance, biology and vulnerability of major target species, which greatly increases confidence in assessing the risk posed by commercial fisheries, thereby contributing to long-term sustainability and viability of these important, intensive and highly selective fisheries. Until now, the lack of rigorous data on the biology and vulnerability of major target species has undermined the surety of ecological risk assessments, as well as greatly constraining effective management of Australian coral fisheries. This study has provided a way forward for industry-based sampling and monitoring programs that will greatly increase the information and data on which to base future risk assessments, as well as leading towards robust determination of sustainable harvest limits for species of concern that are critically important to the continuation and viability of Australian coral fisheries.

Some of the concern regarding the sustainability of Australian coral fisheries is generated, not by direct evidence of increasing or over exploitation, but by widespread and sustained declines in the abundance of corals caused by fisheries independent pressures, and especially environmental change. Experimental tests of temperature sensitivity and bleaching susceptibility for six coral species (*H. australis*, *M. lordhowensis*, *C. jardinei*, *T. geoffroyi*, *D. axifuga*, and *E. glabrescens*) confirmed that these species are vulnerable to elevated temperatures. In particular, *H. australis*, *M. lordhowensis*, *E. glabrescens* and *C. jardinei* exhibited high rates of mortality (>80%) when exposed to prolonged temperature stress, suggesting that sustained and ongoing environmental change could undermine the sustainability and viability of Australian coral fisheries.

While this study has greatly advanced the understanding and management of Australia's coral fisheries there is a lot more that needs to be done, especially given accelerating environmental change that is threatening wild coral stocks, and ongoing changes in the international demand for aquarium corals. Importantly, we need to expand upon the results of this study to consider other coral species that are increasing in importance for this industry (e.g., *Acropora* corals), and that are also particularly vulnerable to ongoing and accelerating environmental change. The increasing pressures facing coral reef ecosystems globally will continue to raise questions about the sustainability and morality of coral harvesting, necessitating increased information on wild populations of harvested coral populations and species, which can be used to develop harvest strategies that will ensure the long-term sustainability and improve social licence for this industry. Reducing pressure on wild stocks (e.g., by increasing captive breeding and mariculture of high risk species) is also prudent given increasing extrinsic threats to the industry.

Keywords

Aquarium fisheries; coral reefs; Scleractinia; Western Australian Marine Aquarium Fish Managed Fishery (MAFMF); Northern Territory Aquarium Fishery (NTAF); Queensland Coral Fishery (QCF).

1. Introduction

Coral reefs are economically and ecologically significant ecosystems (Moberg and Folke 1999; Albert et al. 2015; Grafeld et al. 2017; Spalding et al. 2017), which are extremely vulnerable to increasing and emerging anthropogenic pressures, including direct extractive and destructive activities (e.g., fishing and shipping), coastal development and modification (leading to sedimentation, eutrophication and pollution), as well as global climate change (Bruno and Valdivia 2016; Wear 2016; Hughes et al. 2017a). Accordingly, there has been sustained and widespread degradation of coral reef ecosystems. Even seemingly well-managed coral reef ecosystems, such as Australia's Great Barrier Reef (GBR), exhibit conspicuous evidence of significant and sustained degradation (De'ath et al. 2012; Mellin et al. 2019), linked to the increasing incidence and severity of major disturbances. The degradation of coral reef ecosystems is largely manifest as overall declines in the abundance of habitat-forming and reef-building corals, combined with corresponding increases in the abundance of other, more ephemeral substrate colonisers, such as fleshy seaweeds. On the GBR, rigorous recurrent monitoring (albeit in very specific habitat-types) revealed a 50% decline in average coral cover from 1985-2012 (De'ath et al. 2012). These declines were further exacerbated in recent years due to recurrent years of mass coral bleaching and extensive coral loss in shallow water environments caused by marine heatwaves (Hughes et al. 2017b; Hughes et al. 2018a). Marine heatwaves are now the foremost cause of mass coral bleaching and elevated coral mortality (Hughes et al. 2018a; 2018b), threatening the population viability of vulnerable coral species and undermining the ecological integrity and function of reef ecosystems. Climate-induced coral bleaching, as well as other causes of coral mortality, may also directly undermine the sustainability and viability of harvest fisheries (Rhyne et al. 2014; Albert et al. 2015), which collect corals from the wild, mainly for home and public aquaria (Harriott 2003; Rhyne et al. 2012).

International ornamental and aquarium coral fisheries involve the annual trade of hundreds of thousands of small coral pieces worth millions of dollars (Bruckner 2000; Wood et al. 2012). An increasing portion of the coral sold comes from aquaculture, but the majority is still collected from the wild (Bruckner 2000; Rhyne et al. 2012, 2014). While heavily regulated and limited (Harriott 2001), sustained and ongoing coral harvesting adds to the increasing threats and pressures on coral populations and communities, including large-scale and recurrent disturbances, such as outbreaks of crown-of-thorns starfish (Pratchett et al. 2014), cyclones (Fabricius et al. 2008; Torda et al. 2018) and climate-change induced mass coral bleaching (Hughes et al. 2017b; Hughes et al. 2018b). The total biomass of coral removed through direct harvesting is negligible compared to reef-scale levels of coral biomass and rates of carbonate production and coral replenishment (Harriott 2003). However, widespread and accelerating degradation of coral reef ecosystems is placing increasing pressure on coral fisheries, leading to greater public and political scrutiny regarding the sustainability of coral harvesting (Ferse et al. 2012; Rhyne et al. 2014; Albert et al. 2015). It is also possible that specific species may be over-exploited where harvesting is concentrated on relatively uncommon or highly vulnerable species (Bruckner 2000). Importantly, aquarium corals are mostly selected based on appearance, especially colour, as well as their amenability to harvesting, transport and maintenance within aquaria, rather than rigorous fisheries assessment of their vulnerability (or resilience) to exploitation (*sensu* Fujita et al. 2014).

The principal concern(s) relating to coral harvesting relate to the potential overexploitation and localized depletion of highly vulnerable or ecologically-important coral species (Bruckner 2000; Harriott 2003; Atkinson et al. 2008; Garrabou et al. 2017), and especially where harvested corals are simultaneously being impacted by fisheries-independent threats, including rapid and accelerating environmental change (Ferse et al. 2012; Montero-Serra et al. 2019). Notably, many of the most highly prized and heavily targeted coral species are heavily calcified coral species with large fleshy polyps (e.g., *Micromussa lordhowensis*), which are presumed to be slow-growing and long-lived

(Bruckner 2000). These traits would make these corals vulnerable to over-exploitation (Fujita et al. 2014) and as such, scientists have been advocating for increased monitoring of targeted coral species in areas of concentrated harvesting, combined with increased research into the biology (especially rates of colony growth and population turnover) of these species, for several decades (Harriott 2003). While there has been extensive research on growth and other biological traits of scleractinian corals (Pratchett et al. 2015; Madin et al. 2016), there has been very limited progress in addressing these apparent knowledge gaps for most of the major coral species targeted by international ornamental and aquarium coral fisheries (e.g., *Homophyllia australis*). Moreover, it is largely unknown if or how these corals are vulnerable to environmental changes (mainly increased incidence of marine heatwaves, but also ocean acidification) linked to anthropogenic climate change (Pratchett et al. 2020).

All zooxanthellate organisms are susceptible to temperature-induced bleaching at some level (Buddemeier and Fautin 1993), and very severe marine heatwaves can cause comprehensive bleaching and mortality across a wide range of different coral species (e.g., Hughes et al. 2018b; Vargas-Angel et al. 2019). There are however, apparent taxonomic differences in the susceptibility and responses of corals to increasing temperature (Marshall and Baird 2000; Loya et al. 2001; Grottoli et al. 2014; Hoey et al. 2016). Among common, widespread and well-studied coral taxa, the rank order of bleaching susceptibility (based on the proportion of colonies that bleach or die) appears to be fairly conserved among geographic locations (e.g., McClanahan et al. 2004), whereby *Acropora* spp. are often among the first to bleach and experience the highest mortality rates (Baird and Marshall 2002; Pratchett et al. 2013), but have been seen to be resistant to bleaching in some locations (Guest et al. 2012; Chou et al. 2016). Conversely, other corals, such as *Turbinaria* spp. are rarely observed to bleach (e.g., Marshall and Baird 2000) and appear particularly capable of withstanding thermal stress. There are many coral taxa for which we know very little about temperature sensitivity and bleaching susceptibility, mostly because they do not occur on shallow carbonate reefs, where *in situ* studies of coral bleaching are predominantly conducted (e.g., Hughes et al. 2017b; Gilmour et al. 2019). This includes many of the coral taxa that are collected for the aquarium fishery, especially those from non-reefal environments.

1.1 Australian coral fisheries

In Australia, state-based fisheries (e.g., Queensland Coral Fishery) are managed by each of the relevant state government fisheries management authorities (e.g., Queensland Government Department of Fisheries), though there is critical oversight by the Australian Government Department of Environment and Energy (DOEE), especially in regard to conservation of, and international trade in, endangered species. All hard corals, including reef-building (order Scleractinia) corals, black corals (order Antipatharia), blue corals (family Helioporidae), organ pipe corals (family Tubiporidae), and fire corals (family Milleporidae) are listed in Appendix II of the *Convention for the International Trade in Endangered Species* (CITES). Species listed in Appendix II are not considered to be facing imminent danger of extinction, but are thought to be potentially threatened by *over-exploitation* (Dee et al. 2014). This means that the 183 parties to the Convention (including Australia) are committed to ensuring that any exports of these organisms are only permitted *if the export* (and thereby the direct harvesting) *will not be detrimental to the survival of the species*. The Australian Government Department of the Environment and Energy is Australia's CITES Management Authority and CITES Scientific Authority, and issues Wildlife Trade Operation (WTO) approvals for each jurisdiction and fishery separately (Western Australian Marine Aquarium Fish Managed Fishery, Northern Territory Aquarium Fishery, Queensland Coral Fishery, and Coral Sea Aquarium Fishery), subject to certain conditions, including effective demonstration that the fishery has no detrimental effects (*Non-Detriment Findings:* NDF) on the viability and local persistence of targeted species. WTO assessments are generally conducted with specific consideration of Ecological Risk Assessments (ERA), which assess the specific threat of fisheries activities (both direct and indirect) on each major

target species (see *Extension and Adoption*). WTO approvals are issued for a specified period and can be retracted at any time.

Harvest limits (output controls) across all Australian coral fisheries use weight-based quotas (Table 1.1), which is appropriate and justified (e.g., Atkinson et al. 2008). However, it is difficult to reconcile the potential ecological impacts of coral harvesting without clear understanding of the size and number of coral colonies (or fragments) that are being removed. Moreover, international trade records and limits are based on numbers of corals, not weight (e.g., Rhyne et al 2009). There is also very limited data on size-weight relationships (Longnecker et al. 2015), which would allow necessary conversions and interpretation of harvest limits, and the size and weight of coral colonies vary greatly across the range of corals harvested (Pratchett and Messmer 2017).

1.1.1 Western Australian Marine Aquarium Fish Managed Fishery

Coral harvesting is permitted in Western Australian waters under the authority of the Western Australian Marine Aquarium Fish Managed Fishery (MAFMF), managed by the Western Australia Government Department of Primary Industries and Regional Development (DPIRD), Government of Western Australia. The MAFMF was originally issued a *Declaration of an Approved Wildlife Trade Operation* (WTO) in 2005, with renewals issued in 2008, 2011, 2013, and 2016. There was a temporary lapse in the WTO in October 2011, at which time the Commonwealth Government Department of the Environment (DOTE) requested more detailed information to support the necessary NDF ruling. In response, the MAFMF implemented a formal harvest strategy with precautionary catch limits for all CITES listed target species. The WTO was reissued in 2013 with species-specific limits imposed (at 50% of 2010 catch levels) for *Duncanopsammia axifuga*, *Euphyllia ancora*, *Euphyllia glabrescens,* and *Trachyphyllia geoffroyi*. Given particular concerns about *Catalaphyllia jardinei* (and a lack of rigorous data on stock size or structure) there was a ban on harvesting of this species throughout 2012 and 2013 (Government of Western Australia 2013). The current WTO was issued in October 2019, and is valid until October 14th, 2022.

The MAFMF is a low volume, high value fishery, that operates from the Northern Territory border in the north to the South Australian border in the south, with fishing effort spread over a total gazetted area of 20,781 km^2. Hard and soft corals are primarily targeted by the MAFMF in the tropical waters off Exmouth and the Dampier Archipelago (DPIRD 2018). Most of the coral species targeted by the MAFMF (including *Duncanopsammia axifuga*, *Euphyllia ancora*, *Trachyphyllia geoffroyi*, *Euphyllia glabrescens*, and *Catalaphyllia jardinei*) are harvested from relatively turbid intertidal and/ or inter-reefal habitats. The MAFMF is primarily a dive-based, hand-collection fishery, which places inherent constraints on fishing effort, due to restrictions posed by tides and weather, and also diving limits. The MAFMF is managed through input controls, with limited entry to the fishery, permanent closed areas and gear restrictions, as well as output controls in the form of catch limits (Individual Transferrable Quota) for key species.

The Western Australian Marine Aquarium Fishery dates back to the 1960s, where collection of marine aquarium fish was authorised on Professional Fishing Licences. In 1986, the number of commercial licences that allowed for collection of marine aquarium fish species was limited to 20, though this was increased to 25 in 1991. The MAFMF was formally established in 1995, at which time 14 Managed Fishery Licences (MFL) were granted (DPIRD 2018). Since 2007, only MFL holders in the MAFMF are permitted to collect coral (and live rock) for the aquarium trade. There are currently 12 MAFMF licences, though only six licences originally permitted harvesting of hard corals and soft corals with an annual Total Allowable Commercial Catch (TACC) of 7,500kg (across all species) implemented in 2007. The TACC was increased to 15,000 kg following an ERA and revision of the harvest strategy in 2017 (DPIRD 2018). Allowances for increases in the TACC were staged over several years (with full 15,000 kg available in 2019/20) as part of a gentlemen's agreement between the DPIRD and industry to comply with WTO/NDF conditions. A portion of the additional 'new quota' (the

additional 7,500kg) was allocated across all 12 MAFMF licences, thereby increasing the number of licensees permitted to harvest coral. All 12 licensees are permitted to take fish, coral, live rock, algae, seagrass and invertebrates for live ornamental display purposes.

1.1.2 Northern Territory Aquarium Fishery

The Northern Territory Aquarium Fishery (NTAF) is a small-scale, multi-species fishery, which operates with oversight from the Northern Territory Department of Primary Industry and Resources (NT Fisheries). The relevant *NT Aquarium Fishing/Display Fishery licence*, is limited to 12 licenses (only 11 currently granted), and enables the collection, sale and display of aquarium species. For the purpose of license conditions, the definition of coral and associated benthic species includes all coral and associated benthic species (including sea fans, anemones, corallimorphs and sponges) and live rock. Since 2010, there has been an increasing focus on the collection of corals, with a subsequent broadening of the range of species collected and the areas where they are harvested (DPIR 2019a). A re-assessment of the NTAF was undertaken in late 2019, as part of the necessary process to seek renewal of the WTO, which expires on December 5th, 2022.

NT Aquarium Fishing/Display fishery licensees may harvest from all inland, estuarine and marine waters to the outer boundary of the AFZ in NT waters, which includes an area of 523,946 km^2 of marine habitat. Harvesting is however, prohibited in a number of designated protected areas, Aboriginal sacred sites, aquaculture farm leases and sanctuary zones. Extrinsic limits on fisheries effort (due to tides, weather and dangerous marine animals) are also considered to be much more restrictive than for other jurisdictions (Queensland and Western Australia). The main management control used to limit catch of hard corals, giant clams and live rock in the fishery is the NDF harvest levels set in the WTO (Table 3.1). Overall taxon-specific harvest levels (based on WTO NDF Harvest levels) are distributed among individual licences based on catch levels for the licence in the 5 years prior to 2019-20 (DPIR 2019b). These Interim Harvest Levels (IHL) can be bought, sold, leased or transferred on an annual basis upon written application to the NT Director of Fisheries.

Regulation of NT Aquarium Fisheries began in the 1970s with development of C-Class licences (allowing for collection, trading or culturing of aquarium species), which were later (1993) split into three different licences, leading to the *NT Aquarium Fishing/Display Fishery* licence permitting the collection, display and sale of aquarium species. A cap (12 maximum) on the number of *NT Aquarium Fishing/Display Fishery* was imposed in 2001. Concerns regarding the sustainability of coral harvesting within NT have been raised since 1994, when there was a provisional ban placed on coral collection (DPIR 2019a). There have since been several major reviews of the fishery, culminating in major changes in the fisheries management in 2019 (DPIR 2019a), including i) implementation of electronic logbook returns (to be submitted within 5 days of returning to port) that facilitate reporting of all CITES listed species by weight, ii) refinement of WTO NDF Harvest limits for all taxa, allocated based on Interim Harvest Levels (IHL) applied to individual licences, iii) appointment of an Aquarium Fishery Management Advisory Committee, and iv) mandatory adoption of Vessel Monitoring Systems (VMS).

1.1.3 Queensland Coral Fishery

The commercial Queensland Coral Fishery (QCF) is largely a diver-based, hand-collection fishery operating within permitted zones (including general use, habitat protection and most conservation zones) in the Great Barrier Reef Marine Park (GBRMP). The risk posed by the fishery to wild stocks of reef corals is considered negligible (e.g., Harriot 2001), based on the high turnover of corals, the large extent of coral reef habitats within the GBRMP, and existing protection from harvesting within extensive no-take areas. The combined area of reef habitat within the GBRMP is estimated to be 24,000km^2 (~7% of the entire area of the Park), and ~33% is closed to fishing (Fernandes 2005). There have however, been concerns raised regarding localised depletion of specific coral species in areas of

concentrated fishing activity (Jones 2011), as well as the threat posed by extrinsic disturbances (such as cyclones, outbreaks of crown-of-thorns starfish and mass coral bleaching) that have resulted in widespread and sustained declines in the overall cover and abundance of corals within the GBRMP (De'ath et al. 2012). The current WTO was issued in June 2018, based on outcomes of the 2013 ERA workshop (which found that there were no high risk species, though 17 species were considered to be at moderate risk, and 63 species at low risk; Roelofs 2018) and will expire on June 18th, 2021.

The QCF is managed using both input (effort) and output controls. The current Total Allowable Commercial Catch (TACC) is 200,000 kg per annum, which is split between specialty coral (30%) and other coral (70%). The quota split was originally intended to reflect those corals (speciality corals) that were collected and primarily sold live as aquarium species (e.g., *Catalaphyllia jardinei* and *Trachyphyllia geoffroyi*) versus the relatively fast-growing corals (Acroporidae and Pocilloporidae) that were traditionally collected for curios, as well as dead corals collected as aquarium habitat (McCormack 2005). There are currently no species-specific quotas imposed, though the fishery is considered to be highly selective (e.g., McCormack 2005) and marked changes in the reported catch of specific target species within specific coral catchment areas trigger specific management responses. Fishing effort in the QCF is becoming increasingly diffuse and widespread, though there remain some specific areas of concentrated fishing effort (e.g., near Mackay), mostly related to the restricted distribution of some heavily targeted coral species, mostly *Homophyllia australis*. Widespread species tend to be collected in specific areas closest to the major landing locations for each distinct operator (e.g., Cairns, Mackay or Yeppoon), though many of the operators are extremely mobile and will periodically travel vast distances to obtain specific species necessary to complete export shipments of diverse coral stock. Much of the coral is harvested from deeper water (>10 m) or in shallow turbid environments (Harriot 2001, Jones 2011). There are a maximum of 59 commercial licences endorsed for the QCF (Table 3.1).

Coral has been harvested on the Great Barrier Reef (GBR) since the 1930s, and up until 1980s commercial harvesting was focussed on fast growing branching corals (Acroporidae and Pocilloporidae) that were sold as curios. During this formative period, coral harvesting was restricted to designated coral collection areas. The QCF commenced as a licensed fishery on 1 July 2006, which allowed for roving harvests of all licence holders. From 2009/10 to 2017/18 the total reported annual catch has been between 74 and 99 tonnes, with a maximum of 35 tonnes of specialty coral and 64 tonnes of other coral reported in 2013/14 (Heaven 2018). In 2018/19, the total reported catch increased to 111 tonnes, comprising 43 tonnes of specialty coral and 67 tonnes of other coral (QDAF 2019). This coincided with the highest reported levels of annual fishing effort (1,201 fishing days), which was >20% higher than the previously reported fishing effort (QDAF 2019).

1.1.4 Coral Sea Aquarium Fishery

Coral Sea Aquarium Fishery (CSAF) allows for harvesting of limited coral species (family Acroporidae) within the Coral Sea Marine Park (CSMP) located in Commonwealth waters between the Great Barrier Reef and eastern margin of Australia's Exclusive Economic Zone (EEZ). Management of the CSAF is undertaken by the Australian Fisheries Management Authority (AFMA) and involves input (limited concessions and extensive spatial closures) and output controls (annual catch triggers, rather than strict total annual quotas), with the harvest strategy recognising the low fishery effort, as well as large extent and limited accessibility to the CSMP. There are currently just two operators that are permitted to operate within the CSAF.

Fishing activities in CSMP were spatially restricted with new zoning implemented on July 1, 2018, and there are also significant input controls. The current annual catch trigger is 40,000 kg and the CSAF is restricted to harvesting corals from the family Acroporidae, which are considered to be particularly resilient to overfishing (AFMA 2017). Most crucially, *Acropora* corals are relatively fast growing, often recruit in high densities, have high rates of natural mortality and are relatively short-lived. These life-

history characteristics result in rapid population turnover, which would confer generally high resilience to moderate levels of exploitation (AFMA 2017). The CSAF is included here to provide a comprehensive overview of Australian coral fisheries, though none of the major focal species of this project are currently permitted to be harvested from within the CSMP.

Table 1.1. Current status of Australian coral fisheries operating across northern Australia. Most coral harvested is kept and sold live for the marine aquarium industry. Current quotas do not necessarily reflect contemporary harvest levels.

Fishery	No. licences	Annual TACC (hard corals)	Major target species (hard corals)	Additional quota
Western Australian Marine Aquarium Fish Managed Fishery	12	15,000 kg	*Duncanopsammia axifuga* *Euphyllia ancora* *Trachyphyllia geoffroyi* *Euphyllia glabrescens* *Catalaphyllia jardinei*	i) 60,000 kg of live rock ii) 2,400 individual giant clams
Northern Territory Aquarium Fishery	11 (8 active)	Taxon-specific harvest levels, mostly 40kg for individual species and 160kg for species groups (e.g., *Acropora* spp.).	*Euphyllia paraancora* *Euphyllia ancora* *Heliofungia actiniformi* *Duncanopsammia axifuga* *Acanthastrea echinata*	i) 6,000 kg of live rock ii) 280 *Tridacna* clams
Queensland Coral Fishery	59 (32 active)	200,000 kg, with 30% (60,000 kg) for specialty hard coral	*Acropora* spp. *Micromussa lordhowensis* *Homophyllia australis* *Catalaphyllia jardinei* *Euphyllia glabrescens* *Trachyphyllia geoffroyi* *Duncanopsammia axifuga*	140,000 kg of live rock, including fast-growing (ornamental) corals
Coral Sea Aquarium Fishery	2	40,000 kg but limited to Acroporidae	*Acropora* spp.	40,000 kg of live rock

Australia's coral fisheries (the Western Australian Marine Aquarium Fish Managed Fishery, the Northern Territory Aquarium Fishery, the Queensland Coral Fishery and the Coral Sea Aquarium Fishery) are individually and collectively subject to considerable scrutiny and political pressure. This is because coral harvesting represents the most direct and preventable (albeit fairly minor) cause of coral loss across iconic reef ecosystems, such as the Great Barrier Reef and Coral Sea Marine Park. Moreover, scientific studies and established monitoring programs are consistently and regularly reporting that overall cover and abundance of corals is in decline (e.g., De'ath et al. 2012; Mellin et al. 2019; Gilmour et al. 2019), at least in shallow, clear-water (mostly offshore) locations (see below). Recorded coral loss has been attributed to outbreaks of crown-of-thorns starfish, cyclones, coral bleaching, and general degradation of environmental conditions that have undermined the growth and vitality of reef corals (De'ath et al. 2012; Gilmour et al. 2019). In general, near shore environments are considered to be the most degraded (owing to proximity to coastal processes and exposure to land runoff), but ongoing scientific research and monitoring, and our corresponding

understanding of the cause(s) of coral loss, is mainly restricted to clear water and shallow (<12m depth) reef environments. As such, little is known about changes in the abundance or health of corals from deeper waters, inter-reefal habitats or inshore, turbid environments.

2. Objectives

The overarching objectives of this project were to:

1) Establish the distribution and abundance of commercially important coral species in selected inter-reef habitats;
2) Improve the accuracy of species identifications across the industry;
3) Establish abundance and turnover of representative commercially important inter-reefal corals;
4) Establish a cost-effective industry based long-term monitoring program; and
5) Undertake consistent Environmental Risk Assessments (ERA) in NT and WA to establish vulnerability of major target species.

The specific objectives were further subdivided into three components to establish sustainable harvest limits and vulnerabilities of major target species:

i) **Establish the abundance and turnover of select, commercially important coral species in areas of concentrated fishing across northern Australia** - Improved understanding of the biology and ecology of harvested corals is fundamental for establishing baselines and sustainable harvest levels and to defend Non-Detriment Findings (NDF), necessary for the continued international trade in these CITES listed species. Most importantly, we need to obtain rigorous scientific measures of stock abundance to establish species-specific levels of harvesting that might be sustainable. Complementary changes in the nature and accuracy of catch reporting will then be required to implement necessary reforms within current management frameworks, thereby ensuring sustainability of ongoing harvesting as well as better responding to emerging and increasing extrinsic pressures.

ii) **Refine species-level taxonomy (where required), to better establish what is being harvested** - A significant limitation to understanding the sustainability of coral fisheries across northern Australia is the limited taxonomic resolution, and often contradictory names that are used to report coral harvests and exports. Our focus will be on poorly studied corals (mainly, *Catalaphyllia*, *Duncanopsammia, Euphyllia*, *Homophyllia*, *Micromussa*, and *Trachyphyllia*) which are often harvested from non-reefal habitats, and are also of high value (due to either the inherent demand for brightly coloured corals or restricted geographic range or area of harvest) and are an extremely important component of live coral exports. Discrepancies in the taxonomic identification between aquarium collectors and coral taxonomists will be resolved using morphological and molecular analyses. Improved understanding of taxonomy and species recognition is also a critical component of improved catch reporting and compliance, serving to establish relevant categories for fisheries management.

iii) **Explore species-specific vulnerability to extrinsic pressures on coral stocks, mostly related to environmental change** - The increasing incidence and severity of large-scale disturbances linked to accelerating environmental changes (Hughes et al. 2017b) could undermine the sustainability of ongoing coral harvesting independent of fishery effort or take. Importantly, large-scale monitoring on the GBR has reported a 50% decline in live cover of scleractinian corals over the last 27 years (De'ath et al. 2012). Similarly, in Western Australia there have been reported declines in coral cover around Dampier (Moustaka et al 2019) and Exmouth Gulf (Depczynski et al 2013). However, there is often little taxonomic overlap between the ornamental coral fishery and coral assemblages studied in shallow reef environments, and there is limited understanding of the potential risk posed by large-scale disturbances (e.g., climate change) to corals found in non-reef habitats. Explicit experimental studies, will therefore, be conducted to test for taxonomic variation in the susceptibility of important harvested corals to ocean warming and coral bleaching. We also tested for regional differences in bleaching susceptibility, using common garden experiments to compare bleaching responses of coral species that occur across sample locations in Western Australia, Northern Territory and Queensland.

3. Methods

3.1 Abundance and turnover of commercially important coral species

3.1.1 Study species

This project was necessarily restricted in taxonomic scope, and priority species were selected based on i) their importance to coral fisheries (and especially exports) across Western Australia, Northern Territory and Queensland, and ii) perceived risk to over-fishing and/ or fishery independent threats, as identified during Ecological Risk Assessments (ERA) conducted in Queensland (Roelofs 2018), Western Australia (DPIRD 2018), and Northern Territory (DPIR 2019), as well as the Stewardship Action Plan (SAP) for the QCF (Donnelly 2013). Importantly, there are several distinct groups of corals that are consistently targeted across all three State-based fisheries, including *Euphyllia* species, and *Duncanopsammia axifuga,* though the greatest overlap in species of importance occurs between Western Australia and Queensland. The specific species used in each of the different components of this study (as described below) varies in accordance with the availability of biological material and specific contributions from licensed collectors in different regions. For the most part, we were interested in 6 species (Table 31, Figure 3.1) and considered other closely related species (from families Euphylliidae and Lobophylliidae; Table 3.2), as appropriate.

Table 3.1. Major study species: These six coral species, which are generally readily distinguished in collections and field surveys, and are disproportionately represented in catches, were the predominant (though not exclusive) focus of research into growth, reproduction, abundance, stock structure, and vulnerability to bleaching.

Family	Genus	Species
Dendrophylliidae	*Duncanopsammia*	*axifuga*
Euphylliidae	*Catalaphyllia*	*jardinei*
Euphylliidae	*Euphyllia*	*glabrescens*
Lobophylliidae	*Micromussa (Acanthastrea)*	*lordhowensis*
Lobophylliidae	*Homophyllia (Scolymia)*	*australis*
Merulinidae	*Trachyphyllia*	*geoffroyi*

The focal study species (Table 3.1) represent only a small proportion of the coral species that are harvested across northern Australia. Moreover, there are critical knowledge gaps (as identified during respective ERAs; see Extension and Adoption) that constrain effective species management across a broad range of different coral species that are important in maintaining the viability of the fisheries, and meeting export demand for Australian coral. However, it was not possible to cover all industry research and species priorities during this project, and it was always expected that additional and significant scientific research and monitoring would be warranted even after the completion of this project.

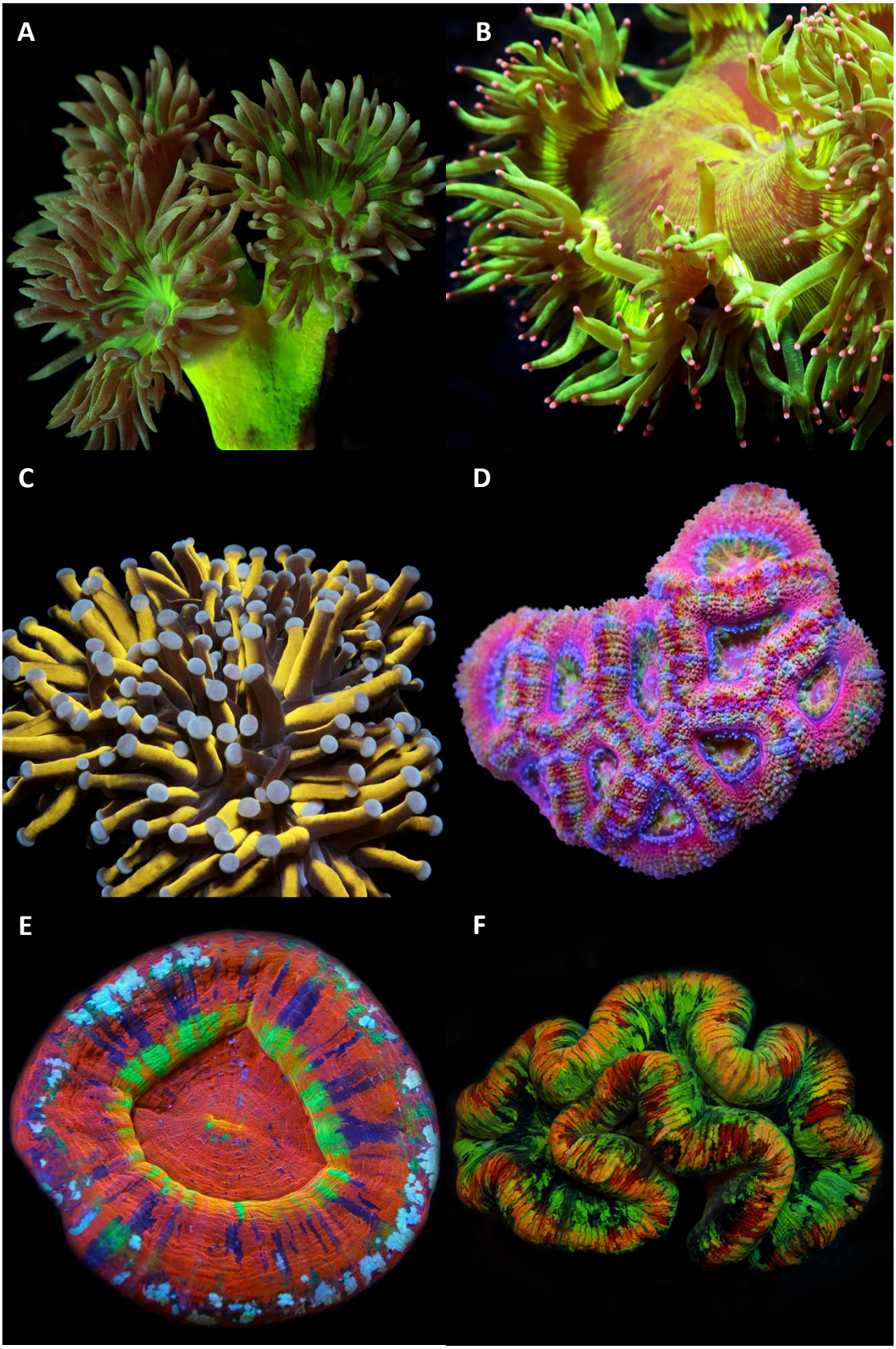


Figure 3.1. Major study species: A) *Duncanopsammia axifuga*, B) *Catalaphyllia jardinei*, C) *Euphyllia glabrescens*, D) *Micromussa lordhowensis*, E) *Homophyllia australis*, and F) *Trachyphyllia geoffroyi.* All photographs taken by Ciemon F. Caballes ©2020.

Table 3.2. Ecological risk levels for major focal species (and their closest relatives) as established during most recent Ecological Risk Assessments (ERA) conducted in Queensland (QLD) in 2013 (Roelofs 2018), Western Australia (WA) in 2014 (DPIRD 2018) and Northern Territory (NT) in 2019 (DPIR 2019a). We standardised risk levels across all ERAs - Negligible risk (Neg), Low risk (Low) and Moderate risk (Mod). Where species were not assessed (or not harvested) the risk level was left blank. All species are listed as per latest and verified nomenclature, following Hoekema and Cairns (2020a), with comments on phylogenetic relationships, including synonymised species (Syn), and change in genera (Orig). "*" indicate the focal species of this study. See also Extension and Adoption.

Family/ Species	QLD (2013)	WA (2014)	NT (2019)	Affinities
Dendrophylliidae				
**Duncanopsammia axifuga*	Mod	Low	High	
Euphylliidae				
**Catalaphyllia jardinei*	Low	Neg		
Euphyllia cristata	Mod	Neg		
Euphyllia fimbriata	Mod			
**Euphyllia glabrescens*	Mod	Neg	Mod	
Euphyllia paraglabrescens			Mod	
Fimbriaphyllia ancora	Mod	Neg	Mod	Orig. *Euphyllia*
Fimbriaphyllia divisa	Mod			Orig. *Euphyllia*
Fimbriaphyllia paraancora	Low	Neg	High	Orig. *Euphyllia*
Fimbriaphyllia paradivisa	Low			Orig. *Euphyllia*
Fimbriaphyllia yaeyamaensis				Orig. *Euphyllia*
Lobophylliidae				
Acanthastrea echinata			Mod	
Acanthophyllia deshayesiana	Mod			
Cynarina lacrymalis	Mod	Neg	High	
Goniopora diminuta			High	Orig. *Micromussa*
**Homophyllia australis*	Mod	Neg		Orig. *Scolymia*
Homophyllia bowerbanki	Mod			Orig. *Acanthastrea* Syn. *Acanthastrea hillae*
Lobophyllia vitiensis	Low		Low	Orig. *Scolymia*
Micromussa pacifica				
**Micromussa lordhowensis*	Mod	Neg		Orig. *Acanthastrea*
Micromussa amakusensis	Mod			Orig. *Acanthastrea*
Merulinidae				
**Trachyphyllia geoffroyi*	Mod	Neg		

3.1.2 Study sites

To limit the geographical scope, and maximise feasibility of this study, we pre-selected sites in areas with concentrated fisheries activity to initiate monitoring of coral growth and survivorship relative to ongoing harvesting. In Western Australia, coral harvesting is concentrated in Karratha, and to a lesser extent in Exmouth (Figure 3.2). Accordingly, our research was conducted across three readily accessible locations within the vicinity of Karratha. Field sampling was conducted predominantly in

intertidal habitats, and took advantage of the lowest annual tides to run transects, tag and collect corals during tidal exposure. However, in-water sampling was undertaken near Exmouth.

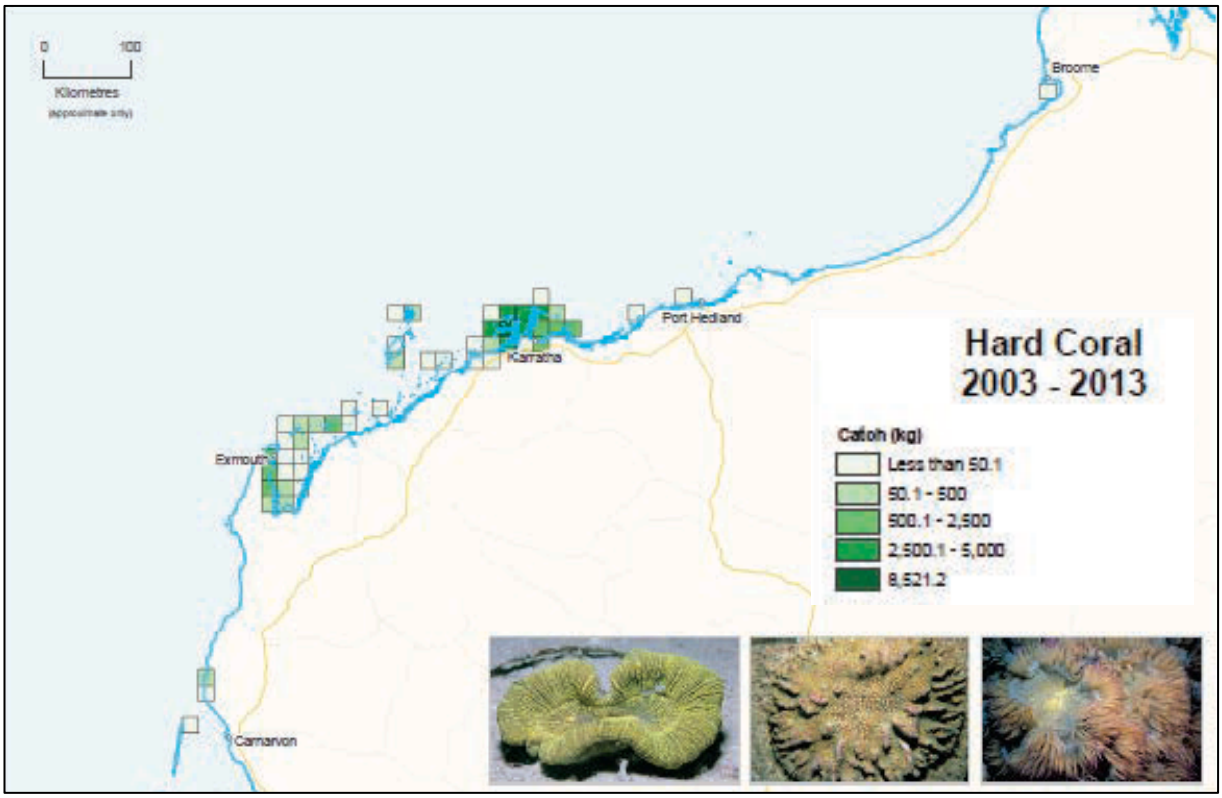


Figure 3.2. Catch and distribution of hard (scleractinian) corals taken by Western Australian Marine Aquarium Fish (MAF) Managed Fishery in northern Western Australia. Data is for total catch averaged annually for the period 2003 – 2013, showing concentration of effort near Karratha, and to a lesser extent near Exmouth. Source: DPIRD (2018).

In Queensland, spatial representation across major fishery areas was achieved mainly by working with distinct license holders operating in the northern versus southern GBR. Specific locations of interest were provisionally set as i) traditional harvest locations within the central GBR close to Cairns, and ii) inshore habitats between Mackay and Yeppoon, reflecting the disproportionate number of licence holders operating within this area and apparent concentration of effort for specific coral species (Figure 3.3). More specifically, we focussed on two distinct 36 nautical mile boxes (I16 and P25; Figure 3.3), as stipulated by the Queensland Government Department of Agriculture and Fisheries (QDAF) for logbook reporting by the Queensland Coral Fishery. These specific fishery areas represent key fishery locations across several of the focal study species (including *H. australis*, *T. geoffroyi* and *C. jardinei*). These study areas did however, each pose significant, but distinct, impediments to fishery-independent research and monitoring; at mid-shelf locations in the northern GBR, corals are generally harvested from inter-reef locations in depths that are beyond the effective working limits (>12m) of research diving. At inshore locations off Mackay, meanwhile, sampling is constrained by large tides, strong currents, and generally poor visibility. This limited opportunities to conduct sampling, though we did manage to conduct extensive sampling (>50 transects) in nearby locations, located further offshore.

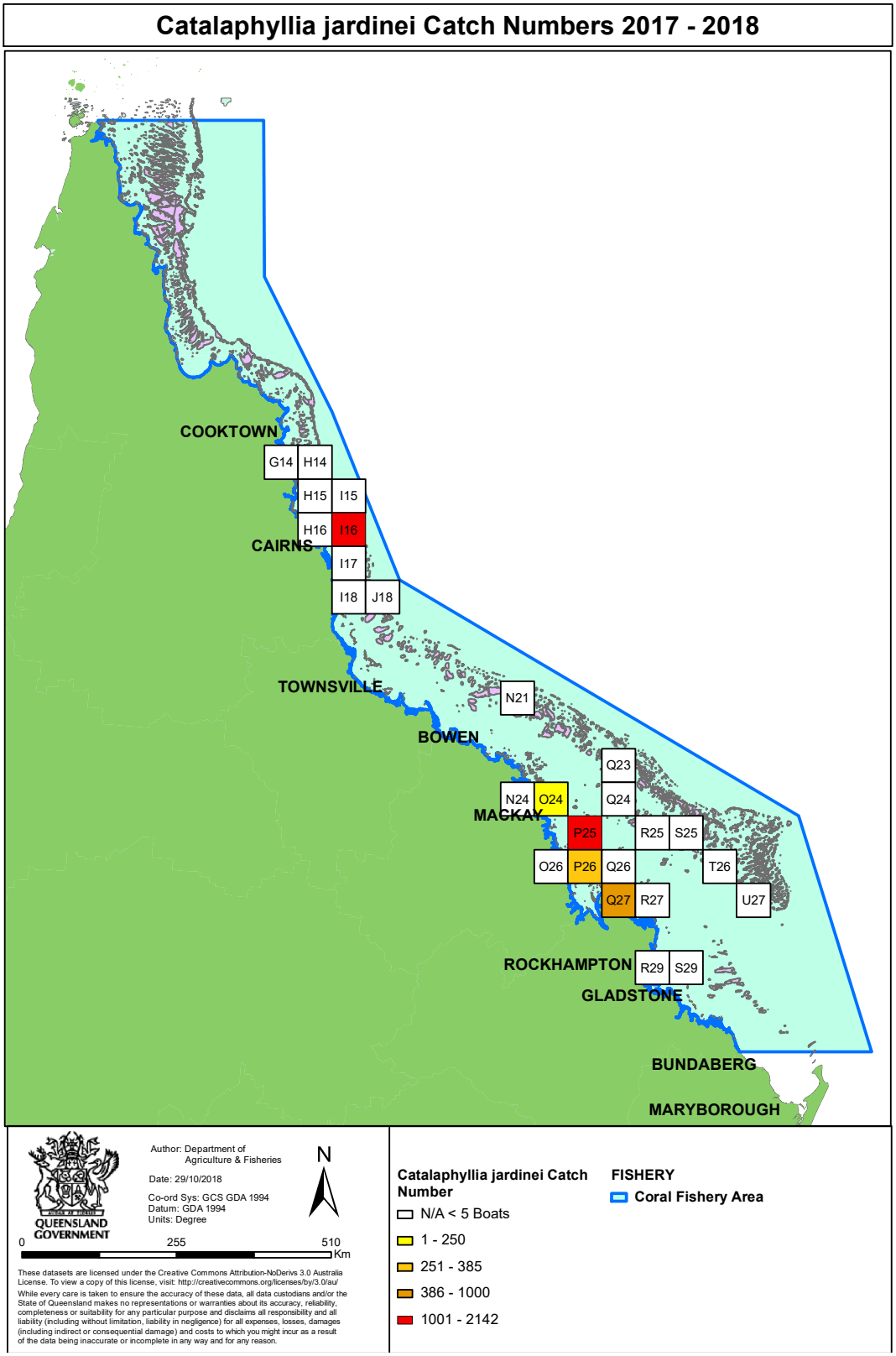


Figure 3.3. Catch distribution of *Catalaphyllia jardinei* for the Queensland Coral Fishery. Data is for total catch annual catch in the reporting period 2017-2018, and excluding confidential data from all locations where this species was harvested but <5 boats were operating (white boxes), showing concentration of catch from boxes I16 (off Cairns) and P25 (off Mackay). Source: QDAF (2019).

The Northern Territory aquarium fishery is dominated by a small number of licensees, who willingly provided required samples as well as conducting independent sampling at sub-tidal locations. These transects allowed for quantification of abundance, but not biomass, of potential harvest species. Additional requirements for genetic material, reproductive samples, and bleaching experiments were met from existing stock or new collections, as available. It is apparent that there are two distinct habitat-types from which corals are harvested, generally distinguished as i) near shore reefs with high tidal flows and turbid conditions and ii) clear water offshore reefs. As expected, these two habitats and distinct environments support very different coral fauna, and both need to be considered to understand fisheries activities and vulnerabilities in NT.

3.1.3 Stock size and structure

Field-based sampling to establish the stock size and structure of major harvest species, and species of concern, was undertaken in pre-selected areas of concentrated fisheries effort, as described above (Section 3.1.2). All sampling was conducted during the course of the current project, from March 2016 to July 2020. Where possible and often with support of industry, we quantified the local abundance of focal coral species within specific study areas using replicate 50 × 1m belt transects. Transect length was assured by deploying a fiberglass measuring tape (or 50 m string line) to the relevant substrate within specific habitats. A 1-m wide path was then surveyed along the length of the transect line, mostly following video recordings taken along the entire length of each transect (Figure 3.4). All corals that were subject to harvesting were recorded within the area of each transect, recording the number of distinct colonies of each species as well as estimating their size. The goal was to estimate the abundance and size-structure of specific coral species within specified habitats. Colony size of specific focal species (Table 3.2) and closely related species (e.g., family Euphylliidae and Lobophylliidae) was estimated based on the maximum and perpendicular diameter.

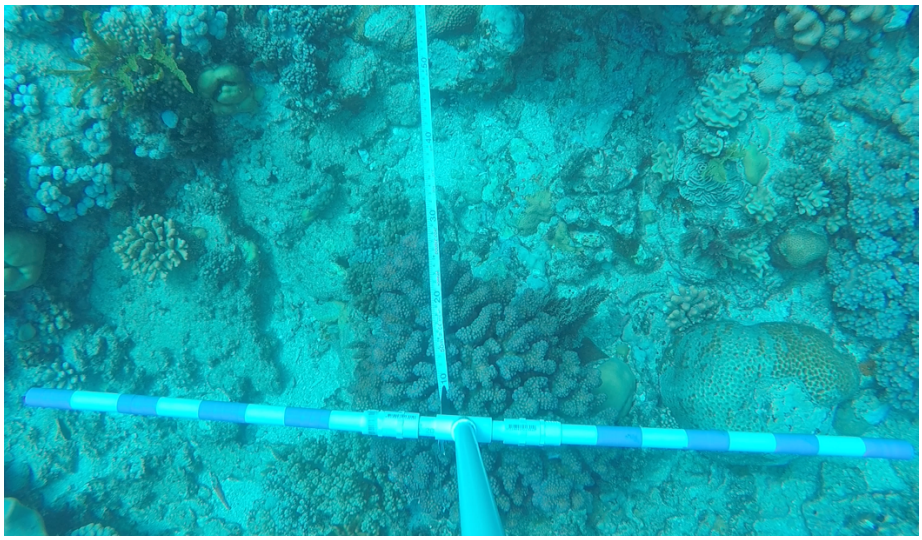


Figure 3.4. Video transect protocol developed in conjunction with aquarium industry representatives to document size and abundance of major target species along 50 × 1m belt transects. The PVC jig (with 1m scale bar) is attached to a GoPro (Hero 4) held by a diver, who swims along the transect line at a maximum of 10m per minute.

A total of 246 video transects (50m^2) were surveyed during the course of this study, providing unprecedented information on the stock-size and structure of harvested coral species within 12,300m^2 of fishery habitat across all three jurisdictions (Western Australia, Northern Territory and

Queensland). There were a disproportionate number of transects run in Western Australia, and especially intertidal habitats near Karratha (Table 6.3), owing to the relative ease of sampling in these locations, and collaborations between researchers, managers and industry that greatly increased efficiency and effectiveness of sampling in this location. Similarly, researchers collaborated with licensees to greatly increase the sampling intensity in subtidal habitats in Queensland (in both Cairns and Mackay regions). In all, the majority of transects (181 out of 246) were run by researchers and/ or managers, albeit in habitats where licensees targeted the main study species. There were however, a number of transects (65 transects) provided by licensees that were conducted completely independently, and entirely at their own expense.

Table 3.3. Extent and distribution of *in situ* video transects completed (in each state and territory) to provide an indication of abundance and biomass of focal coral species. The biomass was calculated based on the size (maximum and perpendicular diameter) of each coral colony, and then averaged across replicate transects in each location.

State	Region	No. of transects	Notes
Western Australia		**130**	
	Karratha	112	Intertidal
	Exmouth	12	Subtidal
	Dampier	6	Subtidal
Northern Territory		**18**	
	Various	18	No scale reference
Queensland		**98**	
	Cairns	35	Subtidal
	Mackay	60	Subtidal
	Keppels	3	Subtidal

To convert two-dimensional size estimates into biomass, we explicitly assessed size and weight relationships for specific coral species based on colonies harvested by licensed coral collectors. A total of 2,585 corals (mostly intact colonies of freshly harvested corals, with little or negligible substrate attached) were measured across the six focal study species (Table 4.1). This included all corals that were provided for dedicated studies on the reproductive biology, genetic structure and bleaching susceptibility (described below). However, these data were supplemented by additional opportunistic sampling conducted during access to aquarium coral facilities in Western Australia and Queensland. For each coral, we measured two perpendicular diameters (which were then averaged) and recorded the wet (but drained) weight. All corals (as selected by licensed coral collectors in Queensland, Northern Territory and Western Australia) were generally small (<30cm diameter, and <2 kg weight), especially for *H. australis*, which almost always occurs as solitary polyps (Huang et al. 2016). However, even specimens of colonial species, such as *M. lordhowensis*, which can grow to >1m diameter, were mostly harvested as small colonies or fragments, up to 200mm average diameter. For larger corals (e.g., *M. lordhowensis*), measurements were based on the overall colony as it was originally collected, though we did want to minimise the amount of additional substrate attached to corals. As such, corals were often weighed only after excess carbonate had been removed, during trimming (see Pratchett and Messmer 2017). The relationship between diameter and weight was expressed using a two-parameter power function, which was subsequently applied to diameter measurements from video transects to estimate species-specific biomass.

3.1.4 Coral Growth

Growth of focal coral species was measured in the field by individually tagging select colonies using UV-stabilised plastic cattle tags. Where possible tags were attached to hard substrate within the immediate vicinity of the focal coral (e.g., using galvanised nails hammered into carbonate pavement), but many of the corals were growing over soft substrate. In these instances, tags were directly attached to the coral colony using cable ties. On each sampling occasion, all tagged colonies were photographed from 1 m above and perpendicular to the surface of the colony. A scale bar was placed on or adjacent to the surface of each colony when photographed (Figure 3.5). The maximum and perpendicular diameter of each coral was also recorded *in situ*. Measuring the growth of corals in their natural habitats is complex, owing to high rates of partial mortality (Tan et al. 2018), which means that corals can effectively increase and decrease in size. Growth was therefore, estimated based on changes in the mean radius, which provides an estimate of the net change in colony area that is independent of colony size (Meesters et al. 1996; Pratchett et al. 2015), both by comparing direct measurements of colony diameter in the field, as well as precise estimates of the horizontal planar (projected) area of colonies (excluding regions of tissue loss) using the software package ImageJ (http://rsbweb.nih.gov/ij/).

Figure 3.5. Individually tagged coral (*Duncanopsammia axifuga*) in the intertidal habitat near Karratha, which was followed through time to estimate growth and mortality.

A total 174 individual corals were tagged, across 4 different species, exclusively within intertidal habitats in Western Australia (Table 3.4), ranging in size from 9-700 mm diameter. The approximate position of each coral was recorded using GPS fixes, while individually numbered tags (Figure 3.5) allowed for reliable identification of individual corals. The species considered in this study were selected based on their local abundance in specific, accessible habitats. Notably, *Homophyllia bowerbanki* was considered herein even though it is not one of the focal species of this study,

because there is a complete lack of scientific knowledge about the natural growth rates of corals within this family (Lobophylliidae).

While this study was conducted exclusively in intertidal habitats, similar protocols could be used to document the growth of corals in sub-tidal environments, though the specific position of individual corals would need to be recorded with reference to permanent landmarks or fixed markers (e.g., stainless steel stakes hammered into the carbonate matrix), owing to limitations of using GPS in and under water. Arrangements were made (including the necessary permit approvals) to allow for extensive tagging of coral colonies in sub-tidal habitats, but licensees were reticent to undertake necessary tagging mainly because they rarely re-visit locations with high densities of focal organisms on requisite timeframes (within 1- year). However, as for transect sampling materials, necessary tags and scale features were distributed to many licensees to allow future studies of coral growth in key locations, especially on the Great Barrier Reef.

Table 3.4. Size and identity of coral colonies that were individually tagged to measure annual growth based on monthly mean changes in colony radius. All corals were located within intertidal habitats in Western Australia.

Species	n	Initial size range Diameter (mm)
Duncanopsammia axifuga	52	38-630
Euphyllia glabrescens	39	9-222
Trachyphyllia geoffroyi	46	58-700
Homophyllia bowerbanki	37	12-110

3.1.5 Reproductive Biology

To establish the reproductive biology, and most critically, the minimum size of reproductive maturity for focal study species, we asked industry representatives to provide freshly collected entire and intact coral colonies inside of 1-month prior to the predicted annual spawning in each location. We specifically requested samples at the smaller end of the size range that is normally collected, including (where possible) the smallest colonies detected within each location.

All reproductive samples (representing small whole colonies) were preserved in 10% seawater formalin solution and then decalcified using formic acid solution. Colonies were initially placed in 5% formic acid solution for 24 hours, which was then refreshed with increasing strength (up to 10%) formic acid solution every 1-2 days. Once decalcified, tissue samples were placed back into 10% seawater formalin for storage prior to dissection. Decalcified samples were dissected around the oral disk of polyps to target mesenteric tissues that represent reproductive sections of the polyp (both laterally and longitudinally) in order to maximize the chance of detecting gametes. These sections were transferred to 70% ethanol solution before being processed at the James Cook University Histology Laboratory. Samples were mounted and then 5 sections per sample (7 microns thick) were taken at different depths across the polyp tissue to give a good representation of the whole specimen. Sections were then mounted onto glass slides and stained with Mayer's haematoxylin (staining nuclei blue) and Young's eosin-erythrosin (staining cytoplasmic components red).

Slides were examined under a microscope to record the occurrence and developmental stages of oocytes and spermaries. The presence of planula larvae from the slides was used to determine the reproductive mode. *Ex situ* observations during the spawning season were also conducted to characterise the reproductive mode of target species. The general maturity based on gravid or empty

samples were recorded. The sexuality of gravid samples was identified as female, male or hermaphroditic based on whether they contained only oocytes, only spermaries, or both oocytes and spermaries, respectively. When located, gametes were graded based on developmental stages adapted from Szmant-Froelich et al. (1985) and Baird et al. (2011). Size at reproductive maturity was assessed by determining the minimum size at first reproduction (MSFR) and by estimating the diameter of the coral at which 50% were reproductively mature (D_{50}). This was done using the 'gonad mature' function in the 'sizeMat' package (Torrejon-Magallanes 2020) in R (R Core Team 2020), where Bayesian regression was performed and a sample from the posterior distribution of a logit regression model using a random walk Metropolis algorithm was generated.

3.2 Refined species-level taxonomy

A significant constraint to the effective management of coral fisheries across northern Australia is the limited taxonomic resolution, and often contradictory names are used in reporting what corals have been harvested and exported. For example, up to 218 different coral taxa (nominally referred to as "species") are recorded among annual exports from the Queensland Coral Fishery. Most of these species are not well resolved; either identified only to genera, or known only by "trade names". Added to this, there have recently been major advances in understanding the phylogenetic affinities of scleractinian corals (e.g., Huang et al. 2011; Arrigoni et al. 2014a, 2019) and necessary changes in nomenclature. For example, many of the major coral species harvested by Australian coral fisheries have been reassigned to different genera or families in recent years following increased molecular sampling and analyses (Table 3.2). Of particular importance to this study, is the recent emergence of several new species of corals (often cryptic species) with large solitary polyps (Arrigoni et al. 2014b, 2016), suggesting that there may be multiple species of Lobophylliidae currently attributed to *H. australis*, which is widely harvested in Queensland, but also collected in Western Australia and the Northern Territory. It is also possible that other coral species reported to occur over large geographic ranges, but with widely disparate morphologies in different locations (e.g., *C. jardinei* and *T. geoffroyi*) may represent multiple species.

Tissue samples (for molecular analyses) were taken from individual and intact coral colonies provided by licensed coral collectors from Western Australia, Northern Territory and Queensland (Table 6.5). Tissue samples were taken from live corals and preserved in ethanol. Samples were then stored at -10^{o}C before being sent to respective genetics laboratories. Tissue samples for all species except *T. geoffroyi* were sequenced at King Abdullah University of Science and Technology, in Saudi Arabia, following Arrigoni et al. (2019). *Trachyphyllia geoffroyi* samples meanwhile, were sequenced at the National University of Singapore, following Huang et al. (2011). Total DNA was extracted form coral tissues using DNAeasy kits, following Arrigoni et al. (2014). Analyses of phylogenetic relationships were tested using a single nuclear (ITS2) marker. This marker (ITS2) is relatively robust and definitive in describing species boundaries among Lobophylliidae spp. (Arrigoni et al. 2014a, b), and was readily aligned using the ClustalW algorithm. Sequence data for individual samples, where provenance is based mainly on the collector, was compared with available sequence data from GenBank.

Table 3.5. Identity and provenance (State and Business – see Table A.1) of all genetic samples analysed to clarify taxonomic identity and where necessary, explore species boundaries. Additional samples have been provided since preliminary analyses were completed, to further resolve species boundaries.

Nominal Species	Queensland				NT	WA	Total
	CM	UCA	CDU	GBRM	MA	ACF	
Catalaphyllia jardinei	23		9	11			43
Duncanopsammia axifuga	26		15			43	84
Trachyphyllia geoffroyi	20	26				35	81
Micromussa lordhowensis		17		28			45
Homophyllia australis		45	18	19	21	10	113
Total	69	88	42	58	21	88	366

Total genomic DNA was extracted using the DNeasy Blood and Tissue kit (Qiagen Inc., Valencia, CA, USA) from coral tissue preserved in ethanol following Huang et al. (2011). For all coral samples, we amplified and directly sequenced ITS2 markers. Maximum likelihood (ML) was then used to construct phylogenetic trees for all samples of each nominal species, along with existing sequences of known identity and origin that represent each species (Table 3.5). Select outgroups (as relevant for each taxonomic group) were also selected and used to assess genetic variability within each group.

3.3 Species-specific vulnerability to extrinsic pressures

Despite extensive field-based sampling to assess taxonomic variation in bleaching susceptibility among reef-building corals (e.g., Loya et al. 2001), there is limited knowledge of temperature sensitivity and bleaching susceptibility for most aquarium coral species. As such, dedicated experimental studies were conducted in the Marine Aquarium Research Facility (MARFU) at James Cook University. Licensed coral collectors provided a total of 257 distinct corals (mostly whole colonies or individual polyps, but sometimes fragments) across 6 different nominal species, which were transported to Townsville within 1-2 weeks of collection (Table 3.6). Where possible, samples of each coral species were obtained from Western Australia (WA), Northern Territory (NT), north Queensland (NQ) and central Queensland (CQ) (Table 3.6). All corals were mounted on ceramic discs, which were coded to distinguish individual corals and their provenance. Corals were randomly assigned to one of 12 different tanks across four different treatments (Figure 3.6), with 3 replicate tanks per treatment.

To test the bleaching responses and temperature sensitivity of the different corals, corals within the "heated treatments" were subject to gradual warming (1.0°C change per week) until the temperature reached a maximum of 32°C. The reason for using prolonged heating to relatively high maximum temperatures was intended to explicitly assess interspecific and regional variation in bleaching susceptibility, based on the time until individual corals exhibited bleaching. Temperatures in control tanks started at 25.6°C, and varied between 25.1-27.5°C through the course of the experiment. Given most of the study species come from turbid inshore or deeper inter-reefal habitats, it was possible that bleaching susceptibility would be moderated by the light environment. To test this, we further divided corals into high and low light treatments, whereby the maximum light intensity (measured using a Li-Cor portable light meter during peak irradiance) was 208.0 ($\pm$ 10.6 SE) and 48. 7 ($\pm$ 2.8 SE) $\mu mol.m^{-2}.s^{-1}$, respectively (Pratchett et al. 2020).

All colonies were acclimated to experimental conditions (ambient temperature and low light) for a minimum of 1-week before being subjected to high light and/ or experimental warming. The day that warming was initiated (April 9th 2018) was set as Day 1, and corals were subjected to experimental conditions until Day 75, at which time experimental tanks with high temperatures were reduced to ambient temperatures over 72 hours. We then continued to monitor all surviving colonies until Day 150. Corals were inspected every 1-2 days to record survival, and scored for colour (following Siebeck et al. 2006) every 1-2 weeks. This provided a non-intrusive method to assess changes in coral health over the course of the study. Survival of individual coral colonies was recorded as the sum of the proportion of time a coral survived during the heating experiment plus the proportion of time the coral survived post treatment; i.e. corals that survived to day 75 (end of heating experiment) were assigned a survivorship of 1.0, and corals that survived to day 150 (end of study period) were assigned survivorship of 2.0. Changes in colour were based on changes in colour saturation (measured on a 6-point scale), between initial records taken on Day 1 versus Day 75 (or the last record of colour hue taken prior to mortality). Bleaching was defined as a change in colour saturation of 2 units or more, following Siebeck et al. (2006).

To test for species-specific differences in temperature sensitivity, we modelled changes in colour (whereby, corals often expel zooxanthellae and "bleach" when exposed to elevated temperatures or other environmental stress) and survival in corals as a function of 'Temperature' and 'Light' using linear mixed effects models (Bates et al 2015). 'Species', 'Temperature', and 'Light' were included as fixed effects. We also included the individual 'Tank' where the corals were placed as a random effect to account for the non-independence of replicates tested within the same aquarium. 'Region' was not included as a factor since some species were only sourced from one locality. Alternative models were compared using Akaike's information criterion corrected for small sample sizes (AICc). Post hoc comparisons were conducted for survival data using the Tukey method in the R package emmeans.

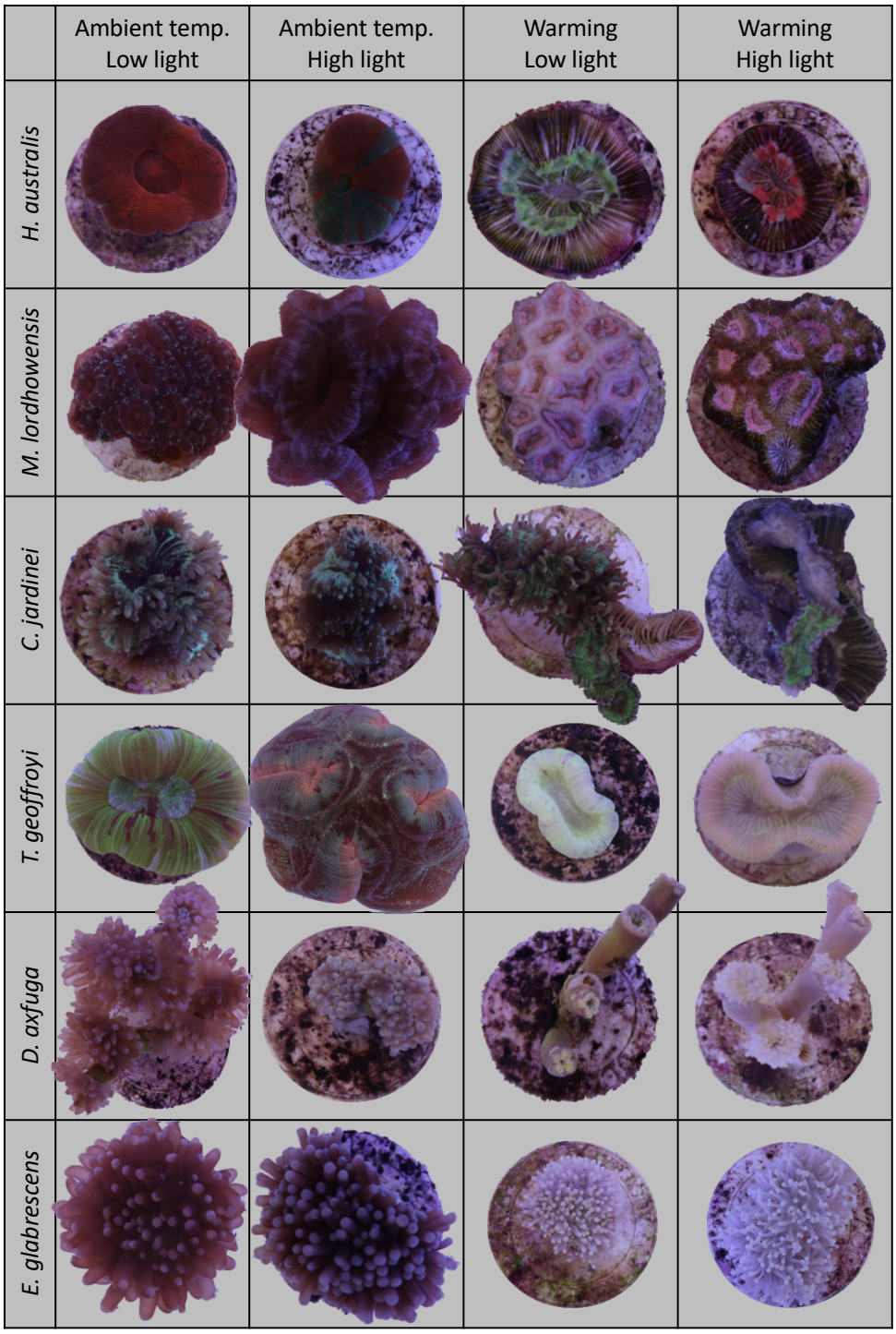


Figure 3.6. Select images of experimental colonies to indicate inter-specific differences in responses of the six coral species (*H. australis*, *M. lordhowensis*, *C. jardinei, T. geoffroyi, D. axifuga*, and *E. glabrescens*) with exposure to increasing temperature and high levels of light intensity. All photographs by D. Pratchett.

To better resolve differences in survival among corals, we obtained nonparametric estimates of the shape of the survivorship curves for each coral species under the two temperature treatments using Kaplan–Meier product-limit analysis. The Kaplan–Meier model is based on estimating conditional probabilities at each time point when an event occurs, and taking the product limit of those probabilities to estimate the survival rate at each point in time (Kaplan and Meier 1958). To test whether survival trends were significantly different for each treatment, survival probabilities were compared using the Log-rank test, which takes into account both individuals that died during the course of the experiment and individuals that were still alive at the end of the study. To assess interspecific and regional variation in the tolerance of corals to temperature and light treatments, standardised mean differences (SMDs), using Hedges' G, as an effect size metric.

Table 3.6. Identity and provenance (region) of corals used in controlled bleaching experiment to test for inter-specific differences in susceptibility to elevated temperature and light. Source region: NT = Northern Territory (Darwin), NQ = North Queensland (Cairns), CQ = Central Queensland (Mackay), WA = Western Australia (Karratha). Corals were equally distributed among the four treatments.

Species	NQ	CQ	NT	WA	TOTAL
Homophyllia australis		17			17
Micromussa lordhowensis		18			18
Catalaphyllia jardinei	18	20			38
Trachyphyllia geoffroyi	18	23		15	56
Duncanopsammia axifuga	18	19	20	21	78
Euphyllia glabrescens	18	16		16	50
Total	72	113	20	52	257

4. Results and Discussion

4.1 Abundance and turnover of commercially important coral species

4.1.1 Size-weight relationships

The mean size (diameter) and weight of corals collected was lowest for *H. australis*, averaging 52.0 mm (with a maximum of 91.2mm average diameter) and 69.1g across colonies (almost invariably single polyps) collected in all three jurisdictions (though see section 4.2, which suggests that only corals harvested in Queensland are truly *H. australis*). The largest corals harvested were *D. axifuga* (averaging 98.6 mm average diameter and up to maximum of 302.5 mm) and *M. lordhowensis* (averaging 97.3 mm average diameter and up to maximum of 206 mm), though colonies of *M. lordhowensis* were on average much heavier than those of *D. axifuga* (Figure 4.1). Interspecific variation in the weight of corals was analysed using ANCOVA, where coral size (diameter) was an obvious and significant co-variate (ANCOVA; $F_{1,5}$= 21,838, p<0.01). However, even after accounting for coral size (diameter), there were significant differences in weight among species (ANCOVA; $F_{1,5}$= 249.7, p<0.01), but also the interaction between species and diameter was highly significant (ANCOVA; $F_{5,2514}$= 19.773, p<0.01). To compare among species, we used Tukey's post-hoc tests, with adjusted p values to account for all possible pairwise comparisons. This showed that the standardised weight (accounting for diameter of corals considered) was highest for *C. jardinei* (2.92), which was significantly higher than for *H. australis* (difference = 0.74, p = <0.01), *D. axifuga* (difference = 0.64, p = <0.01), and *E. glabrescens* (difference = 0.57, p = <0.01), but was not significantly different from that of *T. geoffroyi* (difference = 0.23, p = 0.54) or *M. lordhowensis* (difference = 0.23, p = 0.05).

Table 4.1. Size and weight of corals (mostly intact colonies of freshly harvested corals, with little or negligible substrate attached), which were measured to determine species-specific diameter-weight relationships for each of the six major study species. The majority of corals measured were from Queensland (N = 1986), though some colonies were sourced from Western Australia (*D. axifuga*, *E. glabrescens*, and what was presumed to be *H. australis*) and Northern Territory (*Euphyllia glabrescens* and what was presumed to be *H. australis*).

Species	N	Diameter (mm)		Weight (g)	
		Average (SE)	Range	Average (SE)	Range
Catalaphyllia jardinei	43	57.03 (3.44)	29.1-104.5	166.19 (33.97)	17-985
Duncanopsammia axifuga	219	98.59 (2.92)	25.5-302.5	229.47 (20.65)	10-2750
Euphyllia glabrescens	265	67.48 (1.89)	18.0-168.0	171.76 (14.45)	5-1530
Homophyllia australis	473	51.97 (0.56)	11.0-91.2	69.15 (2.06)	3-448
Micromussa lordhowensis	685	97.27 (1.35)	27.9-206.0	314.06 (11.26)	10-1952
Trachyphyllia geoffroyi	900	72.25 (0.71)	25.0-162.1	220.42 (6.75)	8-1695
Total	2585	77.05 (0.65)	11.0-302.5	244.17 (4.86)	3-2750

Although there were marked interspecific differences in the specific relationship between diameter and weight (Figure 4.2), which prevented pooling of all major target species, the relationship was well represented using a two-parameter power function across all six major target species. The relationship between diameter and weight was particularly strong for *C. jardinei* and *D. axifuga* ($r^2 \geq$

0.92), even though there was relatively limited data for *C. jardinei* (Table 4.1). For other species (*E. glabrescens*, *H. australis*, *M. lordhowensis* and *T. geoffroyi*) the predicted relationship tended to underestimate the weight of larger samples (Figure 4.2), and there were some notable outliers for *E. glabrescens* and *M. lordhowensis*. This suggests that there may be fundamental changes in growth processes among corals that are at or above the upper limit of corals measured in this study. Importantly, the mass of corals is reflective of the amount of carbonate skeleton that has been deposited (Pratchett et al. 2015) which may increase disproportionately to coral diameter if or when corals start growing vertically. In massive colonial corals, such as *M. lordhowensis*, vertical growth (i.e. thickening of the colony skeleton) is often very negligible among smaller colonies, and only becomes apparent once the coral has reached a threshold size in terms of horizontal planar area. This means that there may be altogether different growth functions for corals that are above or below the threshold size for vertical thickening (Pratchett et al. 2015). A disproportionate focus on smaller corals (as seems to be the case when collecting such corals from the wild) will therefore, likely underestimate the weight of larger corals. This issue will be also most pronounced for colonial species that grow predominantly by the addition of new polyps (*M. lordhowensis* and *D. axifuga*) as opposed to somatic growth of individual polyps (*H.* australis, *T. geoffroyi* and C*. jardinei*).

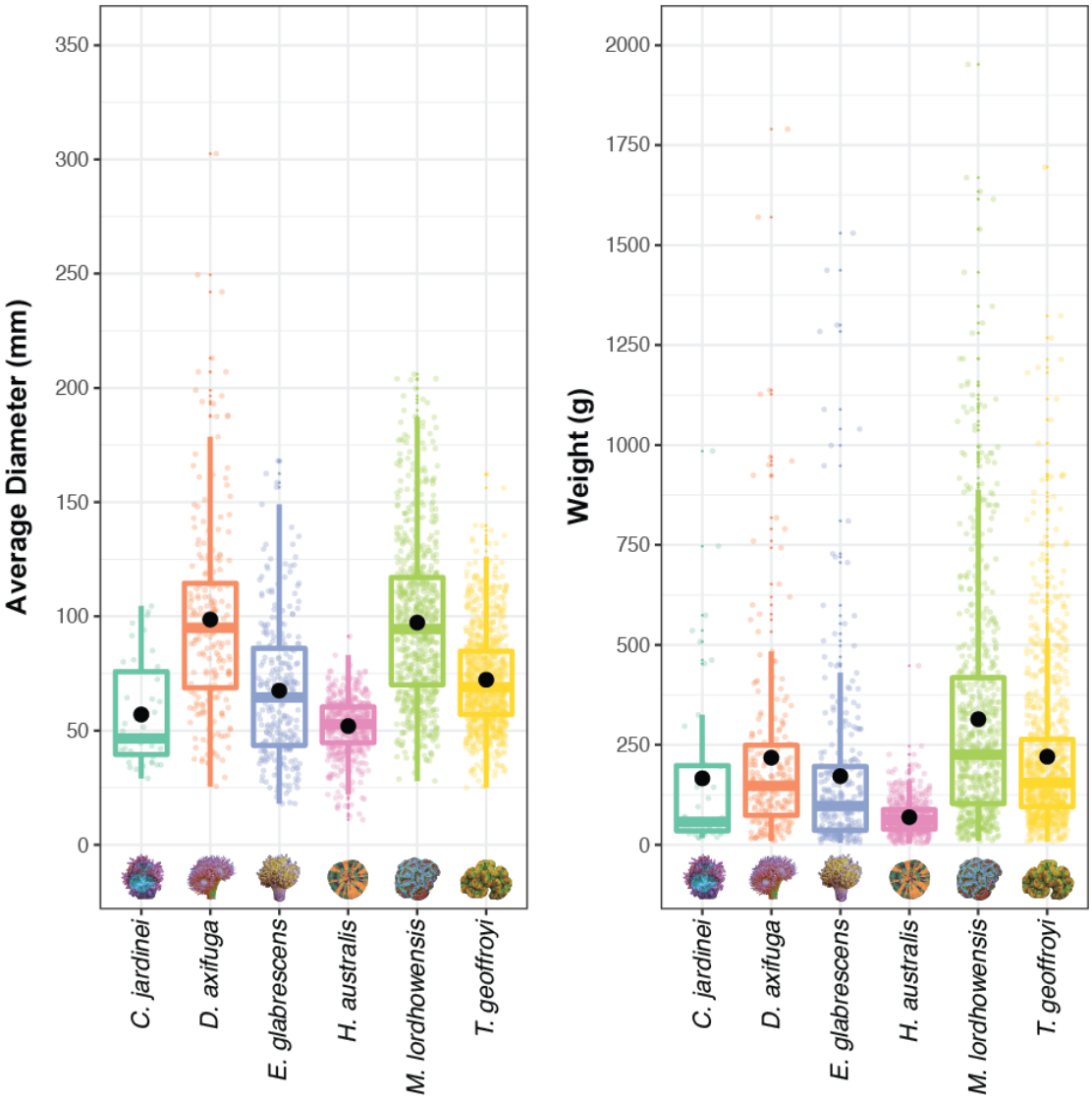


Figure 4.1. Size distribution for corals harvested by Australian coral fisheries, based on average geometric diameter and weight. Plots show median (bold line), 25th and 75th percentile range (box), 5th and 95th percentile range (error bars), and mean value (solid black circle).

Additional bias in the recorded versus predicted weight of corals may arise due to the amount of carbonate material attached to harvested corals that was either part of the underlying substrate or represents remnant skeleton following declines in the effective size of the colony (e.g., following temporary or partial smothering of the coral by sediment). Collectors aim to minimise the amount of substrate collected with harvest corals, or remove it during post-harvest processing (Pratchett and Messmer 2017). Even corals that are not normally or firmly attached to the underlying substrate may be "trimmed" following collection to improve the shape and appearance of corals. There is also strong incentive to minimise the amount of excess carbonate (both due to quota ramifications and shipping costs) though there are occasional colonies (by virtue of their particular shape) where it is not possible to effectively remove excess carbonate. This will result in some corals that are heavier than expected for their size (diameter), and may explain observed outliers in the current data (Figure 4.2).

Despite potential biases, the relationship between diameter and weight was highly significant (at least across the weight range of corals considered) for all 6 target species, providing an effective tool for estimating mass based on the diameter of corals in the wild. The expected (isometric) relationship between diameter and weight of corals has a slope (exponent) of 3, given that mass should increase with changes in colony size in three dimensions (Dornelas et al. 2017). Except for *C. jardinei* (Slope = 2.921; 95% CI: 2.659–3.182; $p = 0.543$), the relationship between diameter and weight for all target species examined were allometric (where the slope was significantly different from and less than 3): *D. axifuga* (Slope = 2.276; 95% CI: 2.186–2.366; $p < 0.001$), *E. glabrescens* (Slope = 2.350; 95% CI: 2.259–2.441; $p < 0.001$), *H. australis* (Slope = 2.165; 95% CI: 2.044–2.286; $p < 0.001$), *M. lordhowensis* (Slope = 2.533; 95% CI: 2.465–2.600; $p < 0.001$); and *T. geoffroyi* (Slope = 2.688; 95% CI: 2.626–2.751; $p < 0.001$). This may suggest that corals grow allometrically, as suggested by Dornelas et al. (2017), whereby there are inherent physiological constraints on the capacity to maintain growth rates as corals attain larger sizes (e.g., as the ratio of surface area to volume declines). Alternatively, the allometric growth recorded in this study may be attributable to limited vertical growth exhibited by colonies that grow predominantly along the substrate. For example, most large colonies of *D. axifuga* that were observed, both in collections and in the wild (Figure 6.5) were very flat and had similar vertical dimensions to other much smaller colonies.

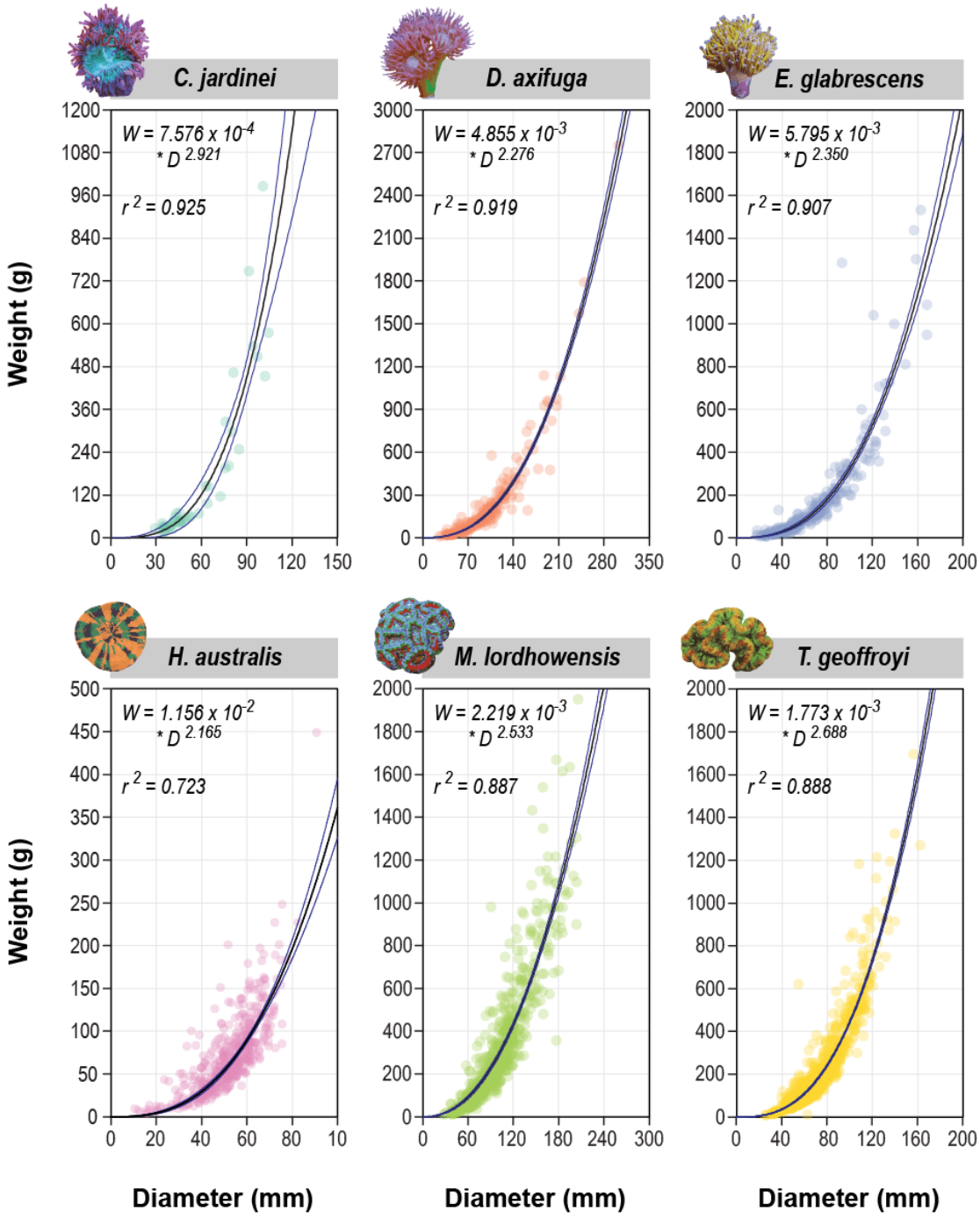


Figure 4.2. Species-specific diameter (average of maximum and perpendicular diameter measurements) and weight relationship for six target species fitted with a two-parameter power equation: Weight (W) = Intercept * Diameter (D) ^ Slope. Blue lines are 95% confidence intervals.

4.1.2 Stock-size and structure

A total of 2,839 corals (including the six focal species of major harvested corals and other related target species) were recorded across all transects (n = 246 transects), corresponding with a mean density of 11.5 (±2.62SE) corals per transect (per 50m^2). The abundance of targeted corals on individual transects was extremely variable (cv = 3.6), ranging from no (0) harvestable corals, which was recorded on 29 (11.7%) transects, up to 372 distinct corals on a single transect. The mean

density of major target species was greatest in Queensland (18.11 colonies per transect ± 2.1SE, n= 98), compared to Western Australia (7.71 ± 1.11SE, n = 130), and Northern Territory (3.44 ± 1.49SE, n = 18). The abundance of harvestable corals was also much more variable in Queensland (cv = 3.8, range = 0-372), compared to Western Australia (cv = 1.9, range = 0-93), and Northern Territory (cv = 1.03, range = 0-25).

Aside from differences in the overall abundance of targeted coral species on transects surveyed in each different region (or jurisdiction) there were marked differences in the composition of coral assemblages, even accounting for some uncertainty regarding the specific identity of corals surveyed in some jurisdictions. The transects run in the Northern Territory had particularly low abundance and diversity of target coral species, limited mainly to colonial corals that resembled *M. lordhowensis* (Table 4.2; Figure 4.3). This data poorly reflects the broad range of corals currently harvested from the Northern Territory (including *D. axifuga*, *E. glabrescens, T, geoffroyi*, but not *C. jardinei* or *M. lordhownesis*; DPIR 2019b), but is attributable to the limited number and extent of surveys, relative to the broad range of different environments and habitats (including reef environments located for offshore) from where coral is harvested. Given apparent discrepancies with catch records, it is likely that the colonial *Micromussa* recorded in video transects (recorded as *M. lordhowensis*) is actually *Acanthastrea echinata* or *M. amakusensis*, but it was very difficult to discern specific species on these video recordings. It is also possible that there are errors and inconsistencies in the catch data for these species, necessitating careful genotyping of corals sampled across a range of habitats to resolve the species identity of major harvest species.

Table 4.2. Number of corals and estimated biomass (± standard error based on the number of transects where species was present) of corals using measurements from 50m^2 video transects. Total Biomass is the sum across all transects per species in each region. No biomass data is provided for the Northern Territory, because we were unable to reliably estimate the size of corals on video transects without scale bar. Mean abundance and biomass is based on only those transects where coral species were actually recorded, whereas the coefficient of variation (cv) captures variability due to both numerical abundance and presence/ absence. It is important to acknowledge that determination and discrimination of coral species was particularly difficult in some areas (especially where there was poor visibility), and high abundance of some species in areas where not reported to be harvested will need to be confirmed with targeted collections and genotyping.

Region: *Species*	**Colonies (Measured)**	**Colonies per Transect**		**Biomass (kg) Transect ± SE**	**Biomass Total (kg)**
		Mean ± SE	**cv**		
Northern Territory	**62 (0)**	**3.8 ± 1.0**	**1.0**	-	-
Acanthastrea echinata	36 (0)	4 ± 1.5	1.1	–	–
Euphyllia sp.	9 (0)	2.3 ± 1.3	1.1	–	–
Micromussa sp.	17 (0)	5.7 ± 2.2	0.7	–	–
Queensland	**1775 (1775)**	**8.1 ± 2.1**	**3.8**	**54.8 ± 12.1**	**5369.7**
Acanthastrea echinata	22 (22)	3.1 ± 0.9	0.8	1.5 ± 1	10.4
Acanthophyllia deshayesiana	172 (172)	6.6 ± 1	0.7	0.3 ± 0.1	7.9
Catalaphyllia jardinei	836 (836)	52.3 ± 26.7	2.0	324.9 ± 151.7	5198.1
Cynarina lacrymalis	28 (28)	1.4 ± 0.2	0.5	0.1 ± 0	1.4
Duncanopsammia axifuga	3 (3)	1.5 ± 0.5	0.5	0.2 ± 0.2	0.4
Euphyllia glabrescens	55 (55)	3.1 ± 0.8	1.1	1.9 ± 0.8	34.3
Euphyllia sp.	24 (24)	8 ± 3.6	0.8	5.5 ± 2.8	16.6
Fimbriaphyllia ancora	21 (21)	1.3 ± 0.2	0.5	1 ± 0.5	15.8
Fimbriaphyllia divisa	3 (3)	1 ± 0	0.0	3.8 ± 3.1	11.4
Homophyllia australis	280 (280)	5.4 ± 0.7	0.9	0.3 ± 0.1	14.2
Homophyllia bowerbanki	22 (22)	1.8 ± 0.3	0.6	2.8 ± 1.3	33.7
Lobophyllia vitiensis	19 (19)	2.1 ± 0.5	0.7	0.2 ± 0.1	2.0
Micromussa lordhowensis	42 (42)	2.3 ± 0.4	0.7	0.6 ± 0.2	10.5
Trachyphyllia geoffroyi	248 (248)	13.8 ± 2.1	0.7	0.7 ± 0.1	13.0
Western Australia	**1002 (1000)**	**4.7 ± 0.6**	**1.9**	**2.7 ± 0.3**	**355.6**
Acanthastrea echinata	229 (229)	3.4 ± 0.3	0.7	2.4 ± 0.3	161.0
Duncanopsammia axifuga	229 (229)	6.9 ± 1.8	1.5	3.3 ± 1.5	109.1
Euphyllia glabrescens	178 (178)	6.6 ± 1.5	1.2	0.7 ± 0.3	18.2
Euphyllia sp.	36 (36)	1.8 ± 0.2	0.5	0.8 ± 0.2	15.0
Fimbriaphyllia ancora	170 (170)	21.3 ± 12	1.6	4 ± 2.5	32.0
Homophyllia australis	12 (12)	1.3 ± 0.2	0.5	0.1 ± 0	0.6
Homophyllia bowerbanki	36 (36)	2.1 ± 0.5	1.0	0.8 ± 0.2	13.6
Micromussa lordhowensis	3 (3)	1.5 ± 0.5	0.5	0.2 ± 0.1	0.3
Trachyphyllia geoffroyi	109 (107)	3.5 ± 0.6	1.0	0.2 ± 0	5.7

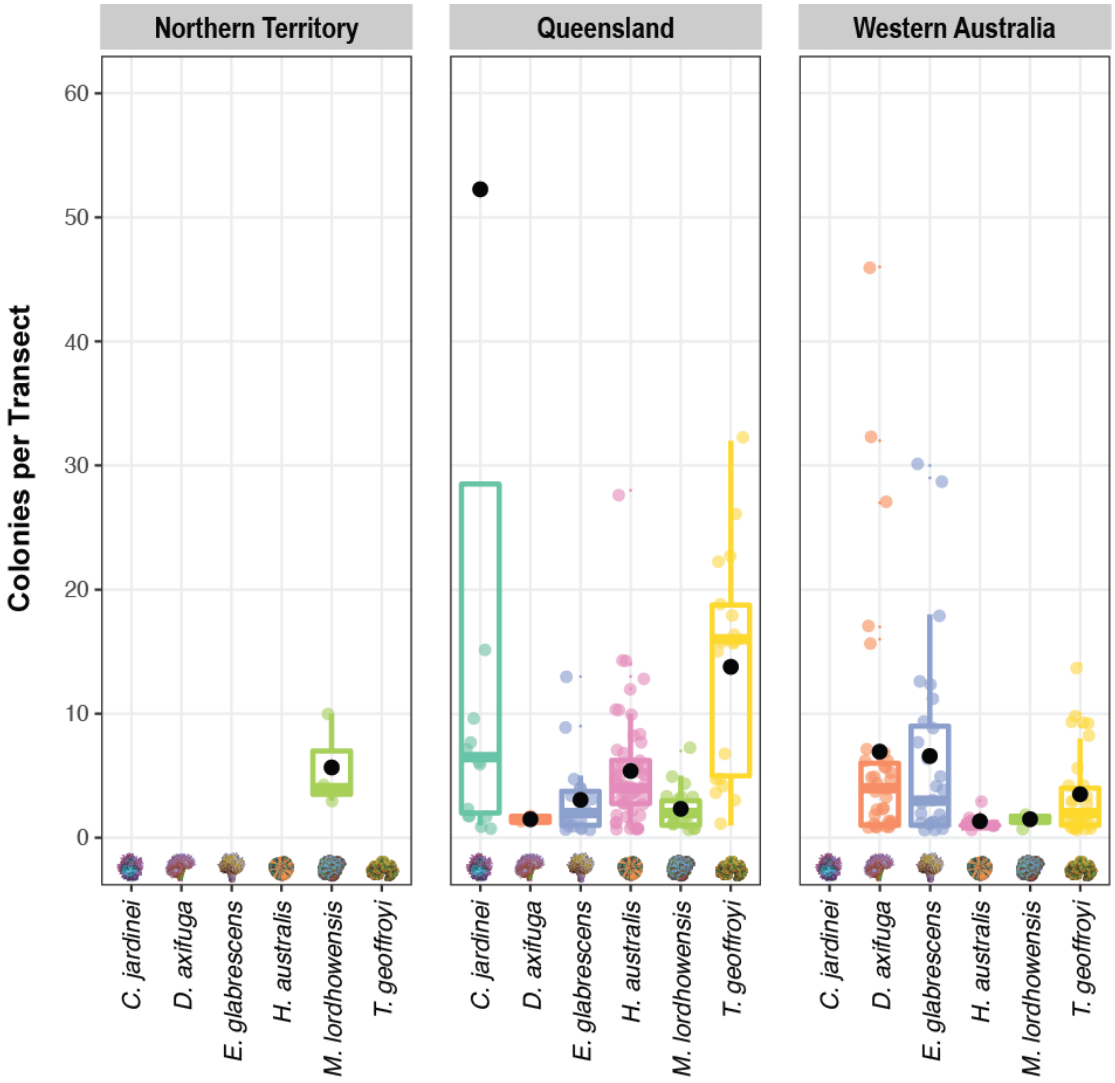


Figure 4.3. Number of colonies per transect for each focal species for each state. Plots show median (bold line), 25th and 75th percentile range (box), 5th and 95th percentile range (error bars), and mean value (solid black circle). Four data points for *C. jardinei* from Queensland transects are not shown: Mackay (67, 77 colonies per transect), Keppels (258, 370 colonies per transect). Unidentified colonies of *Micromussa* sp. recorded in Northern Territory were assumed to be *M. lordhowensis* for the purposes of this analysis, but this will need to be verified. The identity of *M. lordhowensis* recorded in Western Australia is also questionable.

In Queensland, the dominant coral recorded on video transects was *C. jardinei,* though densities were highly varied (occurring on 16.3% of transects; cv = 2.0) and overall abundance was greatly influenced by the very high densities of colonies (69-370 colonies) on a just four transects conducted in the southern GBR (Figure 4.3). The next most abundant coral was *H. australis*, which was recorded on 53.1% of transects and was consistently found in moderate abundance (5.4 colonies per transect $\pm$ 0.7SE) across all transects where it was recorded (cv = 0.9). *Trachyphyllia geoffroyi* was recorded on 18.4% of transects, but was relatively abundant (13.8 colonies per transect $\pm$ 2.1SE) where it was recorded. Both E. *glabrescens* and *D. axifuga* were recorded on only a very small number of transects (2 out of 40), though *E. glabrescens* was abundant where it occurred (Figure 4.3). Notably, *M. lordhowensis* was rarely recorded during surveys in Queensland (Figure 4.3), reflecting low abundance in areas where surveys were conducted Reported catches of *M. lordhowensis* are greatest in the southern GBR (DEEDI 2012), and it is likely that stock estimates would be greatly increased

given sampling in the Keppel region. For example, the combined take of *M. lordhowensis* reported for 2009-2011 was 66kg in the Cairns Coral Collection Area, compared to 1,750kg in the Keppel Coral Collection Area and 3,136kg in all other areas outside of these collection areas (DEEDI 2012).

In Western Australia, coral assemblages surveyed on video transects (n = 130 transects, across intertidal and subtidal habitats) were numerically dominated by *D. axifuga*, *E. glabrescens* and *T. geoffroyi* (Figure 4.3). Notably, densities of *D. axifuga* (cv = 3.3, recorded on 25.4% of transects), *E. glabrescens* (cv = 3.3, recorded on 20.8% of transects) and also *T. geoffroyi* (cv = 2.0, recorded on 23.8% of transects) were highly variable among transects. Densities of colonies were much lower, but also even more variable for *Micromussa* (cv = 8.4; presumed to be *M. lordhowensis*, but this is very difficult to distinguish from *Homophyllia bowerbanki* on video recording in intertidal habitats, where there is often a layer of muddy or murky water covering the corals), and also colonies nominally regarded as *H. australis* (cv = 4.1). Overall, these nominal species (*M. lordhowensis* and *H. australis*) were only recorded on 2 and 9 transects (out of 130), respectively. These data confirm that major target species of aquarium corals are very patchily distributed, but can be extremely abundant in specific habitats. While species that are abundant only in specific habitats or locations will be more vulnerable to exploitation (and more vulnerable to localised disturbances), especially where corals are concentrated in specific habitats that are easily accessible and subject to high fisheries pressure, the high overall abundance of these different corals would suggest that the currently low and increasingly diffuse fisheries effort in Western Australia (DPIRD 2018) poses a very limited threat to wild stocks.

Regional differences (between Queensland and Western Australia) in the relative availability of different coral species were even more apparent when comparing *in situ* biomass (Figure 4.4), estimated based on the diameter of colonies recorded on all video transects. Note, no biomass data could be obtained for the Northern Territory, because the lack of any scale bar in video recording prevented effective estimates of coral size, and therefore mass. For species with no diameter-weight relationship data, the relationship for the species with the closest growth form was used to calculate the biomass (Table 4.1). The combined biomass of all corals considered herein (Table 4.2) was summed for each transect ($50m^2$) and averaged per species for each region. It is important to note, that there were other potential target species that occurred on transects (most notably, high densities of *Cycloseris cyclolites* occurred on transects surveyed in the northern GBR), but given their limited importance or concern, were not considered in these analyses. Average biomass of major target species of aquarium corals in Queensland (54.79kg ±12.13SE) was much higher than in Western Australia (2.73kg ±0.3SE), though the data from Queensland was heavily skewed by transects which were conducted in expansive beds *of C. jardinei* in the southern GBR, resulting in extreme (up to 1,802kg per transect) estimates of biomass for this species (Figure 4.4).

The overall biomass of corals considered was substantially higher in Queensland (5370kg) compared to Western Australia (356kg), and was dominated by *C. jardinei*, which accounted for >98% of overall biomass recorded in Queensland. Compared to *C. jardinei* (5198.1kg), the total biomass of other focal coral species recorded in Queensland was negligible: *H. australis* (14.1kg) and *T. geoffroyi* (13.0kg). In Western Australia, *A. echinata* (161.2kg) and *D. axifuga* (109.2kg) contributed most to the overall biomass of aquarium corals recorded on all transects (130 transects with a combined area of $6,500m^2$), accounting for 45.3% and 30.1%, respectively. Although abundant and widespread, *T. geoffroyi* contributed relatively little to the biomass of corals recorded in Western Australia.

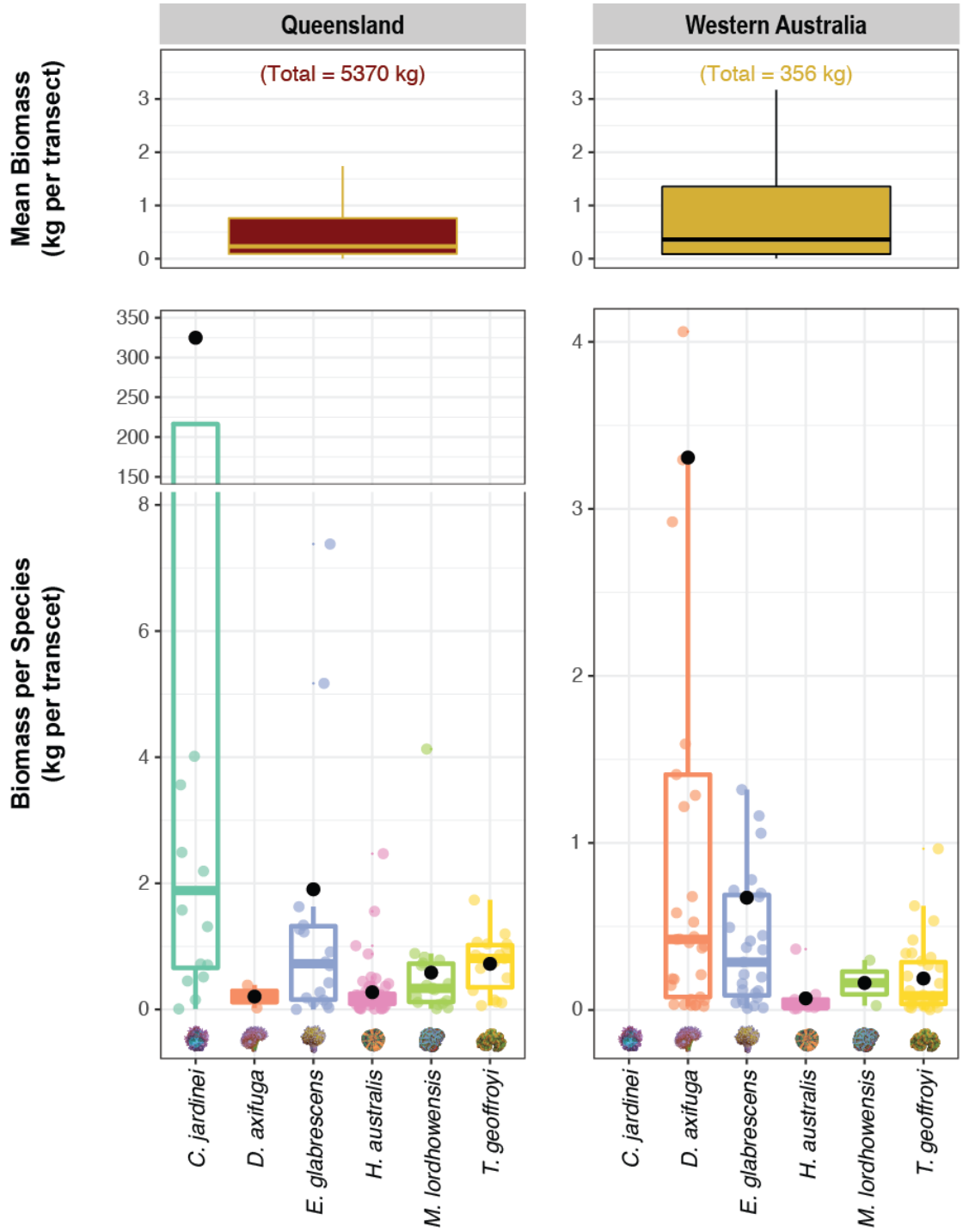


Figure 4.4. Distribution of biomass data, showing sum total per state (Top) and biomass of each focal species for each state. Four data points for *C. jardinei* from Queensland transects are not shown: 854, 1100, 1434 and 1802kg. Plots show median (bold line), 25th and 75th percentile range (box), 5th and 95th percentile range (error bars).

The harvestable biomass estimates obtained in this study provide important, and unprecedented, reference points for assessing the sustainability of current harvest limits. In Queensland, where there are no specific quotas or limits on individual species, the current TACC for all speciality coral species (which includes all major species considered in this study) is 60,000 kg, though the maximum recorded harvest level of specialty hard coral is just 43 tonnes (QDAF 2019). Based on the combined biomass of the key focal study species and their relatives of 54.8kg per transect (per 50m^2), the total annual quota for specialty hard corals (60,000 kg) would be contained in an area of just 5.47

hectares. Even if aiming to remove only 1% of harvestable biomass per year, the required harvest area is just 547 hectares. For *C. jardinei*, for which the average harvestable biomass was 325.6 kg per transect (restricted to only those transects where it occurred), the maximum annual harvest (which peaked at 2,210kg in 2010/11) occurs in just 340m^2. Indeed, the maximum recorded biomass of *C. jardinei* approached 40kg per m^2, though only small portions of these large and very dense colonies would ever be harvested. In Western Australia, where the biomass estimates were much more moderate, the current harvest limits (which are also very moderate compared to Queensland) were nonetheless represented by relatively small areas of habitat. For *D. axifuga*, for example, the 2014-2016 NDF level of 550kg (see Section 11.1), would be contained in just 0.83 hectares of habitat with mean biomass recorded here. The next step in this research is to characterise and map the specific habitat types that support high abundance and biomass of aquarium corals (e.g., Fisk 1983), to thereby estimate that absolute stock size of each species.

4.1.3 Growth and survivorship

Individual tagging of 174 coral colonies in intertidal habitats in Karratha has provided vitally important and largely unprecedented data on growth and survivorship rates of commonly harvested aquarium corals. For example, corals in the families Lobophylliidae and Euphylliidae are under-represented in published studies of coral growth (Pratchett et al. 2014), and the lack of species-specific growth data greatly constrains rigorous and robust assessment of fisheries vulnerability (Donnelly 2013). Of the four species studied (*D. axifuga, E. glabrescens, H. bowerbanki, and T. geoffroyi*), growth was greatest for *D. axifuga*, where the radius of colonies increased at an average rate of 1.02 mm ± 0.25SE per month, or 12.28mm per year (Table 4.3; Figure 4.5), reflecting the average extent of horizontal growth that occurs along the colony margin. This is roughly equivalent to the average annual rate of colony extension recorded for foliaceous *Turbinaria* corals (Harriot 1999), which makes intuitive sense given many of the colonies considered in this study had a thick base resembling foliaceous or plate corals (Figure 4.5), rather than arborescent branching corals, which can grow very quickly (Pratchett et al. 2015). Growth rates of *D. axifuga* may however, be much higher among smaller corals, and for colonies exhibiting the more open branching, sprawling morphology, given the lower investment in carbonate skeleton among these corals.

Table 4.3. Estimated annual growth rates for tagged colonies based on extrapolation of average monthly rates of radial extension (mm).

Species	n	Annual Growth (mm)
Duncanopsammia axifuga	30	12.28 ± 2.97
Euphyllia glabrescens	27	8.64 ± 2.77
Homophyllia bowerbanki	43	0.80 ± 2.09
Trachyphyllia geoffroyi	18	-0.03 ± 1.25

Coral growth can be measured in numerous different ways, depending on the specific growth form and growth processes of different corals (Pratchett et al. 2015). However, expressing growth as radial extension captures the predominant growth processes exhibited by colonial corals, where polyps are added at the periphery of the colony. As such, the rate of radial extension should be independent of colony size (but nonetheless vary greatly within and among species, mostly depending on their specific investment in carbonate deposition and skeletal density), and can be compared among corals of vastly different size and shape (Pratchett et al. 2015). Radial extension rates of *D. axifuga* and *E. glabrescens* were comparable, and much greater than recorded for *H. bowerbanki* and *T. geoffroyi* (Table 4.3; Figure 4.5). The average growth rate recorded for *H. bowerbanki* was very low (equating

to <1mm per annum) even when compared with generally low rates of radial extension recorded for corals with massive (hemispherical) growth forms (Pratchett et al. 2015). However, there was apparent variation in growth rates recorded among different colonies (Figure 4.5), possibly linked to the high incidence of partial mortality (and often very high levels of injury) recorded for this species (Table 4.4). Notably, maximum growth rates recorded for colonies of *H. bowerbanki* with no partial mortality were 2.43mm per month (29.1mm per year).

Partial mortality (or tissue loss due to localised injuries) can be highly prevalent among colonial corals (Pisapia et al. 2015) and effectively reduces the amount of live coral tissue. In some instances, the overall level of partial mortality (due to severe acute injuries or accumulation of frequent small injuries) is sufficient to offset sustained growth, resulting in net declines in colony size. Moreover, colonies may invest energy into repairing injuries, which will detract from energy available to sustain growth (Babcock 1988). In this study, it was apparent that the coral with the lowest incidence of partial mortality (*D. axifuga*) exhibited the highest overall growth rates (Figure 4.5, whereas *H. bowerbanki* had the highest incidence of partial mortality and the lowest recorded growth rate (except for *T. geoffroyi*). Even so, the maximum radial extension rate for colonies of each species was higher for *D. axifuga* (equivalent to 59.6mm per year) compared to *E. glabrescens* (42.0mm per year), *H. bowerbanki* (29.2mm per year) and *T. geoffroyi* (10.4mm per year) suggesting that differential growth rates are not entirely attributable to differential susceptibility to partial mortality.

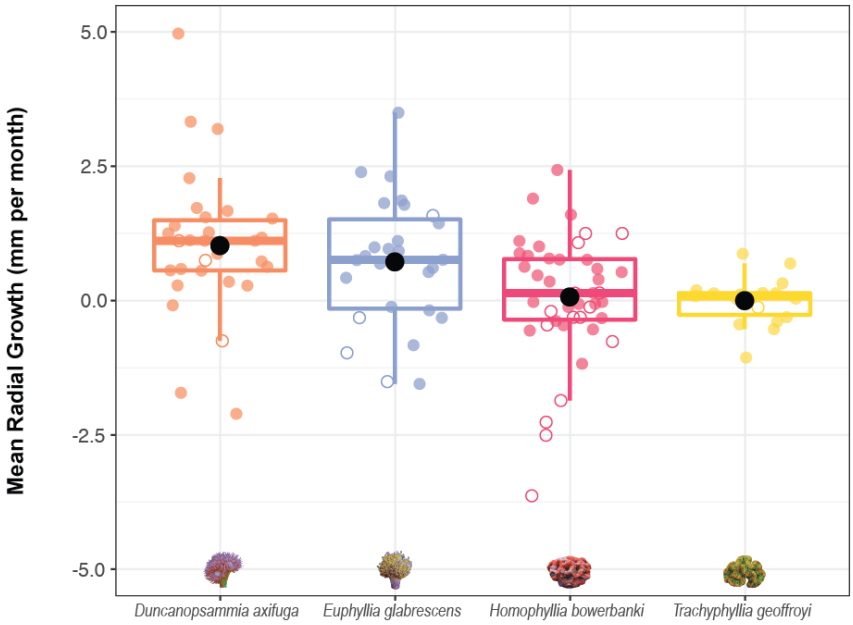


Figure 4.5. Monthly growth rates of individually tagged corals within intertidal habitat in Western Australia. Plots show median (bold line), 25th and 75th percentile range (box), 5th and 95th percentile range (error bars), and mean value (solid black circle). Solid jitter points are "healthy" intact colonies, while outline circles are colonies with partial mortality. Points below zero indicate colonies that had negative growth (shrinkage).

In this study, we recorded very low (essentially negligible) rates of colony growth for *T. geoffroyi* (Figure 4.5). While there was evidence of some partial mortality (Table 4.4) this was extremely limited. Most individuals of *T. geoffroyi* encountered and sampled in this study were relatively small and monocentric, which meant that any injuries incurred would likely result in whole colony mortality, rather than independent loss of distinct polyps (which can occur in larger colonial corals), which effectively reduces coral size. It was also very rare to find completely dead *T. geoffroyi*, though many of the corals were not re-located (up to 27%) which might be attributable to removal by coral

collectors or physical movement of corals (noting that these corals are rarely attached to the underlying substrate), which may or may not have survived. Overall, it is difficult to explain the consistently low growth rates we recorded for *T. geoffroyi* other than simply acknowledging that these corals grow very slowly, at least in the habitat considered herein.

Survivorship of all coral species considered herein was generally high (>60-70%), and even higher (>90%) if we exclude corals that could not be physically re-located. Definitive rates of whole colony mortality (where corals were found, but were completely dead) were extremely low (≤3%), and it is not known whether corals that could not be located had been displaced (e.g., dislodged by large waves, or quickly eroded following whole colony mortality) or potentially subject to harvesting (though there is very limited fishery effort and licensees were asked not to collect tagged corals).

Table 4.4. Condition of corals during survey months showing proportion of colonies that were healthy live corals (LC), colonies with partial mortality (PM), dead coral (DC), and colonies that were not located during re-visitation (NL) or colonies at sites that were not re-visited (NV).

Species / Survey Month	Condition				
	LC	PM	DC	NL	NV
Duncanopsammia axifuga (n = 52)					
2016-Apr	73%	0%	0%	0%	27%
2017-Jan	62%	8%	4%	27%	0%
2018-Aug	23%	0%	0%	10%	67%
Euphyllia glabrescens (n = 39)					
2016-Apr	51%	0%	0%	0%	49%
2017-Jan	85%	3%	0%	3%	10%
2018-Aug	31%	15%	0%	44%	10%
Homophyllia bowerbanki (n =46)					
2016-Apr	61%	0%	0%	0%	39%
2017-Jan	70%	15%	0%	15%	0%
2018-Aug	50%	39%	2%	7%	2%
Trachyphyllia geoffroyi (n=37)					
2016-Apr	51%	0%	0%	0%	49%
2017-Jan	73%	0%	0%	27%	0%
2018-Aug	24%	3%	3%	22%	49%

4.1.4 Reproductive biology

Histological analyses of reproductive samples (Figure 4.6) show the distribution of oocytes and spermaries within the coral gonads. Sexuality of focal species was determined based on the presence of ovaries and spermaries and whether these are found in the same individual (hermaphroditic) or in different distinct colonies (gonochoric). Across six focal species examined, the predominant form of sexuality encountered was hermaphroditism (Table 4.5). Given simultaneous occurrence of both oocytes and spermaries (Figure 4.6), this study confirms that both *E. glabrescens* and *M. lordhowensis* and *T. geoffroyi* are hermaphroditic, as has been reported previously (Table 4.5). We also show, for the first time, that *H. australis* is also hermaphroditic. *Catalaphyllia jardinei* was

previously reported to be gonochoric (Willis et al. 1985), but we found simultaneous occurrence of both oocytes and spermaries in several colonies, showing that this coral can be hermaphroditic.

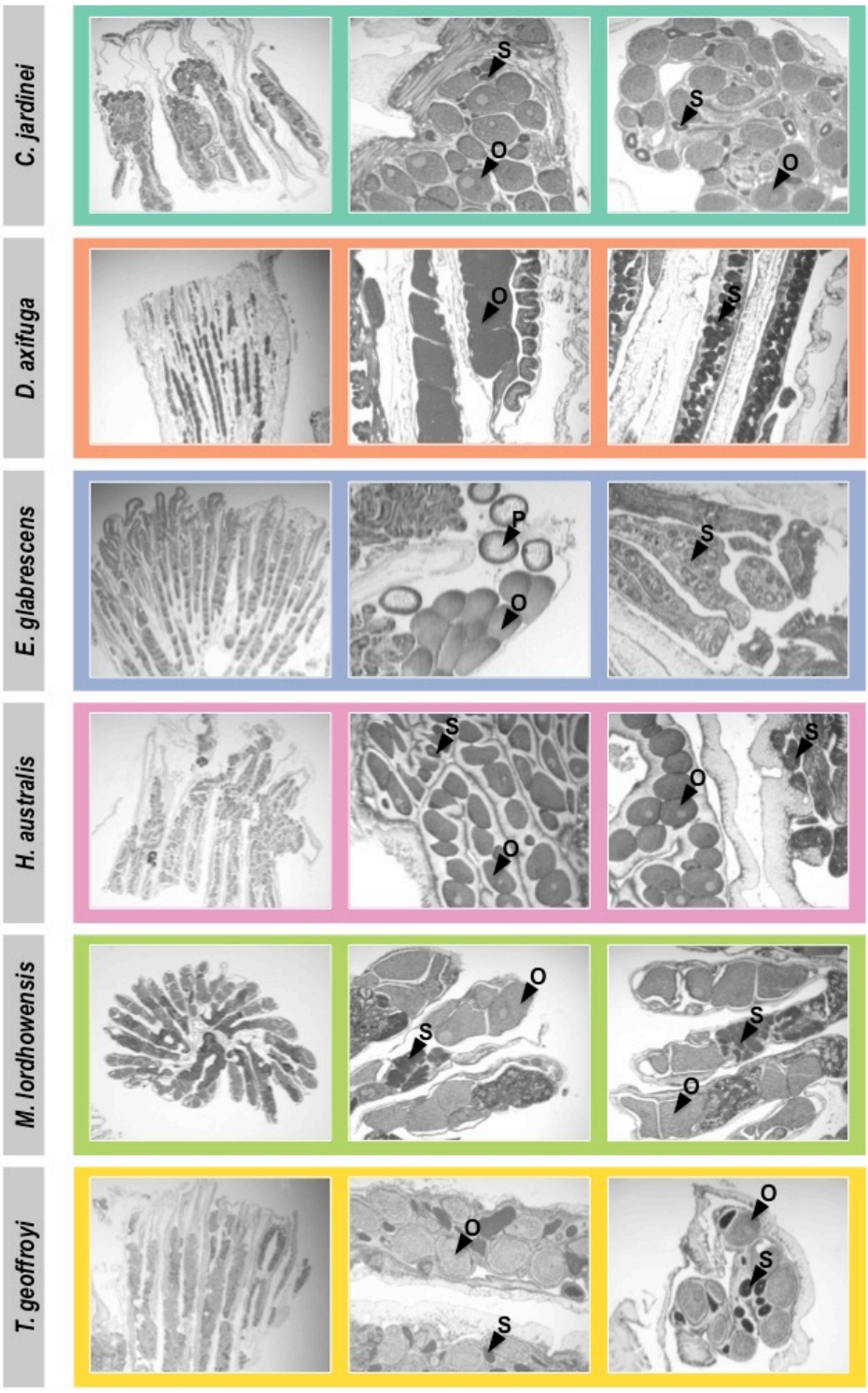


Figure 4.6. Representative histological images of focal species gonads (**O** = oocyte, **S** = spermary, **P** = planula).

Table 4.5. Sexuality and reproductive mode of target species based on literature and based on assessment of histological slides and spawning observations as part of this study. Sources: [1]Willis et al. 1985; [2]Fan et al. 2006; [3]Wilson and Harrison 2003; [4]Baird et al. 2009.

Species	Sexuality		Reproductive Mode	
	Literature	This Study	Literature	This Study
Dendrophylliidae				
Duncanopsammia axifuga	gonochoric[1]	stable gonochoric	spawner[1]	spawner
Euphylliidae				
Catalaphyllia jardinei	gonochoric[1]	hermaphroditic	spawner[1]	spawner
Euphyllia glabrescens	hermaphroditic[2]	hermaphroditic	brooder[2]	brooder
Lobophylliidae				
Homophyllia australis	?	hermaphroditic	?	spawner
Micromussa lordhowensis	hermaphroditic[3]	hermaphroditic	spawner[3]	spawner
Merulinidae				
Trachyphyllia geoffroyi	hermaphroditic[4]	hermaphroditic	spawner[4]	spawner

Within hermaphroditic species (all but *D. axifuga*), a high proportion of female colonies were found within samples from earlier months (before October). These findings support the early onset of oogenesis compared with spermatogenesis. Oocytes are expensive and time consuming to produce, and so are typically detected more than 6 months prior to spermaries within the same colony (Fadlallah 1983). For this reason, a large proportion of the colonies classified as female in the earlier sampling periods of this study demonstrate a shift to hermaphroditism with the onset of spermatogenesis. *D. axifuga* was the only gonochoric species encountered, and demonstrated a 51:39 ratio of male to female colonies (Table 4.6). Sex ratios that favour male colonies have been repeatedly recorded in gonochoric coral species (e.g., Glynn et al. 2012). Spermatozoa are far smaller than oocytes, and are easily diluted in the environment once released, posing a significant problem when considering the low population density of many corals (Oliver and Babcock 1992; Rapuano et al. 2017). Given their small size relative to oocytes, and resulting low expense of production, a greater number of sperm can be produced to maximize the chance of gamete encounters and successful fertilization (Oliver and Babcock 1992). Therefore, we typically see a higher proportion of male colonies in gonochoric populations, while in hermaphroditic species this is represented by a greater production of sperm when compared with oocytes within colonies (Hall and Hughes 1996).

Reproductive mode (which is generally divided into those coral species that spawn unfertilised gametes versus those that have internal fertilisation and brood planulae; Baird et al. 2009) was determined based on the presence or absence of planula larvae within the mesenteries. Except for *E. glabrescens*, which is a brooder, all focal species were found to be broadcast spawners. The reproductive mode of *H. australis* was previously unknown, and is questionable in light of subsequent genetic sequencing for corals collected in Western Australia, which do not appear to be *H. australis* (see section 4.2). However, Baird et al. (2009) do suggest that reproductive mode is generally conserved among families of corals, and similar (largely comprised of a single, solitary polyp) corals in the family Lobophylliidae (*Lobophyllia vitiensis* and *Cynarina lacrymalis*) are also broadcast spawners. *Ex situ* spawning in outdoor aquaria by *M. lordhowensis* and *E. glabrescens* further confirmed the contrasting reproductive modes of these two corals, with *M. lordhowensis* releasing relatively large gamete bundles, while copious amounts of planula larvae were released through the mouth and through the tentacles of *E. glabrescens*. It is widely known that *E. glabrescens* is a brooder (Richmond

and Hunter 1990; Fan et al. 2006), but this is interesting given most *Euphyllia* species are spawners (Baird et al. 2009).

The timing of spawning or planulation in corals is strongly influenced by environmental factors, such as temperature, daylength, and lunar cycles. Broadcast spawning can be highly synchronized, with the majority of populations releasing gametes over a few consecutive nights following the full moon during the summer months. Brooding species release planula larvae during the week following the full moon (at any time of the day) for several consecutive months, often around the time of the seasonal peaks for broadcast spawning species. Extensive histological analyses (measurement of oocyte area) of *H. australis* samples from Queensland have shown that this species may spawn before the peak spawning season for most broadcast spawning species (Figure 4.7). This explains the absence of gametes in all *H. australis* samples collected from Queensland in November.

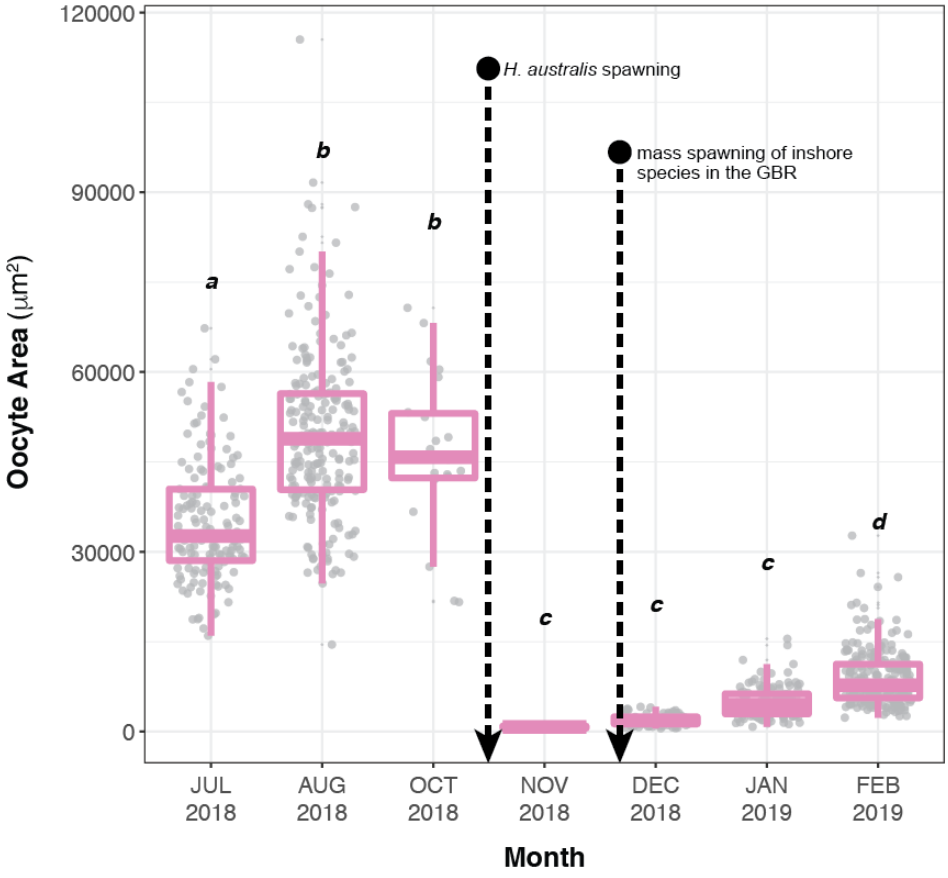


Figure 4.7. Monthly variation in oocyte size, measured as area (μm^2). Plots show median (bold line), 25th and 75th percentile range (box), 5th and 95th percentile range (error bars), and jitter points (circles). Different letters indicate significant differences based on Tukey's *post hoc* test.

Size at reproductive maturity (expressed as D_{50} in fisheries science) is estimated by modelling the relationship between whole colony size (diameter) and the proportion of sexually mature (gametes present). The reliability of these results depends on having reasonable sample sizes of mature and immature individuals (Table 4.6). Given the general lack of small and non-reproductive corals, size at reproductive maturity could only be reliably estimated for *C. jardinei*, *D. axifuga*, and *H. australis* (Figure 4.8). These data show that *C. jardinei* matures at a larger size (99mm; 95% CI = 81 – 120 mm);

compared to *D. axifuga* (83mm; 95% CI = 72 – 94 mm) and *H. australis* = 63mm (95% CI = 56 – 75 mm). The size-specific onset for reproduction was particularly striking for *D. axifuga*, where virtually all colonies >80mm diameter were reproductively mature. The number of small and immature corals was too low for *E. glabrescens*, *M. lordhowensis*, and *T. geoffroyi* to reliably estimate size at reproductive maturity (D_{50}). However, the minimum size at first reproduction (MSFR) is reported (Table 4.6), which shows the smallest size of colonies in which we recorded gametes (Table 4.6). The MSFR has limited value in terms of predicting the size of reproductively mature corals, but has important implications in terms of the size of colonies being harvested by the coral collectors.

Table 4.6. Sexuality and reproductive mode of target species based on literature and based on assessment of histological slides and spawning observations as part of this study. Samples were collected prior to spawning. MSFR = minimum size at first reproduction, based on reproductively mature sample with smallest diameter; Oocyte *D* = mean oocyte diameter as measured from histological slides.

Species	N	Gonad Samples		% Sexuality			MSFR	Oocyte *D*
		Empty	Gravid	H	F	M	(mm)	(µm)
Catalaphyllia jardinei	31	12	19	5	95	0	41.2	108 ± 27
Duncanopsammia axifuga	70	29	41	10	39	51	50.0	168 ± 47
Euphyllia glabrescens	50	0	50	56	36	8	26.0	211 ± 56
Homophyllia australis	108	57	51	41	51	8	36.3	97 ± 31
Micromussa lordhowensis	35	4	31	97	3	0	31.5	400
Trachyphyllia geoffroyi	86	10	76	46	54	0	30.0	123 ± 30

The minimum size at first reproduction recorded across the six coral species is very small (30-50mm), based on the smallest colonies that had gametes (Table 4.6). By comparison, Hall and Hughes (1996) showed that minimum reproductive size for fast-growing branching corals (including *Acropora hyacinthus*) were often >80mm dimeter, whereas the colonies of slower growing massive coral, *Goniastrea retiformes* were reproductive from 27.6mm diameter (or 6cm^2). It is also possible that smaller reproductive corals will not actually spawn (Okubo et al. 2007). Okubo et al. (2007) compared gametogenesis and spawning among different sized fragments of the spawning coral, *Acropora formosa,* and showed that while the smallest fragments (50mm long) did develop oocytes, these were ultimately resorbed, whereas only larger fragments (>100mm long) spawned.

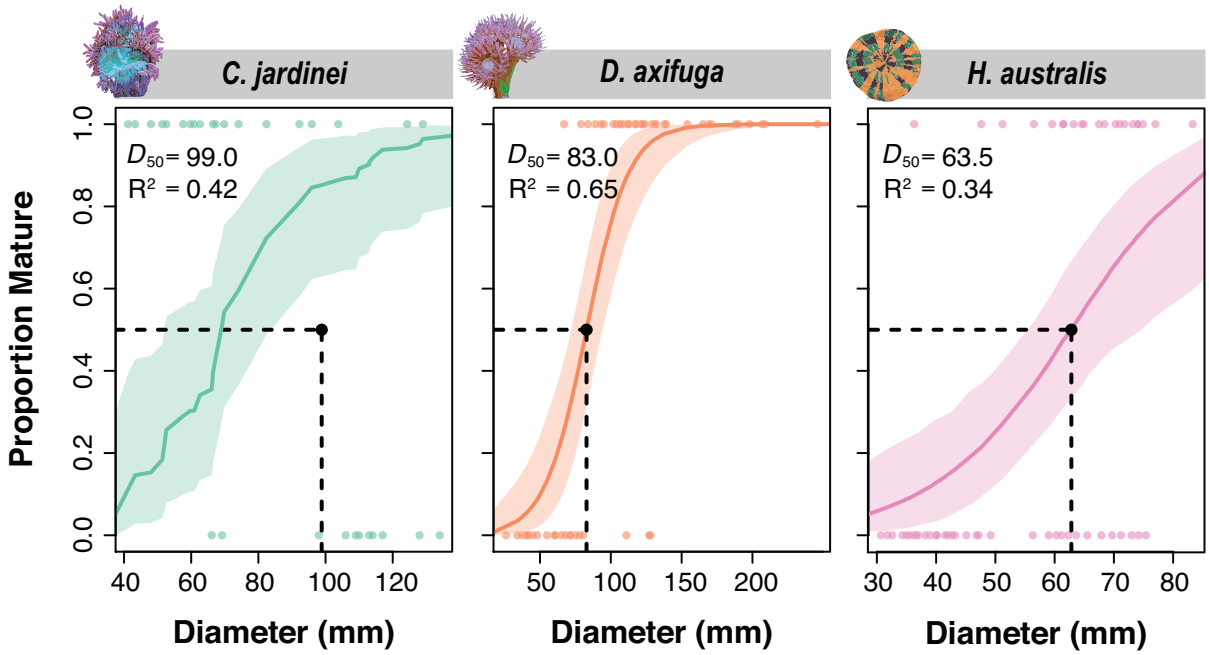


Figure 4.8 Estimated size (diameter) at reproductive maturity for *C. jardinei*, *D. axifuga*, and *H. australis*. Black dashed lines show the size at which 50% are predicted to be reproductively mature. Fitted lines are shown with 95% confidence interval bands.

4.2 Refined species-level taxonomy

Extensive genetic sequencing (molecular analyses) of scleractinian corals is leading to widespread revisions of taxonomy and nomenclature (e.g., Arrigoni et al. 2014a, b; Huang et al 2016). Of specific relevance to this project is the establishment of the Indo-Pacific coral family Lobophylliidae (Arrigoni et al. 2014a), which includes many of the genera and species formerly regarded as family Mussidae, as well as some species previously considered to belong to the families Faviidae and Pectinidae. The family Lobophylliidae, characterised by irregular and lobate teeth, which vary in size within and among septa, includes 12 genera, including *Acanthastrea*, *Micromussa* and *Homophyllia* (Table 4.7). Given the recent revision of this diverse group, and incomplete genetic sampling of species, there are still some species affinities that are yet to be completely resolved. For example, Huang et al. (2016) maintained that the large solitary corals, placed in the genus *Acanthophyllia* Wells 1937, were indistinguishable from *Cynarina*, based on the size of septal teeth and development of septal lobes, as originally suggested by Veron and Pichon (1980). However, Hoeksema and Cairns (2020c) recognise *Acanthophyllia* as a valid genus, following consistent differences in the morphometrics of *Acanthophyllia deshayesiana* and *Cynarina lacrymalis* (Darus et al. 2016; Table 4.7), though there is yet to be any molecular (genetic) analyses to confirm or refute the validity of *Acanthophyllia deshayesiana*.

Table 4.7. Major groups (genera) of corals in the family Lobophylliidae, with specific importance to coral fisheries across northern Australia, and recent changes in their taxonomic status and relevant sources; [1]Arrigoni et al. 2014a; [2]Arrigoni et al. 2016; [3]Budd et al. 2012; [4]Huang et al. 2016; [5]Hoeksema and Cairns 2020c; [6]Darus et al. 2016.

Current Nomenclature	Old species	Explanation (and source)
Micromussa		
Micromussa amakusensis	*Micromussa amakusensis*	Valid (monophyletic) group[1]
Micromussa lordhowensis	*Acanthastrea lordhowensis*	Monophyletic with *M. amukensis*[2]
Micromussa pacifica	*Scolymia* cf. *australis*	New species[2]
Acanthastrea		
Acanthastrea echinata	*Acanthastrea echinata*	Valid (monophyletic) group[1]
Acanthastrea hemprichii	*Acanthastrea hemprichii*	Valid (monophyletic) group[1]
Homophyllia		
Homophyllia australis	*Scolymia australis*	Type species for resurrected genus[3]
Homophyllia bowerbanki	*Acanthastrea hillae*	Monophyletic with *H. australis*[2]
Homophyllia bowerbanki	*Acanthastrea bowerbankii*	Indistinguishable from *H. hillae*[2]
Lobophyllia		
Lobophyllia vitiensis	*Parascolymia vitiensis*	Monophyletic with *L. corymbosa*[4]
Cynarina		
Cynarina lacrymalis	*Cynarina lacrymalis*	Valid (monophyletic) group[1]
Acanthophyllia		Considered to be valid genus[5]
Acanthophyllia deshayesiana	*Cynarina lacrymalis*	Not synonymous with *C. lacrymalis*[6]

Preliminary genetic sequencing of 366 distinct coral colonies provided by licensed coral collectors across northern Australia has confirmed the monospecific status of *C. jardinei*, *D. axifuga and T. geoffroyi*, despite sampling multiple morphs across widely separated locations (Table 4.8). Moreover, the newly sequenced corals were closely related (and intermixed) with existing sequences for the same nominal coral species already contained within GenBank. In contrast, there was striking and surprising diversity apparent within samples that were nominally considered to be *Homophyllia australis*, which has revealed a new and undescribed species of Lobophylliidae, currently being harvested as *Homophyllia australis*/ *Lobophyllia vitiensis* in Western Australia and the Northern Territory (Figure 4.9).

Table 4.8. Summary of findings from phylogenetic analyses, using a single nuclear (ITS2) marker. Genetic differences within nominal species were compared to relevant outgroups, and mostly showed that there was a single consistent grouping for each nominal species. The only exception was *H. australis*.

Nominal species	WA	QLD	NT	No. species
Catalaphyllia jardinei		43		1 species
Duncanopsammia axifuga	43	41		1 species
Homophyllia australis/ Lobophyllia vitiensis	10	82	21	3 species
Micromussa lordhowensis		45		1 species
Trachyphyllia geoffroyi	35	46		1 species

To better resolve the distribution of *H. australis*, as distinct from other similar corals (e.g., *Lobophyllia vitiensis*) that are considered to be much more widespread, we sequenced a total of 113 monocentric Lobophylliidae corals collected from a range of different locations and habitats, including Western Australia, the Northern Territory and also both inshore and offshore GBR, Queensland. Maximum parsimony analysis revealed three distinct genetic lineages, or species; i) *Homophyllia australis* which was restricted to samples from the GBR, Queensland, and only collectors that were operating in the southern GBR, ii) *Micromussa pacifica* which was also recorded only among the samples provided from the GBR, Queensland, and iii) an undescribed species which is strongly differentiated from both *H. australis* and *M. pacifica* and includes all samples that were provided from both Western Australia and the Northern Territory. Given the limited extent of sampling in Western Australia (n = 10) and the Northern Territory (n = 21) we cannot confidently assert that neither *H. australis* and *M. pacifica* occur within these jurisdictions, though it is clear that the majority of monocentric Lopophyllidae corals currently harvested and sold in these locations are neither *H. australis* or *L. vitiensis*. Subsequent sequencing of carefully selected samples collected in Western Australia have further confirmed that these corals, while belonging within the family Lobophylliidae, do not have close phylogenetic affinities with either *Homophyllia* or *Micromussa*, and likely belong in an altogether different genus (Figure 4.9). These corals can be distinguished based on morphological features, as described in our *Identification guide to commonly harvested aquarium corals* (section 12.2), though it does require careful examination of bleached skeletons (Figure 4.9).

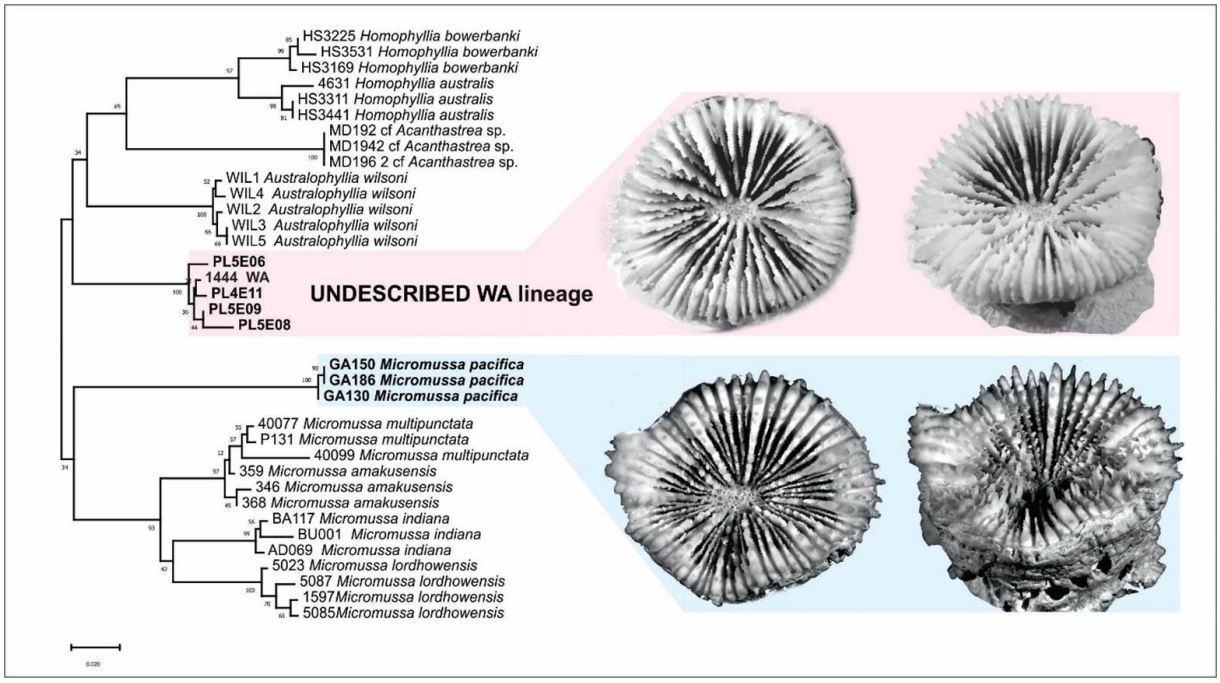


Figure 4.9. Maximum likelihood (ML) phylogenetic tree of *Micromussa*, *Homophyllia*, *Australophyllia*, and closely related genera based on the ITS2 locus (231 bp). The newly obtained sequence for specimen 1444 clusters with the WA material previously analyzed in the same well supported lineage. Branch support is based on ML bootstrap analysis.

For monophyletic groups and confirmed species (*C. jardinei*, *D. axifuga and T. geoffroyi*), genetic sequencing nonetheless provides new insights into the genetic structure and putative levels of gene flow among distinct wild stocks. For *T. geoffroyi*, which occurs throughout the Indo West-Pacific (Hoeksema and Cairns 2020b), we compared the genetic structure of corals from Western Australia, northern GRB (near Cairns) and southern GBR, based on proportional representation of different haplotypes (Figure 4.10). All samples belonged to a single species and 7 distinct haplotypes were

detected. There were some shared haplotypes between all three populations/ regions. The GBR populations were most similar and genetically distinct from individuals sampled from Western Australia. In all, individuals sampled from Western Australia were much more diverse than all individuals sampled on the GBR, even combining populations from the northern and southern GBR (Figure 4.10). Accordingly, analysis of molecular variance (AMOVA) revealed that there was greatest variation within populations (75.7% of variation), rather than among populations (25.3%). Most notably, pairwise fixation indices (Fst) for population differentiation showed that there was essentially no difference between populations in the northern versus southern GBR (Fst = 0.04), though GBR populations were distinct from those sampled in Western Australia (Fst = 0.38), as computed using *Arlequin* version 3.5.

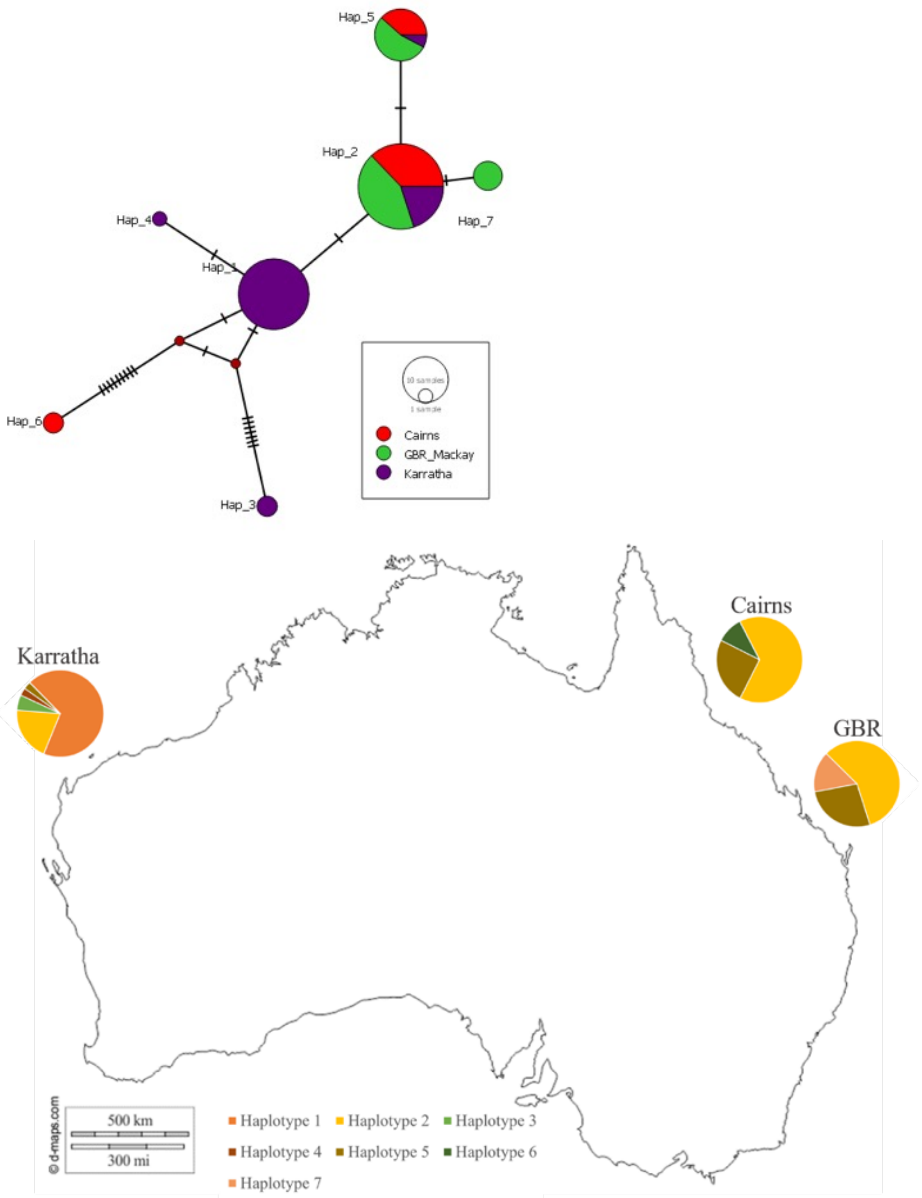


Figure 4.10. Network based on ITS2 haplotypes (240bp) calculated using Median-Joining. The area of each circle is proportional to haplotype frequency and is colour-coded according to populations. Each hash mark is one mutational step away from the next one (excluding insertions/deletions). Small red circles indicate branch splits. Pie charts (on map) show haplotype assignments according to populations sampled in each distinct location around Australia.

4.3 Species-specific vulnerability to extrinsic pressures

A total of 257 small (< 60mm diameter) corals were used in controlled experiments to test the temperature sensitivity and bleaching susceptibility of commonly harvested aquarium corals from across northern Australia. Of these, 128 (49.8%) corals exhibited declines in colour saturation through the course of the experiment, with bleaching (where declines in colour saturation were > 2) recorded for 74 corals (28.8%). All six species exhibited bleaching at some level (Figure 4.6). The incidence of bleaching was consistently higher for corals subject to experimental warming (35.6%), though 16.67% of the colonies maintained at ambient temperatures also bleached. The overall incidence of bleaching (across all treatments) was greatest for *M. lordhowensis* (38.9%, n = 18) and *E. glabrescens* (38.0%, n = 50). Lower incidence of bleaching was recorded for *C. jardinei* (26.3%, n = 38) and *T. geoffroyi* (23.2%, n = 56), and particularly for *H. australis* (14.6%, n = 17) and *D. axifuga* (11.5%, n = 78). For *E. glabrescens*, it was notable that only colonies collected from the GBR (northern and southern GBR) exhibited bleaching (even when exposed to high light at ambient temperatures), whereas none of the colonies from Western Australia exhibited major colour loss even when exposed to elevated temperature. For *D. axifuga*, bleaching incidence ranged from 10-17% with no obvious difference among regions.

Variation in the extent of colour loss recorded among corals was influenced by 'Species', 'Temperature', 'Light', and the interaction between 'Temperature' and 'Light' (Table 4.9). Based on standardised mean differences, elevated temperature resulted in significant colour change for *C. jardinei*, *T. geoffroyi*, and *D. axifuga*, while high light intensity accounted for significant colour loss in *M. lordhowensis* and *D. axifuga* (Figure 4.12). For *E. glabrescens*, the median level of colour loss was greatest in the high temperature and high light treatment, but bleaching was recorded across all treatments (Figure 4.12). For *H. australis*, the incidence of bleaching was low across all treatments (Figure 4.12). For *M. lordhowensis*, *C. jardinei*, *T. geoffroyi* and *D. axifuga*, bleaching (declines in colour saturation > 2) was more prevalent and more pronounced for corals subject to warming, but the extent of colour loss was exacerbated by exposure to high light (Figure 4.12).

Table 4.9. Linear mixed-effects model (LMM) results for (a) survival and (b) colour change predicted as a function of 'Species', 'Temperature', 'Lighting', and their interaction effects. All models include the tank as the random effect. Shown below are the degrees of freedom (df), maximum log-likelihood (LL), Akaike's information criterion corrected for small sample sizes (AICc), AICc weight (wAICc), and the adjusted R2 (adj R2). Only models with ΔAICc<2 are shown, in addition to the saturated and null models, and are ordered by increasing AICc.

Model	*df*	*LL*	*AICc*	*wAICc*	*adj R^2*
a) Colour change					
Species + Temperature + Light + (1 | Tank)	10	-421.3	863.5	0.347	0.229
Species + Temperature * Light + (1 | Tank)	11	-420.7	864.5	0.207	0.229
(1 | Tank)	3	-432.5	871.1	0.008	0.131
Species * Temperature * Light + (1 | Tank)	26	-410.0	878.2	0.000	0.253
b) Survival					
Species * Temperature + (1 | Tank)	14	-177.3	384.3	0.922	0.535
Species * Temperature * Light + (1 | Tank)	26	-179.3	416.8	0.000	0.555
(1 | Tank)	3	-232.4	471.0	0.000	0.080

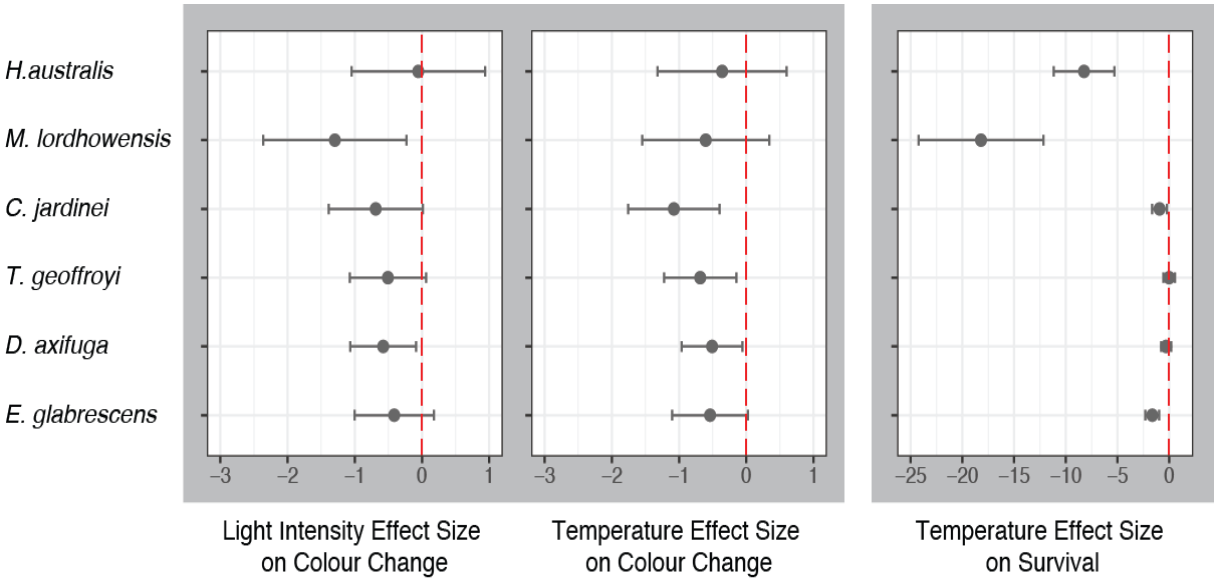


Figure 4.11 Inter-specific differences in the effect of light intensity and temperature on colour change and the effect of high temperature on survival, based on Hedge's *G* (i.e. effect size). Red dashed line indicates zero effect, while points to the left of this line suggest a negative treatment effect on colour change or survival.

This study adds greatly to the otherwise limited information on the bleaching susceptibility of coral species that are harvested from the marginal reef environments across Northern Australia, and all six species of coral (*H. australis*, *M. lordhowensis*, *C. jardinei*, *T. geoffroyi*, *D. axifuga*, and *E. glabrescens*) considered herein, did exhibit bleaching when exposed to elevated temperature and/ or high light conditions. This contradicts the prevailing rhetoric that aquarium corals are generally immune to extreme environmental conditions, and are intentionally selected based on their resilience to a range of different conditions. For example, aquarium corals from the Northern Territory are often marketed as "Territory tough", given the extreme tidal fluctuations, and associated temperature fluctuations and turbidity, to which these corals are exposed in nearshore habitats (Wolstenholme et al. 1998).

While bleaching is commonly recorded among scleractinian corals exposed to elevated temperatures, there are marked interspecific differences in their responses to environmental stress (Loya et al. 2001; Dandan et al. 2015) and the ultimate measure of a corals sensitivity to changing environmental conditions is survival (Hughes et al. 2018b). In this study, eighty-five (out of 257; 33.1%) corals survived to the end of the experiment (150 days). Survivorship was lower (21.3%) among corals subject to warming, than for corals maintained at ambient temperatures (57.8%). However, there was also marked interspecific variation in the survival of corals between the two temperature treatments. The best model (based on *wAICc*) for explaining variation in survivorship accounted for the interaction between 'Species' and 'Temperature', but did not include light levels (Table 4.9). *Post hoc* pairwise comparisons showed that there were significant differences in survival between corals subject to warming versus ambient temperatures for *H. australis* ($p < 0.001$), *M. lordhowensis* ($p < 0.001$), *C. jardinei* ($p = 0.028$), and *E. glabrescens* ($p < 0.001$); but not for *T. geoffroyi* ($p = 0.791$) and *D. axifuga* ($p = 0.270$).

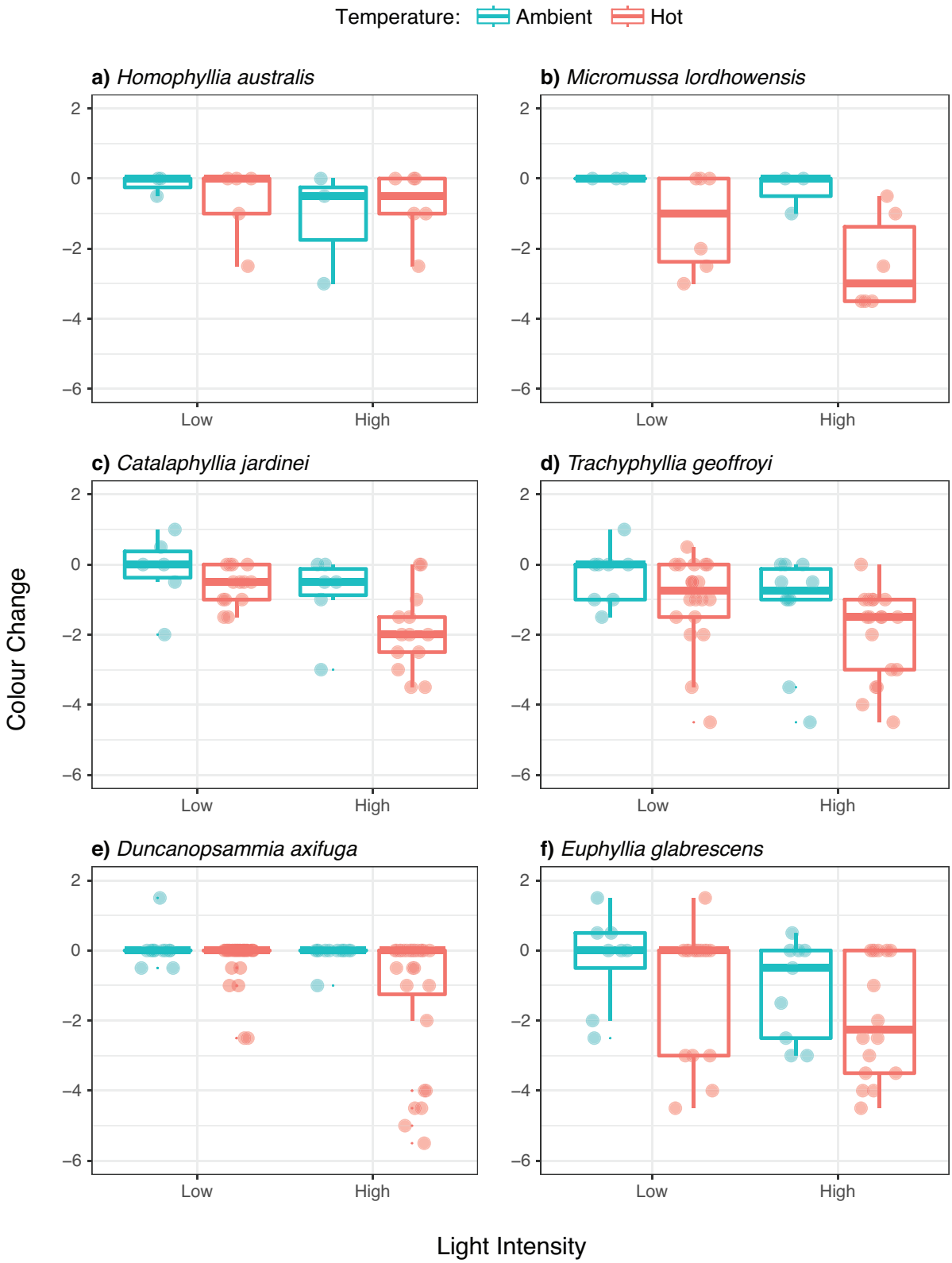


Figure 4.12 Boxplots showing species-specific colour change response to temperature and light intensity treatments. Plots show median (bold line), 25th and 75th percentile range (box), 5th and 95th percentile range (error bars), and jitter points (coloured circles) pooled across temperature treatments for each light treatment.

Survivorship of the different coral species varied both in extent and timing. For *H. australis* and *M. lordhowensis,* survival declined sharply from day 1 to day 75, during the treatment period for corals subjected to warming (Figure 4.13). Importantly, many colonies of *H. australis* died without exhibiting prior bleaching. For *C. jardinei* and *E. glabrescens*, there were also significant differences in survival with respect to temperature treatments, though this difference was most pronounced after the recovery period, on Day 150. For *C. jardinei*, differences in survival between temperature treatments were limited (92% versus 81%) during the treatment period, from day 1 to day 75, but overall survivorship (at day 150) was much lower for corals subjected to warming (19%) compared to colonies maintained at ambient temperatures (75%) (Figure 4.13). There was no difference in survival of *T. geoffroyi* or *D. axifuga* with respect to temperature treatments (Figure 4.13). For *D. axifuga*, <50% of corals survived 50 days and there was ongoing mortality throughout the subsequent treatment and recovery period (Figure 4.13). Survival of *T. geoffroyi* was much higher than for *D. axifuga*, but there were sustained levels of mortality throughout the experiment both for corals exposed to elevated temperatures and those maintained at ambient temperatures (Figure 4.13).

Given interspecific differences in both bleaching and survivorship, *H. australis* was arguably the most sensitive to elevated temperature, whereby all colonies subjected to warming had died within 60 days, even though they rarely exhibited bleaching prior to mortality. Conversely, *T. geoffreyi* exhibited a high incidence of bleaching, but low levels of mortality when exposed to elevated temperature. Rather than losing colour, tissues of *H. australis* would retract in response to warming (Figure 4.6) and once there was only a very small area of tissue remaining, the colony would inevitably and quickly die. Comprehensive mortality, without preceding evidence of bleaching, observed for *H. australis* would suggest that we overestimated the resilience of this species (collected exclusively from the southern GBR, where maximum summer temperatures are generally <29°C) and the temperature treatment was too extreme (*sensu* Leggat et al. 2019). Similarly, the moderate incidence of coral bleaching recorded for *C. jardinei* belies their temperature sensitivity, as tissues would often detach from the underlying skeleton when subjected to elevated temperature (Figure 4.6). In some instances, the free-living tissue persisted *ex situ* and retained its colour intensity for the duration of the experiment, though survivorship was low. Moreover, the persistence of free-living tissues of *C. jardinei* is likely to be an experimental artefact, as they would likely be very vulnerable to smothering or predation once dislodged in the wild.

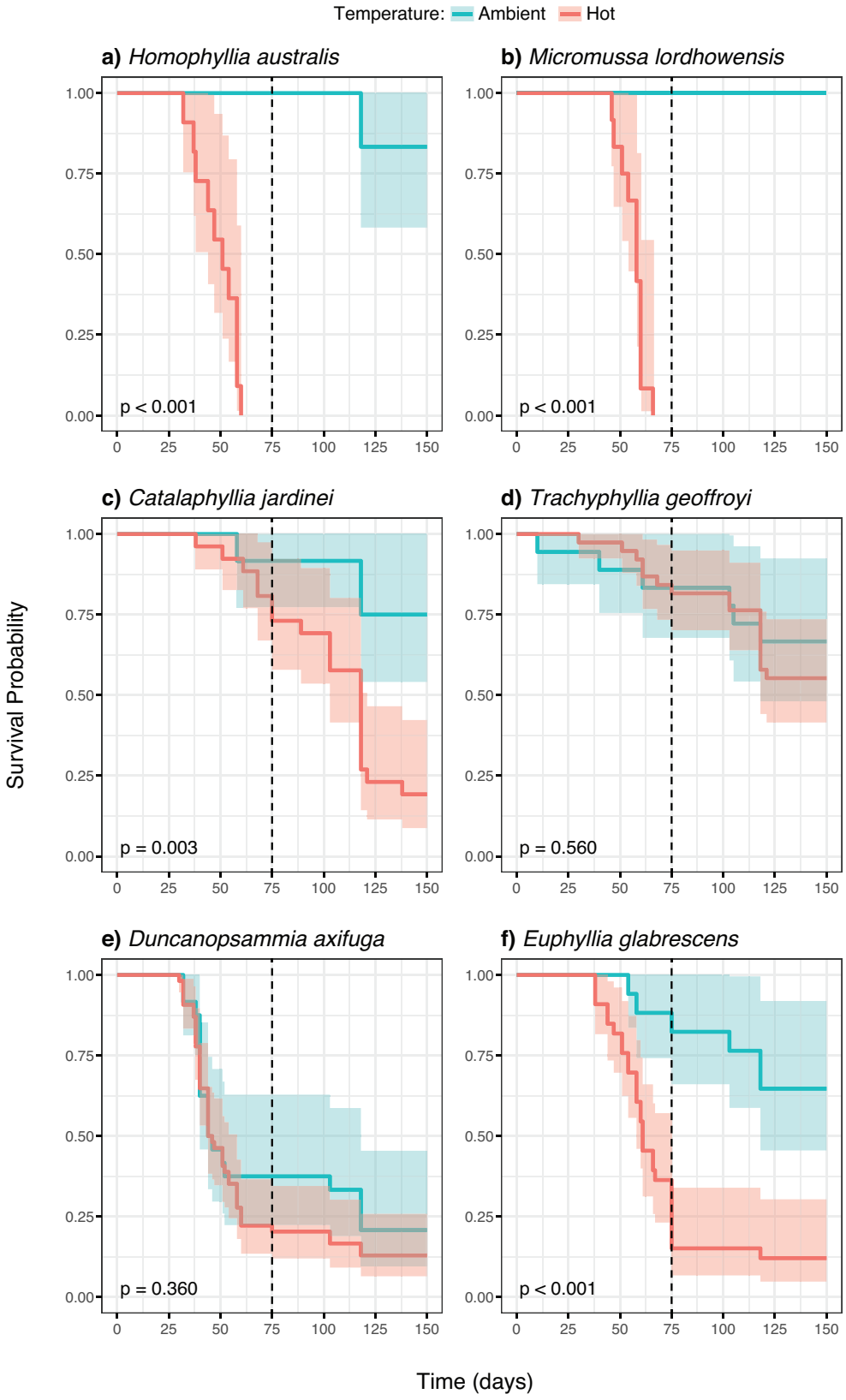


Figure 4.13 Species-specific Kaplan-Meier-estimated survival probabilities under two temperature treatments. P-values for the log-rank test comparing survival curves between 'Ambient' and 'Hot' treatments are shown. Dashed line indicates termination of experimental treatments and start of recovery period at 75 days.

5. Conclusions

5.1 Abundance and turnover of commercially important coral species

Output controls used to manage Australian coral fisheries are invariably based on the mass (weight) of harvested corals (Table 3.1). In Western Australia, for example, the latest revised TACC (across all hard corals) is 15,000kg (DPIRD 2018). To assess the relevance of these harvest limits in terms of wild stocks, it was first necessary to establish species-specific diameter-weight relationships for focal study species, which could then be used to estimate the mass of all individual corals surveyed during *in situ* sampling (video transects) based on the projected size (diameter) of each coral. While size-weight relationships are fundamental in determining both harvestable biomass of scleractinian corals and production (where growth rates are known), the only currently available data are for arborescent and corymbose *Acropora* (Longnecker *et al*. 2015) that are harvested to make lime in Papua New Guinea. The diameter-weight relationships established as part of this study will greatly advance field-based studies of stock size and structure, though they do encompass only a limited size range of corals (as collected by Australian coral fisheries). Further field-based sampling of larger corals that are not normally harvested in their entirety, but also encompassing a much broader range of different corals species is important. Despite extensive coral fisheries throughout the world, which often require reporting of the individual (or collective) weight of corals, it is unfortunate that these data have never been utilised to explore size-weight relations of harvested corals.

Having established size-weight relationships and thereby estimating biomass of corals *in situ*, this study provides the first estimates of harvestable biomass, albeit for a limited range of the extensive range of coral species that are targeted by Australian coral fisheries. Assessments of the stock status of harvested corals, while critically important for effective management, is very rarely conducted for aquarium fisheries anywhere in the world (Fujita et al. 2013). This is partly because traditional surveys of coral assemblages focus on measuring live coral cover, as an indicator of ecosystem function and condition (e.g., Johns et al. 2014) rather than the number or biomass of corals. Moreover, most of the corals harvested by global aquarium fisheries do not actually come from shallow, clear-water reef systems (e.g., Ferse et al. 2012). Accordingly, *in situ* estimates of stock size and structure need to be conducted with specific regard to the particular fishery. Our results show that the current standing biomass of select coral species in areas with highly concentrated and sustained fisheries pressure, and also in the aftermath of very significant extrinsic pressures (most notably widespread coral bleaching in both Western Australia and Queensland; Hughes et al. 2017b, Gilmour et al. 2019) is substantial, especially compared to current limits and reported harvest levels. Simply comparing the total biomass of harvested species versus standing biomass in major fishing areas does not, however, accurately represent potential fisheries impacts, nor the harvestable biomass of aquarium corals. Importantly, harvesting of most species is extremely selective, either taking only certain colours, size or shapes of corals (Donnelly 2013). In terms of the environmental impact, this selectivity greatly reduces risk of over-exploitation or localised depletion. However, fishery reliance on particular coral types means that *in situ* surveys of species abundance may greatly overestimate harvestable biomass, and will ultimately need to be constrained to just those individuals that are likely to be harvested.

While high levels of coral abundance and biomass recorded across Queensland and Western Australia (relative to current limits and reported harvest levels) point to limited risk of fisheries depletion, these data do not necessarily reveal the extrinsic vulnerability of coral species to fisheries exploitation. Importantly, the vulnerability of species to fisheries exploitation (even if normally large and abundant; e.g., Myers and Worm 2005; Andrews et al. 2006) is dependent on key demographic rates (e.g., rates of reproduction, replenishment, growth and mortality) or population turnover. For

corals, there is widespread concern that many of the larger, massive corals (e.g., *M. lordhowensis*) are extremely long-lived and slow-growing, and therefore highly vulnerable to fisheries depletion (Bruckner 2000). However, these concerns are predicated on assumed knowledge regarding the demography and turnover of such corals (though there is relevant data that suggests that massive corals grow more slowly than branching corals; Pratchett et al. 2015), and there is in fact very little data on demography and turnover for several of the key focal species. This study partly redresses this knowledge gap, presenting new data on the growth and survivorship of four corals species (*D. axifuga*, *E. glabrescens*, *H. bowerbanki*, and *T. geoffroyi*), as well as documenting reproductive mode and size at first reproduction for six coral species (*C. jardinei*, *D. axifuga*, *E. glabrescens*, *H. australis*, *M. lordhowensis*, and *T. geoffroyi*).

Growth rates recorded in this study (expressed as average annual rates of radial extension) were very low, especially for *H. bowerbanki* (0.80mm; -43.56-29.16mm) and *T. geoffroyi* (-0.03mm; -12.72-10.44mm), which are concerning. These growth rates were partly constrained by a high incidence and severity of partial mortality, possibly reflecting a period of elevated environmental stress and disturbances (see Tan et al. 2018). Also, the specific intertidal habitat where these measurements were taken may represent marginal habitat for these species, such that corals can persist (and grow well in some years) but have limited energy available for growth, and possibly also reproduction (though this was not measured for these specific individuals), at other times. Notably, the size of *T. geoffroyi* monitored in this study was relatively small (31.6mm: 10.5-48.2mm) and may reflect environmental constraints on growth in these habitats, whereas these corals get much larger (>150mm diameter) in other locations, such as the southern GBR. While fisheries management needs to take into account environmental pressures on wild stocks, which will vary both spatially and temporally, we caution against using the provisional growth estimates obtained in this study to assess the risk to these corals in other habitats, especially for *T. geoffroyi*, which can be found in a broad range of environments. Measuring growth rates of heavily harvested coral within habitats representative of where these corals are commonly harvested (e.g., sub-tidal habitats on the GBR) is a key priority for better understanding the vulnerability of these corals of ongoing harvesting.

Variation in the reproductive mode of different corals species may also influence vulnerability to fisheries exploitation. For example, brooding corals (e.g., *E. glabrescens*) have more restricted larval dispersal and will be much more vulnerable to localised depletion (Noreen et al. 2009), compared to spawning corals, where there is much greater rates of larval production and capacity for larval dispersal to replenish areas following localised depletion (Ayre and Hughes 2004). Most of the corals considered in this study (*C. jardinei*, *D. axifuga*, *H. australis*, *M. lordhowensis*, and *T. geoffroyi*) were found to be spawners (Table 4.5). Moreover, all corals appear capable of spawning at very small sizes. If, however, spawning corals have a relatively restricted distribution, as might be the case for *H. australis*, then opportunities for larval input from other source populations will be constrained. Also, large-scale perturbations have the capacity to supress replenishment of spawning corals at regional scales (Hughes et al. 2019). Measuring rates of replenishment, based on settlement rates or local densities of juvenile corals, will therefore, contribute greatly to understanding the resilience of coral populations to fisheries exploitation and increasing environmental pressures (Section 10.1.2).

5.2 Refined species-level taxonomy

Genetic sequencing has greatly improved the accuracy and consistency of taxonomic classification across a broad range of organisms (e.g., Torstom et al. 2014; Victor 2015), including hard (scleractinian) corals (Kitahara et al. 2016). At the higher taxonomic levels, genetic sequencing is revealing, and correcting, errors in the grouping of species to families and genera, to better reflect their phylogenetic affinities and ancestry (Benzoni et al. 2012; Arrigoni et al. 2014a; Kitahara et al. 2016). However, more refined examination and sequencing of individual species groups is also revealing many new coral species that were formerly regarded as local variants of widespread and

highly variable species (Stefani et al. 2011; Schmidt-Roach et al. 2013; Arrigoni et al. 2016), as was the case for nominal colonies of *H. australis* considered in this study. Indeed, genetic sequencing is focussing attention on morphological differences that are readily apparent among even well studied groups of corals (e.g., *Pocillopora* and *Stylophora*), once groups are clearly differentiated (Schmidt-Roach et al. 2014), leading to a proliferation in the discovery of new (mostly cryptic) coral species. We had expected, therefore, that striking regional differences in the size, and growth form of *C. jardinei*, and to lesser extent *T. geoffroyi*, as well as contrasting growth forms (plating versus branching) of *D. axifuga* might actually reflect cryptic speciation in these groups. Our provisional sequencing, based on just one nuclear (ITS2) sequence, could possibly be too coarse or too conserved to reveal cryptic species in *C. jardinei*, *D. axifuga*, and *T. geoffroyi*. However, our findings are generally consistent with previous studies that detected limited genetic structure among disparate specimens of *D. axifuga* (Arrigoni et al. 2104c) and *T. geoffroyi* (Huang et al. 2011, 2014).

While there is a scarcity of rigorous scientific studies, and substantial knowledge gaps, regarding the natural biology and ecology of harvested coral species from non-reefal environments, the taxonomy of these corals is fairly well established. This is probably not surprising, given that many studies on the molecular biology of scleractinian corals source specimens through the aquarium industry (e.g., Bollati et al. 2020). There is however, considerable uncertainty regarding the taxonomy of *H. australis* and *M. lordhowensis*, which are among the best-known of the exported Australian aquarium corals. The taxonomy of corals within the family Lobophyllidae (including *Acanthastrea*, *Acanthophyllia*, *Homophyllia*, *Lobophyllia*, and *Micromussa*) has been subject to several major revisions in a short space of time (Huang et al. 2011, Arrigoni et al. 2014a, b) and is still likely to yield some major surprises. Resolving the taxonomy, and thereby the real distribution, of these two important corals (*H. australis* and *M. lordhowensis*) is a major priority for Australian coral fisheries, and especially Queensland, given it is very likely that the centre of abundance for these corals is located in the southern GBR.

Resolving the taxonomy of harvested coral species is also important for aligning domestic harvest records with international import and export records. It was recently advised, for example, that *Acanthophyllia deshayesiana* (while a valid and verified species; Hoeksema and Cairns 2020c) would no longer be accepted as a valid name for Australian coral exports, given it is not recognised by the UK and EU. This issue reflects the level of subjectivity involved in species taxonomy when based solely on morphological characteristics; Huang et al. (2016) suggested that *A. deshayesiana* are indistinguishable from *Cynarina lacrymalis*, though Darus et al. (2016) report clear and consistent differences in the morphology of these two species, based on samples from Indonesia. Importantly, however, there is yet to be any genetic sequencing to confirm or refute the affinity of these species, though this is now underway.

5.3 Species-specific vulnerability to extrinsic pressures

Much of the concern regarding the sustainability of Australian coral fisheries is generated, not by direct evidence of increasing or over-exploitation, but by widespread and sustained declines in the abundance of corals caused by fisheries independent pressures, and especially environmental change (De'ath et al. 2012; Gilmour et al. 2019). On the Great Barrier Reef, for example, rigorous long-term monitoring across 214 reefs has revealed major declines in coral cover from 28.0% in 1985 down to 13.8% in 2012 (De'ath et al. 2012). Since 2012, sustained coral loss has been further exacerbated by major tropical storms (Madin et al. 2018), outbreaks of crown-of-thorns starfish (Pratchett et al. 2014), and most importantly, unprecedented incidence and severity of mass coral bleaching (Hughes et al. 2017b, 2018b). Similarly, reefs in Western Australia are increasingly subject to heatwaves and coral bleaching (Depczynski et al. 2013) and coral cover on most reefs is at or near the lowest levels on record (Gilmour et al. 2019). It must be acknowledged however, that these data come mainly from shallow, open-water coral reef environments (Hughes et al. 2017b; Gilmour et al. 2019), and it

is largely unknown whether the reported incidence of major disturbances and corresponding declines in the abundance of corals are generally applicable in a wide range of different habitats where aquarium corals are harvested, including intertidal, nearshore turbid and mid-shelf inter-reefal environments.

Given the general lack of information pertaining to the bleaching susceptibility of coral species that are important target species for aquarium fisheries in Queensland, the Northern Territory and/ or Western Australia, this study conducted experimental tests of temperature sensitivity and bleaching susceptibility for six different coral species; *H. australis*, *M. lordhowensis*, *C. jardinei*, *T. geoffroyi*, *D. axifuga*, and *E. glabrescens*. All six coral species exhibited bleaching to a greater or lesser extent. Most notably, *M. lordhowensis, C. jardinei, D. axifuga* and *T. geoffroyi* exhibited significant colour loss (or bleaching) when exposed to elevated temperatures, and bleaching was exacerbated by high light intensity for *M. lordhowensis* and *D. axifuga*. Even more alarming however, were the high levels of coral mortality (>80%) recorded for *H. australis*, *M. lordhowensis*, *E. glabrescens* and *C. jardinei* when these corals were subjected to elevated temperatures. Moreover, there are many other coral species (mainly, *Acropora* spp.) that are important components of aquarium coral exports (Dee et al 2014; Barton et al. 2017), which are even more susceptible to environmental change (Baird and Marshall 2002; Pratchett et al. 2013; Hughes et al. 2018b; Burt et al. 2019). This shows that sustained and ongoing environmental change (Hughes 2003) is likely to impact on the health and abundance of at least some fisheries target species and increasingly undermine the sustainability and viability of Australian coral fisheries. However, further research is required to establish the specific vulnerability (or resilience) of specific coral species, as outlined below (see Section 10.1.3).

6. Implications

The foremost contribution of this study to Australian coral fisheries is to provide new and unprecedented data on the distribution, abundance, biology and vulnerability of major target species (*Catalaphyllia jardinei*, *Duncanopsammia axifuga*, *Euphyllia glabrescens, Homophyllia australis*, *Micromussa lordhowensis*, and *Trachyphyllia geoffroyi*), which greatly increases confidence in assessing the risk posed to these species by commercial fisheries, thereby contributing to the long-term sustainability and viability of the relevant fisheries. Explicit demonstration of sustainability is fundamental to the continuation of Australian coral fisheries, both to meet Australian government (EPBC Act 1999) and State government (e.g., Queensland's Fisheries Act 1994) commitments to ecological sustainable development in the use of natural resources, and also to satisfy NDF requirements necessary to secure ongoing WTO and export approvals. Previous independent assessments have consistently concluded that Australian coral fisheries are operating well within sustainable limits (e.g., Oliver and McGinnity 1985; Harriott 2001; Cartwright et al. 2002) and reported harvest levels have not dramatically changed since these assessments were completed. Nonetheless, these previous assessments did highlight possible concerns regarding localised fisheries depletion (see also Jones 2011) and the vulnerability of specific species to over-exploitation (Bruckner 2000, Harriott 2001). There have also been repeated calls for much more rigorous data on the distribution, abundance and biology of major target species, for establishing sustainable harvest limits of individual species (Bruckner 2000, Harriott 2001). Added to this, there have been some notable changes in the nature of Australian coral fisheries (changing demand and selectivity for species), as well as dramatic increases in the fishery independent threats (e.g., climate-induced coral bleaching) that bring into question the current sustainability of coral harvesting in Australia, and globally (Jones 2011; Rhyne et al. 2014; Albert et al. 2015).

In the absence of biological and ecological data necessary to determine sustainable harvest limits of major target species for Australian coral fisheries (especially given the broad range of different species that are targeted), fisheries management authorities rely on a combination of fisheries catch and effort data and trends, precautionary harvest levels, and ERAs, to permit ongoing coral harvesting and seek WTO approvals. However, the lack of rigorous data on the biology and vulnerability of major target species also undermines the surety of ERAs (despite the input of relevant experts), which are an important foundation of recurrent environmental assessments of Australian fisheries, as required by the EPBC Act. For example, there have been persistent concerns about the risk of over-exploitation for *D. axifuga*, given it is very rarely reported in established coral monitoring programs (e.g., Johns et al. 2014) and is therefore, regarded as to be rare (e.g., Atkinson et al. 2008; see Section 11.1). However, this study conducted sampling in the specific areas of concentrated fishing activity for *D. axifuga* (and other major target species) in Western Australia and confirms that this species can be very abundant in certain habitats.

It is widely recognised that the lack of relevant data pertaining to the biology and vulnerability of fisheries target species represents a considerable constraint to effective management of Australian coral fisheries, especially given that there is limited overlap in the species and habitats used by coral fisheries versus well-established monitoring programs (e.g., AIMS LTMP). However, the burden of undertaking necessary research, and demonstrating ongoing sustainability of fisheries operations, will increasingly fall to commercial fisheries (Dayton 1998; Fitzpatrick et al. 2011). Accordingly, this study has provided a way forward for industry-based sampling and monitoring programs that will greatly increase the information and data on which to base future risk assessments, as well as leading towards robust determination of sustainable harvest limits for species of concern that are critically important to the continuation and viability of Australian coral fisheries.

The best way for Australian coral fisheries to demonstrate that recent and future harvesting are not having any detrimental effect on wild stocks of harvested coral species, nor the structure and function of coral reef ecosystems, is to show that the abundance (or biomass) of target species in areas of concentrated fishing effort is relatively stable or unchanged over years to decades. Moreover, temporal trends in the abundance and stock structure of harvested corals in fished areas should be compared with suitable reference locations where fishing is prohibited (e.g., established no-take areas) or temporarily suspended (i.e. industry established reference locations). This will require a considerable commitment to appropriate data collection, as well as extensive prior planning to develop necessary sampling designs. Ideally, surveys should be conducted in both fished and unfished areas annually or biannualy to account for extrinsic (non-fishery related) causes of coral loss, such as climate induced coral bleaching and cyclones. The payoff for increasing information and confidence regarding stock size and structure, would be possibly increased harvest limits, especially if it can be shown that the biomass of target coral species in fished areas is above 40-60% of the unfished biomass in suitable reference locations (e.g., QDAF 2017). Rigorous demonstration of relevant patterns and trends will likely require further collaboration with researchers and fisheries managers, though commercial fisheries operating in each region (WA MAFMF, NTAF and QCF) can take a lead role in acquiring the necessary information and data streams.

Further implications of this study, specific to each fishery (and as discussed with relevant fisheries managers in each State), are discussed below.

6.1 Western Australian Marine Aquarium Fish Managed Fishery

The Western Australia Marine Aquarium Fishery (MAFMF) is currently in an expansion phase, whereby increasing information (albeit largely anecdotal to this point) regarding the distribution and abundance of major target species (e.g., *D. axifuga*) is reducing the perceived risk of over-exploitation. The current study largely reaffirms information provided during recent ERAs, and will likely serve to further relax precautionary harvest limits currently placed on species of greatest concern (See Section 11.1). For *D. axifuga*, which was recorded on >25% of transects and had an average biomass of 3.3kg ±1.5SE across these transects, the 2014-2016 NDF level of 550kg would be contained in area of just 0.83 hectares. The maximum biomass of this species on a single transect was 47.2kg, or just under 1kg per m^2. Recorded biomass (and densities) for *E. glabrescens* and *T. geoffroyi* also suggest that there is significant capacity for increases of current harvest levels and limits.

6.2 Northern Territory Aquarium Fishery

The Northern Territory Aquarium Fishery (NTAF) is the only Australian coral fishery that has introduced (and only very recently) species-specific NDF harvest limits across all target coral species, which are set by default at 40kg per species per annum (DPIR 2019b). Since July 1st 2019 the NDF harvest limits for each nominal species have been managed by dividing the total allowable catch among individual licences, based partly on their previous catch history. However, the NTAF has also introduced electronic logbooks and requires weight-based reporting for all CITES listed species, which enabled temporary closures to be implemented in 2018 when reported catches of individual species approached NDF harvest limits. Species-specific harvest limits are the best way to individually manage the diverse range of coral species that are targeted by Australian aquarium fisheries, but does place increased importance on the ability to readily distinguish and identify different coral species, especially for compliance. While this study has shown that the current nomenclature is fairly stable across most major groups (e.g., Dendrophylliidae and Euphylliidae, where the latter now includes *Catalaphyllia*) there are critical questions relating to the taxonomy and nomenclature of key target species within the family Lobophylliidae (including, *Lobophyllia*, *Homophyllia* and *Acanthastrea*). Most importantly, further samples and genetic testing will be needed to resolve the

identity and variability among monocentric corals, currently reported as *Lobophyllia (Scolymia) vitiensis*.

6.3 Queensland Coral Fishery

The Queensland Coral Fishery (QCF) is Australia's largest coral fishery (in terms of both the number of operators and also the total annual reported catch), but operates over a vast area. The large area of marine habitat, with a considerable portion (~33%) closed to fishing, significantly moderates any effect that coral harvesting might have on the GBR ecosystem as a whole (Harriott et al. 2001). However, persistent concerns do remain about the potential overexploitation of specific species and in specific areas. This study does little to allay concerns of localised depletion, especially given limited relevant data on the abundance of *M. lordhowensis* in areas of concentrated harvesting for this species (Jones 2011). Moreover, genetic sequencing suggests *H. australis* might be endemic to the GBR (or at least the south-west Pacific), as suggested previously for *M. lordhowensis* (see Atkinson et al. 2008). If so, localised depletion may threaten not only local concentrations of these species, but the entire species.

To manage localised concentrations of fishing effort, and potential localised depletion of specific species in these locations, the QCF implemented a targeted Performance Management System (PMS), to explicitly monitor catch and effort trends and implement appropriate management responses (as required) to prevent over-exploitation in defined areas. Notably, there is not currently any specified limits on the TACC of individual species, other than overarching limits for all speciality coral (60,000kg). The PMS will be further refined during the development of a new harvest strategy for the QCF, whereby specific efforts will be taken to reduce annual harvests of high risk species. There are also proposals to establish fisheries closures that encompass areas with high densities of *H. australis*, which might then provide spawning stock to ensure replenishment in surrounding areas that are open to fishing, but could also serve as appropriate reference locations for explicitly testing whether fisheries impacts are apparent for this species. Above all the results of this study will contribute directly to the next ERA in 2020/21.

7. Recommendations

7.1 Further development

The research presented in this report was necessarily focussed on a restricted range of the coral species, whereas marine aquarium fisheries across northern Australia target a broad range of different coral species. Moreover, the market demand for different coral species is ever-changing, with technical advances in marine aquarium systems and changes in the capacity to keep different types of coral (Delbeek 2001), as well as priority and premium prices given to corals or colour morphs that are new to the industry. Accordingly, the research and information needed to support Australian coral fisheries is vast and rapidly evolving (Jones 2011). Aside from simply expanding the coverage of coral species for which we have basic information on distribution, abundance, turnover and vulnerability necessary for developing robust and defensible species-specific harvest limits and management strategies, there are many questions about biology and sustainability that are unique or specific to certain types or groups of corals. Further research and sampling is needed to: i) build upon baseline information presented herein to test for temporal changes in stock size and structure (ideally comparing trends in heavily fished areas to comparable reference locations with negligible or no fishing), ii) further assess the vulnerability of major harvest species to increasing environmental change, and other unanticipated pressures on wild stocks, iii) explore opportunities for captive breeding to both reduce reliance on wild stocks, but also select for highly desirable colours and/ or morphologies, and increase genetic diversity (potentially leading to new and valuable phenotypes), and iv) further resolve species boundaries and distribution limits of poorly resolved species groups, especially monocentric Lobophyllidae corals.

7.1.1 Assessing temporal trends

Aside from major results and findings arising, the key contribution this project makes to ongoing improvements in sustainability and management of Australian coral fisheries relates to the development and establishment of protocols for monitoring stock size and structure into the future. Most notably, video transects (50 $\times$ 1m belt transects marked with a fiberglass tape and filmed using a waterproof camera attached to 1m scale bar; Figure 4.4) provide a readily tractable method for documenting the abundance and biomass (when combined with data on species-specific diameter and weight relationships) of corals across most (but not all) environments in which they occur and are harvested. There was an initial reticence on the part of many licensees to undertaking video transects, both due to concerns about the confidentiality and misuse of information arising, as well as the need to commit limited time underwater to running transects, rather than actively harvesting, (especially given very limited opportunities for fishing, due to extended periods of bad weather in Queensland over the last two years). The proposed transect protocols are also ineffective for sampling in areas with very strong current and/ or very poor (<1m) visibility, further limiting the opportunities to obtain useful data from such environments. As such, the most efficient and effective method for sampling involved researchers working alongside licensees, whereby the licensees facilitated access to relevant field sites while continuing to fish (albeit with some concessions made to facilitate the necessary research), while necessary sampling was undertaken by the research team. This approach resulted in a disproportionate number of transects from intertidal habitat in Karratha. However, there were some important contributions to the data collected by licensees working independently, who were greatly underwhelmed by the effort required to obtain the necessary information. Video transects will be particularly useful, and even more effortless, for documenting the size and abundance of corals (e.g., *Acropora*) that grow in shallow clear-water reef environments.

Although video transects are very effective for documenting the stock size and structure of corals, there is considerable image processing required to extract the necessary information pertaining to

the size and abundance of individual species. It is likely therefore, that relevant expertise will need to be contracted to facilitate necessary processing of video transects. Nonetheless, extensive sampling can be undertaken by licensees independent of any involvement or oversight by external scientists or managers, whereby video transects can be run at regular intervals and in a range of different environments. If so, the resulting video files can be stored indefinitely and only processed if and when the need arises. Importantly, if protocols that were developed for this project are followed exactly (see section 12.1), all necessary information will be contained within the video file to allow for future processing.

The benefit of having extensive video transects from a wide range of locations and over an extended period is that it will allow examination of temporal trends in stock size and structure, showing that either: i) ongoing fishing is having negligible effects on wild stocks or ii) that any declines in the condition and status of wild stocks are independent of fishing activity and attributable to extrinsic factors (e.g., environmental change, see section 10.1.3). The power of these analyses will be greatly improved if temporal trends in stock size and structure can be compared among locations with different levels of fishing effort, ideally including reference locations that are closed to fishing. Indeed, comparisons between areas that have been subjected to sustained fishing effort and comparable areas contained within established no-take areas, or relevant reference locations that have been subjected to little or no fishing, represent an immediate and obvious opportunity to build on collaborations between Australian coral fisheries and researchers, and thereby explicitly test for effects of fishing as opposed to extrinsic pressures on major harvested coral species or species of concern.

7.1.2 Vulnerability to increasing environmental change

Increasing incidence and severity of marine heatwaves, caused by accelerating global warming (Hobday et al. 2016, Oliver et al. 2018, Skirving et al. 2019) represents the greatest threat to corals that are highly susceptible to temperature-induced bleaching and mortality (Hughes et al. 2017b, 2018a; Skirving et al. 2019), and the threat posed by climate change will only get worse in coming decades. While most studies that assess the incidence and severity of mass coral bleaching are conducted in shallow open-water reef environments (Hughes et al. 2017b; Gilmour et al. 2019), the current study highlighted the potential vulnerabilities of important target species for aquarium fisheries in Queensland, Northern Territory and Western Australia, whereby *H. australis*, *M. lordhowensis*, *E. glabrescens* and *C. jardinei* were particularly susceptible to experimentally-imposed temperature stress. However, experimental studies are highly constrained in their capacity to assess how corals respond to elevated temperatures in the wild (Camp et al. 2018), and results from these preliminary experimental studies do need to be verified and validated by assessing the bleaching incidence and survivorship of major target species in their natural environment. *In situ* bleaching assessments can be readily carried out using video transect protocols as described above, where licensees should conduct video transects whenever and wherever high incidence of bleaching is recorded.

Aside from mass coral bleaching, which is the most obvious effect of changing environmental conditions among coral population and communities, corals may exhibit a wide range of responses to changing environmental conditions. Most importantly, Hughes et al (2019) showed that recent mass-bleaching in the GBR not only lead to extensive coral loss in the worst affected parts of the reef, but that there was widespread suppression in rates of coral recruitment, measured by deploying settlement tiles before and after the bleaching. At the scale of the entire GBR, overall levels of coral recruitment had declined by close to 90%, from a mean of 43.1 corals per tile ($\pm$1.5SE) in 1996-2016 down to 4.9 corals per tile ($\pm$0.2SE) in 2016-2017 (Hughes et al. 2019), which will greatly constrain the recovery of coral populations in the aftermath of the bleaching. This widespread recruitment failure of corals on the GBR is partly attributed to the loss of corals that died due to extreme

bleaching, though the spatial extent of observed effect was much greater than the extent of severe bleaching, suggesting that even if corals survived and did not bleach, they exhibited a compromised reproductive output in 2016-17. For corals that are subject to fisheries exploitation, such declines (90%) in population replenishment will likely result in long-term declines in stock size and significantly undermine sustainability of harvesting. Measuring coral recruitment on settlement tiles (*sensu* Hughes et al. 2019) is a significant and costly undertaking, but useful information on population replenishment may be obtained by carefully and systematically assessing densities of smaller corals on natural substrates (e.g., Hoey et al. 2011; Pratchett et al. 2017; Evans et al. 2020). Information on changes in population replenishment of major target species will not only provide insights into the extrinsic pressures posed by environmental change, but will broadly assess the capacity of coral populations to recover from localized disturbances or fisheries depletion.

7.1.3 Opportunities for captive breeding

Regardless of the current sustainability of Australian coral fisheries, there is a major imperative to reduce the reliance on wild collection fisheries and increasingly develop intensive land-based mariculture to partially meet growing international demand for Australian aquarium corals (Delbeek 2001, Harriott 2001; Arvedlund et al. 2003). Land-based mariculture is an obvious way to add value to existing harvest fisheries, building on fragmentation (asexual propagation) of colonial corals collected from the wild, which is already widespread (Arvedlund et al. 2003). However, fragmentation is not viable for many of the high value corals harvested in Australia, and captive breeding (sexual propagation) will greatly increase potential production for new corals, as well as providing opportunities to breed selectively and potentially generate new and novel phenotypes (Delbeek 2001; Arvedlund et al. 2003).

Culturing corals in captivity could become increasingly important in the future, not only to meet market demand, but also to conserve corals that may go extinct in the wild. This will mitigate the ecological impacts of the coral fishery by significantly reducing wild harvest, while maintaining the economic benefits from the industry (Dee et al. 2014). This body of work has contributed significantly in improving our knowledge of the reproductive biology of coral species targeted by the aquarium industry. We now know the sexuality and reproductive mode of these corals and this vital information can be used to identify candidate species for captive breeding through sexual propagation. Our ability to accurately predict the timing of gamete release for broadcast-spawning species (e.g. *Homophyllia australias*, *Micromussa lordhowensis*) has also improved significantly (Foster et al. 2018; Wolstenholme et al. 2018); which, in addition to data on size-at-sexual-maturity, will be valuable in selecting species to propagate and deciding the size and time to collect colonies for broodstock. Recent advances in aquarium technology now make it possible to closely simulate natural conditions (lighting, temperature, lunar cycles) so that the timing of spawning can be artificially altered for broadcast spawning corals in captivity (Craggs et al. 2017). Alternatively, the availability of ready-to-settle larvae from brooding species (e.g. *Euphyllia glabrescens*) for an extended period of time makes it a good candidate for propagation (Nietzer et al. 2018), although further studies are needed on settlement preferences and post-settlement growth.

Realistically, captive-bred corals are likely to supplement, rather than completely replace wild harvest, though captive breeding does have significant potential to significantly alleviate the impacts of collection on coral reefs. For this to succeed, however, it will require a consumer base that is willing to pay a price premium for captive-raised corals and considerable prior investment to develop effective and viable mariculture systems. Importantly, dedicated closed systems for large-scale sexual propagation require considerable investment and maintenance, but are a necessary step towards developing viable captive breeding, if not further exploring the reproductive biology of high value coral species.

7.1.4 Genetic sampling and sequencing

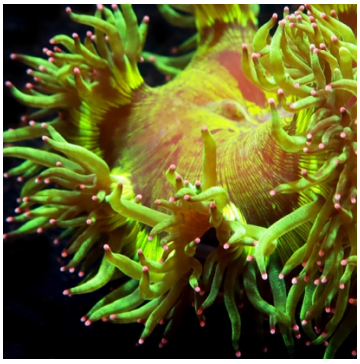
This study has highlighted a critical need for increased sampling and sequencing of Lobophyllidae corals, to resolve both species boundaries and distribution limits of each species. More specifically, systematic sampling of monocentric Lobophyllidae corals (including both *H. australis* and *M. pacifica*, but also *L. vitiensis*, *Cynarina lacrymalis* and *Acanthophyllia deshayesiana*) from a broad range of locations and habitats (e.g., inshore versus offshore locations) on the GBR, Queensland. Given the lack of genetic sequencing among some of the lesser studied species (e.g., *A. deshayesiana*) it is quite possible that this research will reveal further new species. However, the primary goal of this research is to establish the distribution limits of each species. Further sampling and sequencing of monocentric Lobophyllidae corals from a broad range of locations in Western Australia and Northern Territory is also required to explicitly test for the presence of *H. australis*, *M. pacifica* and *L. vitiensis*, while also obtaining necessary voucher specimens to formally describe the newly discovered species. Similarly, explicit sampling and sequencing is required for putative colonies of *Micromussa lordhowensis* from Western Australia, which are yet to be formally assessed, though there are definite questions regarding their species affinity (Arrigoni et al. 2016).

Extension and Adoption

Ecological risk assessments

Australian (Commonwealth) Government legislation (specifically, the *Environment Protection and Biodiversity Conservation Act 1999* and the *Environment Protection and Biodiversity Conservation Amendment (Wildlife Protection Act) Act 2001*) require that fisheries management agencies (State based management authorities) must demonstrate (through periodic ecological assessments) compliance with objectives of ecological sustainable development. These requirements are particularly important where harvested species are intended for export, and subject to the *Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES)*, as is the case for all hard (scleractinian corals). *In lieu* of limited specific data on the population status and fisheries impacts on many target species, the sustainable harvest of individual species or taxa is often assessed using the ERA framework, following Fletcher (2005).

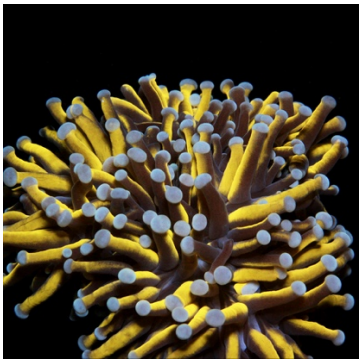
A key component of this project involved contributions to development and/ or refinement of ERAs in Queensland (Roelofs 2018), the Northern Territory (DPIR 2019a) and Western Australia (DPIRD 2018). While full details of the ERA procedures and outcomes are published in stand-alone documents (*ibid*), which cannot be reproduced in their entirety herein, we have combined key outcomes and commentary as it pertains to the specific focal coral species considered in this study. Species-specific information arising from this project is provided alongside this existing risk ratings (scores are presented along with colour coding of overall risk level: green – low, yellow – moderate, red – high), with comments on suggested changes in risk ratings, where relevant.

Catalaphyllia jardinei (Elegance or wonder coral)	Fishery	Risk	Comments
	QCF	3	Widely distributed and can be very abundant in certain habitats, with large colonies in southern GBR. Localised depletion apparent in areas of sustained harvesting over many years/ decades.
	MAFAF	2	Can be common in sheltered coastal waters with sandy or muddy substrate. Potentially vulnerable to localised depletion such that daily limit (5kg) applies. Doubling of 2014-2016 NDF level (180 kg) not considered to materially affect risk rating
	NTAF	-	Not assessed

This study confirmed that *C. jardinei* has very high abundance and biomass in specific habitats (approaching 40kg per m^2). However, most corals are harvested as relatively small and discrete colonies, from areas with fairly moderate abundance and biomass. Preliminary genetic sampling (based on the ITS marker) suggests that there is no difference (and potentially high levels of genetic exchange) among these seemingly disparate populations. The risk posed by fisheries exploitation on the viability and persistence of this species is therefore, considered to be negligible. However, experimental studies of their temperature sensitivity do raise concerns about the risk posed by increasing incidence and severity of marine heatwaves, which may threaten wild stocks, especially in low latitudes. The capacity for this species to recover from localised disturbances (including localised fisheries depletion) is also unknown, and research on the natural replenishment (e.g., settlement rates and habitat requirements) and growth rates of this species should be prioritised, both to inform fisheries management and assess viability of captive breeding and rearing.

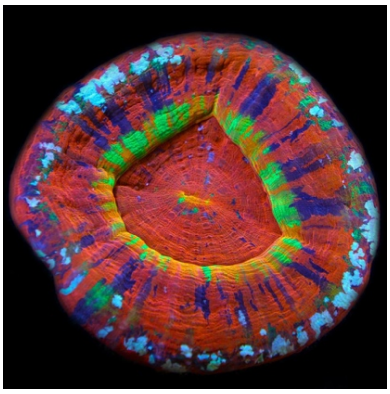
Duncanopsammia axifuga (Whisker coral)	Fishery	Risk	Comments
	QCF	2-6	Considered to be rare, but collectors report it to be very common in appropriate habitats. Many pieces are harvested, but their combined weight is low (e.g., 6,286 pieces - 1,016kg in 2010-11)
	MAFAF	3	Can be extremely abundant. Generally attached to hard substrate but proliferates over surrounding soft bottom habitat. Doubling of 2014-2016 NDF level (550kg) not considered to materially affect risk rating
	NTAF	12	Coral is widespread, but catch consistently above specified NDF limit (80kg)

This study confirmed industry assertions that *D. axifuga* can be very abundant in some habitats, especially in Western Australia. The broad size range and high abundance of *D. axifuga* within intertidal habitats surveyed in Western Australia suggests that this species will be extremely resilient to fisheries exploitation, especially given the relatively small size (~50mm diameter) at which they start reproducing, as well as consistent growth and high survival of adult colonies. Genetic sequencing confirms that *D. axifuga* is monospecific throughout Queensland and in Western Australia. Moreover, experimental studies of their temperature sensitivity suggest that *D. axifuga* will be relatively resilient to changing environmental conditions. At current harvest levels (and limits) the risk posed by fisheries exploitation to wild stocks of *D. axifuga* is considered negligible. Local resilience of this species will be further enhanced by harvesting fragments from larger colonies (which can be readily fragmented), rather than taking entire small colonies, as suggested in the *QCF Stewardship Action Plan* (Donnelly 2013)

Euphyllia glabrescens (Torch coral; golden torch)	Fishery	Risk	Comments
	QCF	2-6	Very common in specific habitats (inshore reefs), though only specific colour morphs and smaller colonies are harvested. There are concerns regarding lack of recent recruitment in some areas.
	MAFAF	2	Most common on deep reefs. Does occur in intertidal habitats, where it withstands high temperatures in tidal pools. Doubling of 2014-2016 NDF level (320 kg) not considered to materially affect risk rating.
	NTAF	6	Largely grows in somewhat inaccessible areas, though NDF limit (80kg) was exceeded in 2018-19.

This study confirms that *E. glabrescens* is monospecific, and occurs in a wide range of different habitats, often in reasonably high abundance. Colonies monitored in intertidal habitats in Western Australia exhibited high survivorship and moderate growth, though this species does appear to be susceptible to environmental change, with high rates of bleaching and mortality when subject to experimental warming. Their specific reproductive mode (brooding larvae) does mean that new colonies will really only establish within the immediate vicinity of reproductive adults, such that localised depletion will have lasting effects on population replenishment. At current harvest levels (and limits) the risk posed by fisheries exploitation to wild stocks of *E. glabrescens* is considered negligible, though the fishery is most reliant on specific colour morphs. As such, the research priority for this species is to explore whether highly desirable colours have a genetic basis, which will be readily achieved using selective breeding experiments.

Homophyllia australis
(Saucer, doughnut or button coral)



Fishery	Risk	Comments
QCF	12	Occurs in a wide range of locations and habitats, but highest densities and best colonies (based on size, colour and shape) occur in relatively turbid habitats. High harvest levels (>10,000 per year) in areas of concentrated fishing effort may pose a risk of localised depletion
MAFAF	1	Uncommon, but very conspicuous. Inherent limits on catches (due low abundance and diving limits) are reflected in low harvest levels (averaging 6kg from 2003-2013)
NTAF	4*	Recognised as vulnerable to cyclones and bleaching events. Average harvest level is low (10kg) compared to proposed NDF limit (80kg)

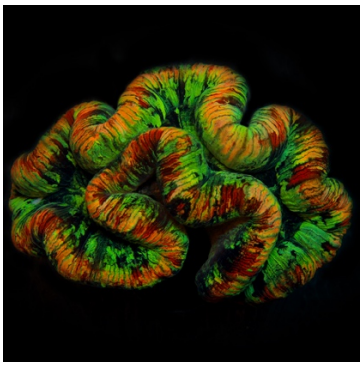
Homophyllia australis is easily confused with other similar coral species, especially *Micromussa pacifica*. While *H. australis* is widespread (with verified occurrences on offshore reefs of the GBR and Coral Sea), it is generally uncommon outside of the area where harvesting is concentrated. In this area, recorded densities were low, but consistent across a wide range of habitats. Genetic sequencing of corals collected from Western Australia and Northern Territory show that button corals collected in these jurisdictions are neither *H. australis* or *L. vitiensis*, but an undescribed species of monocentric Lobophylliidae. Given their apparent scarcity or restricted distribution, and small size of colonies, the risk posed by fisheries exploitation is considered moderate. Experimental studies suggest that *H. australis* is very sensitive to environmental changes, and the capacity for this species to recover from localised disturbances (including localised fisheries depletion) is also unknown. Research on the abundance, replenishment and growth rates in key habitats should be prioritised to inform fisheries management, while the capacity to produce offspring of specific colours is key to the viability of captive breeding.

*ERA risk rating based on 2019 assessment for *Lobophyllia (Scolymia) vitiensis* (current limit of 80 kg)

Micromussa lordhowensis
(Starry cup coral)

Fishery	Risk	Comments
QCF	2-6	Widespread and sometimes common, though majority of colonies are brown/ green (which are not harvested). Readily fragments during collection, and often retain only a portion of the initial colony. Large quantities and weights are routinely harvested (>2,000kg), mainly in southern GBR
MAFAF	-	Not assessed. Reported to be harvested, though only in low numbers
NTAF	-	Not assessed. Never knowingly harvested from NT, though small quantities of *Acanthastrea* sp (no species identity recorded) are reported.

Micromussa lordhowensis is a massive colonial coral that can attain very large sizes, though most of the colonies/ pieces harvested are <0.5kg and there remain questions about how fast this coral grows. We recorded moderate growth rates for a closely related species (*M. bowerbanki*), representing the first ever growth rates recorded for Lobophylliidae corals, though the relevance to *M. lordhowensis* is unknown. The broader geographical distribution and taxonomic identity of this species is also unclear, and genetic sequencing of nominal species from Western Australia and Northern Territory should be prioritised. This species appears to be highly susceptible to environmental change, potentially explaining why it is most abundant on high latitude reefs (e.g., Lord Howe Island; Arrigoni et al. 2016). Current data suggest that *M. lordhowensis* is generally uncommon, which combined with their extrinsic vulnerability, suggests that there is a moderate risk from fisheries exploitation. Explicit sampling needs to be conducted in major harvest areas to provide more robust estimates of stock size, and also assess the proportion of colonies of different colours.

Trachyphyllia geoffroyi (Nudibranch or brain coral)	Fishery	Risk	Comments
	QCF	1-9	Widely distributed and can be abundant in certain habitats (inter-reefal habitats with ephemeral algae). Sustained harvesting over many years has anecdotally resulted in limited size and abundance in some areas.
	MAFAF	2	Occurs in variety of habitats with soft substrates, but most abundant in subtidal habitat with strong currents. Larger individuals are vulnerable to storms. Doubling of 2014-2016 NDF level (450 kg) not considered to materially affect risk rating
	NTAF	-	Not assessed. Very low harvest levels (2 kg) in 2016-2019

Trachyphyllia geoffroyi is confirmed to be widespread, and despite differences in size, shape and colouration (e.g., from the northern versus southern GBR), is a single species, albeit with strong genetic differentiation between Queensland and Western Australia. Densities of *T. geoffroyi* can be reasonably high, though colonies are generally small and contribute little to overall biomass of corals in any given location or habitat. Growth rates recorded in the field were extremely low, with negligible change in the size of corals over 1-2 years, though there was high survivorship (and minimal injuries) throughout this period. While *T. geoffroyi* readily bleaches when exposed to elevated temperatures it rarely succumbs to temperature stress and is much more resilient to environmental change than any of the other corals species examined, though given they are rarely attached, they may be particularly vulnerable to severe storm and cyclones. The risk posed by fisheries exploitation on the viability and persistence of this species is considered to be low. The slow growth recorded for these corals greatly increases their vulnerability to over-exploitation, and it is unknown to what extent localised fisheries depletion and effective reductions in mean coral size may undermine reproductive capacity and population viability. A key priority for future research is to measure growth rates in wide range of different environments, including subtidal environments where these corals can reach large sizes.

Project coverage

A dedicated media release was issued on June 30th 2020, to coincide with the formal publication of the relevant journal article (included below). The media release was printed on a wide range of online media outlets, and had a large reach both nationally and internationally.

Bleaching affects aquarium corals, too

30
JUN 2020

A new **study** illustrates the potential impact of recurrent heatwaves on coral species collected by the Australian aquarium coral industry.

The study's lead author, Professor Morgan Pratchett from the ARC Centre of Excellence for Coral Reef Studies at James Cook University (Coral CoE at JCU), says there are active and expanding aquarium coral fisheries operating across the country in Western Australia, the Northern Territory and Queensland.

"With widespread coral bleaching again affecting the Great Barrier Reef, and also occurring on coral reefs in Western Australia, there is inevitable concern regarding the sustainability and defensibility of ongoing coral harvesting," Prof Pratchett said.

Prior to the study, scientists didn't know much about the temperature sensitivity and bleaching susceptibility of Australian aquarium corals.

The researchers tested these parameters on six of the most important exported coral species from Australia.

"We found two of the most striking species were particularly susceptible and died at the temperatures you would expect when bleaching occurs," Prof Pratchett said.

"These corals are most abundant within the nearshore habitats of the southern Great Barrier Reef—an area that bleached earlier this year."

One of these species is the Australian saucer coral (*Homophyllia australis*), found just off the coast of Mackay.

With the worldwide demand for Australian aquarium corals increasing, a single aquarium specimen of *Homophyllia australis* fetched more than $8,000 AUD in Japan in 2017.

The study found the other, more widespread, aquarium corals were able to cope with higher temperatures. They bleached but didn't die—the corals are already regularly exposed to extreme temperatures in a wide variety of different environments, including shallow tidal pools in north Western Australia.

"Understanding the differential susceptibilities of different coral species to environmental change is a very important aspect of managing coral fisheries," Prof Pratchett said.

Australian coral fisheries are often the first to provide reports of coral bleaching across diverse reef environments, as they need to respond to changes in coral health.

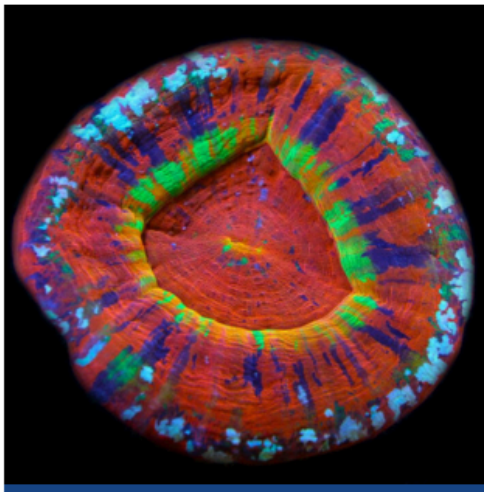
"Those in the industry don't collect bleached corals and actively avoid areas where there has been recent and severe mass bleaching," Prof Pratchett said.

He said the study, which was supported by the Fisheries Research and Development Corporation, highlights the need for more specific and targeted in-situ monitoring for these popular aquarium corals.

This is especially crucial with the increasing threat posed by ongoing environmental change.

PAPER

Pratchett M, Caballes C, Newman S, Wilson S, Messmer V, Pratchett D. (2020). 'Bleaching susceptibility of aquarium corals collected across northern Australia'. *Coral Reefs*. DOI: **10.1007/s00338-020-01939-1**



The Australian saucer coral (Homophyllia australis), lives just off the coast of Mackay. With the worldwide demand for Australian aquarium corals increasing, a single aquarium specimen of Homophyllia australis fetched more than $8,000 AUD in Japan in 2017. However, bleaching events kill this particular species. Image: Ciemon Caballes.

Project materials developed

Video transect protocols

This protocol was initially developed in close collaboration with Ryan Donnelly (form ProVision Reef) for the Queensland Coral Fishery and distributed, along with GoPro video cameras (purchased by Pro-Vision Reef with funding from the Queensland Government Gambling Community Benefit Fund), transect tapes and camera jigs at the 2017 Annual General Meeting of Pro-Vision Reef. Further details (and equipment) were distributed as requested throughout 2017, 2018 and 2019 to encourage industry contributions to documenting the stock size and structure of key harvest species at specified locations. The current version of the *video transect protocol* was presented at the most recent meeting with QCF licensees, held in Brisbane, Queensland in March 2019, in conjunction with QDAF harvest strategy meeting.

Australian Government
Fisheries Research and Development Corporation

ARC Centre of Excellence
Coral Reef Studies

JAMES COOK UNIVERSITY
AUSTRALIA

FRDC Project 2014-029

Vulnerability of commercially harvested corals to fisheries exploitation versus environmental pressures

The objectives of this project are to:
i) Refine species-level taxonomy (where required), to better establish what is being harvested and where,
ii) Establish the abundance and turnover of select, commercially important coral species in areas of concentrated fishing across northern Australia, and
iii) Explore species-specific vulnerability to extrinsic pressures on coral stocks, mostly related to environmental change and bleaching risk

Six priority species were selected as the focus of this project. These species (*Cataphyllia jardineri, Duncanopsammia axifuga, Euphyllia glabrescens, Homophyllia australis, Micromussa lordhowensis*, and *Trachyphyllia geoffroyi*) represent fairly readily distinguishable species that are also among the most heavily harvested individual species (by pieces).

This project is critically dependent on the effective and ongoing relationship between researchers and industry, especially in areas where OH&S regulations prevent scientists from effectively undertaking required research in key areas where corals occur and are being harvested.

The purpose of these video transects is to estimate the biomass of focal coral species (*Cataphyllia jardineri, Duncanopsammia axifuga, Euphyllia glabrescens, Homophyllia australis, Micromussa lordhowensis*, and *Trachyphyllia geoffroyi*) based on the size and abundance of colonies that can be seen in replicate 50 x 1m transects. As a minimum, we need 20 transects in each of the key harvest areas for these species, specifically the 36-mile management boxes P25 and I16.

Equipment needed

- GPS
- Depth Gauge
- 50m fiberglass tape
- PVC camera jig
- GoPro camera set to video mode.

Protocol

STEP 1 - Before entering the water, briefly film GPS to record the exact position on the video. Alternatively, you can write the reef name and position on a slate and wave this in front of the camera before starting filming each transect. We cannot really use the video transect unless we know where it comes from, but no one other than the scientists processing the data will ever see this specific detailed information without your express permission.

STEP 2 - At normal or representative collecting sites, lay out 50m transect tape to mark the transect path. Start by attaching the end of the transect to the substrate or hold it in position using a weight or temporary stake, then roll out the tape by swimming in approximately a straight line, though it is more important to stay parallel to depth contours, and remain within the specific habitat type where corals are harvested.

STEP 3- Make sure the camera is firmly attached to the PVC jig and turned on. Before filming the transect, briefly place depth gauge in front of the camera to record depth of the transect. We recommend using GoPro (Hero 4) cameras, as provided, but you can use an underwater camera. Just be aware that you might need to adjust the distance between the camera and the horizontal bar of the jig, to ensure the entire 1m bar is visible when filming in water.

STEP 4 - Swim slowly along the transect tape (aiming to finish the entire transect in approximately 7-10 minutes) keeping the PVC measuring bar just above the substrate, and centered on the transect tape. It would help (but not necessary) if you point out any colonies of the focal species as you go, whereby you just carry a pointer, or point to it with your figure in front of the camera.

STEP 5 - Stop the camera when you reach the end of the transect. Wind up the tape as you return to the initial starting point.

STEP 6 - Do multiple (non-overlapping) transects in each site/ area. I'd suggest it is somewhat pointless to get everything setup and then do only one transect at a site, so do multiple transects (moving to a different area, depth or habitat within the same general area) on the same dive, by repeating steps 2-5.

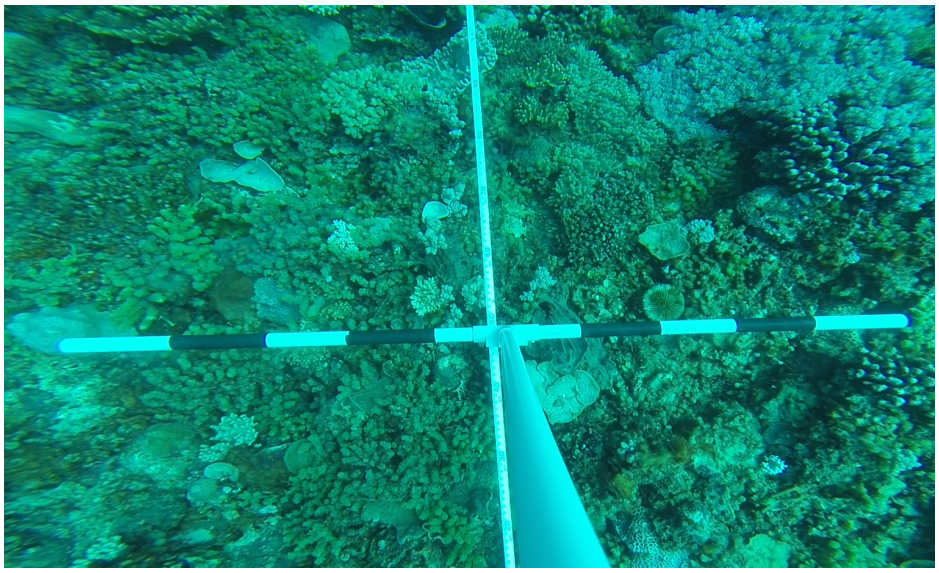
STEP 7 – Send us the data. Once you have recorded 3 or more transects, please send us the video files as soon as you can. If worried about security of information, the best way to do this is give us the memory card directly (e.g. at one of the industry working group meetings). Otherwise, you can post us the memory card and we will return it as soon as it is downloaded, or use file sharing software (e.g., Dropbox) and send it to us via the internet.

Tips and tricks

1. While you are welcome to use any 50m tape measure, we recommend Komelon brand tapes because the tape is negatively buoyant and drapes over the substrate when deployed (if there is not too much current or swell). We have distributed a large number of these tapes, and do still have a limited number that we can give to people committed to conducting video transects.

2. There is no need to secure the tape, other than at the start and end, and don't worry if the tape is twisted, or twisting, during filming.

3. The PVC jigs are intended to improve the quality and utility of the video recordings. Most importantly we use this to estimate the size of the individual coral colonies (so if you are too far above the substrate our estimate of the size will be greatly reduced). Make sure that when you initially mount the GoPro camera it is pointing to the center and just in front of the measuring bar (as shown in image below). The measuring bar (where there are white sections) can also provide a useful colour reference when filming bleached corals.

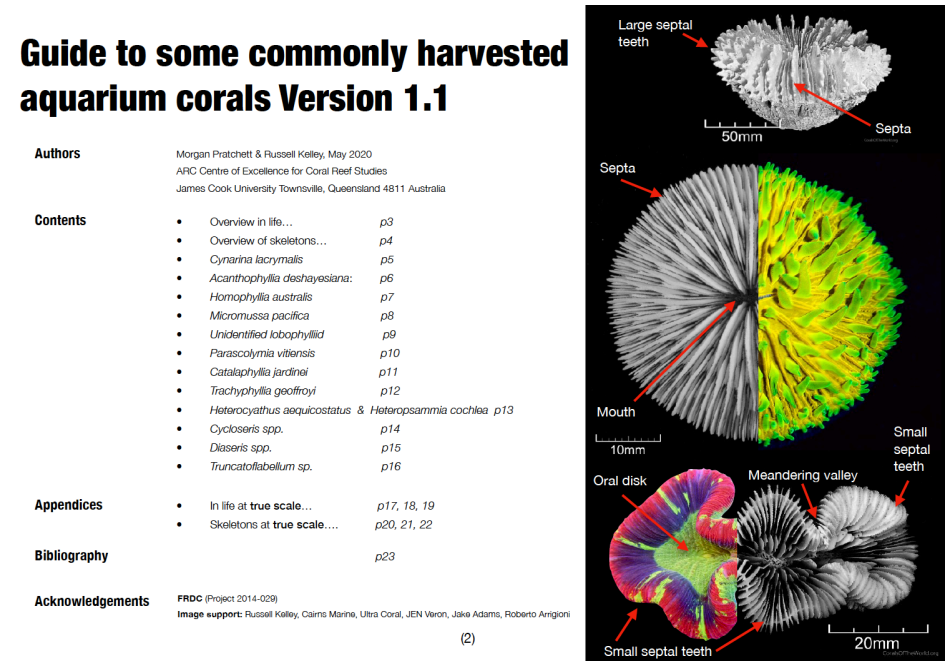


4. The jigs are made from 20mm PVC pipe. Essentially there is a measuring bar (exactly 1m across, with markers indicating 10m intervals, marked using electrical tape of a contrasting colour) with a tee fitting in the middle that as another piece of pipe to allow the camera to be fixed ~70cm from the tee. I suggest you glue or screw all the connections on the PVC jig, and make sure the camera is carefully secured as well (we use a small fitting called a tripod mount, shown inset below, to attach the Go Pro to the jig).

5. When filming transects, don't focus on the camera but make sure the horizontal bar of the PVC jig is held at right angles to the direction of the transect, and flat and level with the substrate.

Identification guide to some commonly harvested aquarium corals

A 23-page, full colour, guide to some commonly harvest aquarium corals, was prepared by Morgan Pratchett and Russell Kelley. This guide (version 1.1, May 2020) focusses on the species that mostly occur as mono-centric and free-living polyps, including *Homophyllia australis*, *Acanthophyllia deshayesiana*, and *Trachyphyllia geoffroyi*. This guide is specifically targeted at aquarium collectors, but also particularly relevant fisheries managers and compliance officers. The guide was used extensively during recent workshops aimed at increasing the capacity of Queensland fisheries patrol and compliance officers to recognise and distinguish important coral species targeted by the Queensland Coral Fishery. This guide can be embedded into the appendix of this report, but it is a very large file, and also currently subject to change, following resolved taxonomy of the unknown Lobohyllidae coral from Western Australia and the Northern Territory.



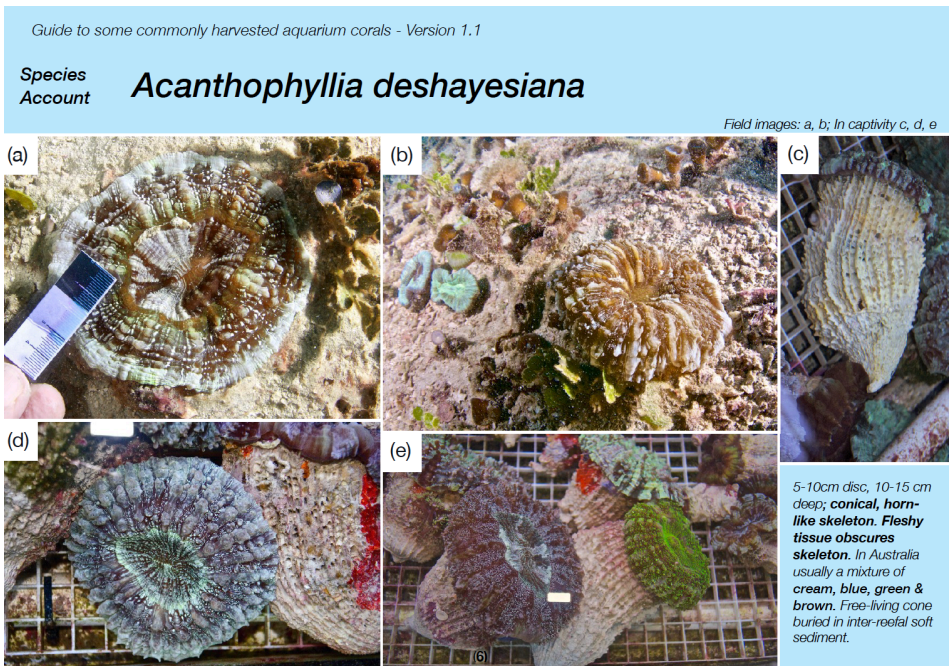
Guide to some commonly harvested aquarium corals Version 1.1

Authors

Morgan Pratchett & Russell Kelley, May 2020
ARC Centre of Excellence for Coral Reef Studies
James Cook University Townsville, Queensland 4811 Australia

Contents

(2)



Scientific papers

One scientific journal article that has been published thus far (appended below), which detailed the findings of the experimental bleaching experiment. Two additional papers will be submitted very shortly; i) presenting size-weight relationships and estimating harvestable biomass and ii) presenting the reproductive biology of the 6 focal study species. We also anticipate that there will be at least two more papers relating to the taxonomy and genetic structure of these corals.

Coral Reefs
https://doi.org/10.1007/s00338-020-01939-1

REPORT

Bleaching susceptibility of aquarium corals collected across northern Australia

Morgan S. Pratchett[1] · Ciemon F. Caballes[1] · Stephen J. Newman[2] · Shaun K. Wilson[3,4] · Vanessa Messmer[1] · Deborah J. Pratchett[1]

Received: 1 December 2019 / Accepted: 15 April 2020

Abstract There are a wide range of Scleractinian corals that are collected for the global reef aquarium market, often from non-reefal environments. The sustainability of coral harvesting is potentially threatened by increasing anthropogenic disturbances and climate change, though it is unknown to what extent many commonly harvested corals are susceptible to environmental change, or actually bleach during marine heatwaves. In this study, we experimentally tested the temperature sensitivity and bleaching susceptibility of six coral species (*Homophyllia australis*, *Micromussa lordhowensis*, *Catalaphyllia jardinei*, *Trachyphyllia geoffroyi*, *Duncanopsammia axifuga*, and *Euphyllia glabrescens*), which are important components of the aquarium coral fisheries across northern Australia, in Western Australia, the Northern Territory, and/or Queensland. Interspecific differences were evident in the temperature sensitivity and bleaching susceptibility among the study species. *Homophyllia australis*, and *M. lordhowensis* were found to be particularly susceptible to elevated temperatures, whereby all corals subjected to elevated temperatures died within the course of the experimental treatment (75 d). *Catalaphyllia jardinei* and *E. glabrescens* also exhibited significant increases in mortality when exposed to elevated temperatures, though some of the corals did survive, and *C. jardinei* mostly died only after exposure to elevated temperatures. The other species (*T. geoffroyi* and *D. axifuga*) exhibited marked bleaching when exposed to elevated temperatures, but mortality of these corals was similar to that of conspecifics held at ambient temperatures. This study highlights the potential for environmental change to impact the sustainability and viability of Australian coral harvest fisheries. More importantly, this study highlights the need for specific and targeted in situ monitoring for important stocks of coral fishery target species, to assess their vulnerability to fishery and fishery-independent effects.

Keywords Controlled experiment · Scleractinia · Temperature · Light intensity · Survivorship

Topic Editor Andrew Hoey

✉ Morgan S. Pratchett
morgan.pratchett@jcu.edu.au

[1] ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, QLD 4811, Australia

[2] Western Australian Fisheries and Marine Research Laboratories, Department of Primary Industries and Regional Development, Government of Western Australia, Hillarys, WA 6025, Australia

[3] Marine Science Program, Department of Biodiversity, Conservation and Attractions, Western Australian Government, Kensington, WA 6151, Australia

[4] Oceans Institute, University of Western Australia, Crawley, WA 6009, Australia

Introduction

Mass coral bleaching is an increasingly familiar and recurring phenomenon, whereby many different species of zooxanthellate corals lose their endosymbionts and associated photosynthetic pigments (Glynn 1984), mainly in response to environmental stress, including freshwater inundation, aerial exposure, sedimentation and anomalous temperatures (Wiedenmann et al. 2013). The severity, extent and frequency of mass coral bleaching has increased since the 1980s (Hughes et al. 2018a) in line with ocean warming and increasing incidence of marine heatwaves (Heron et al. 2016; Hobday et al. 2018; Skirving et al.

Appendices

Project staff

James Cook University (JCU), ARC Centre of Excellence for Coral Reef Studies

Professor Morgan Pratchett
Dr Ciemon Caballes
Dr Vanessa Messmer
Professor Andrew Baird
Russell Kelley
Cassandra Thompson
Deborah Pratchett
Peter Doll
Bethan Lang

James Cook University (JCU), Marine Aquarium Research Facility (MARF)

Simon Weaver

Department of Primary Industries and Regional Development (DPIRD), Government of Western Australia

Dr Stephen Newman
Paul Lewis
Dion Boddington
Craig Skepper
Brett Crisafulli
Selina Crawley

Queensland Department of Agriculture and Fisheries (QDAF)

Anthony Roelofs
Danielle Stewart

Department of Primary Industry and Resources, Northern Territory Government

Dr Shane Penny
Mark Grubert

Department of Biodiversity, Conservation and Attractions (DBCA), Government of Western Australian

Dr Shaun Wilson
Molly Moustaka

King Abdulla University of Science and Technology (KAUST)

Professor Michael Berumen
Dr Roberto Arrigoni
Dr Francesca Benzoni

National University of Singapore (NUS)

Dr Danwei Huang
Lufti Afiq Bin Rosli

Intellectual property and data sharing

While specific details pertaining to location of fishing (collection) activities, as well industry-led or industry-supported stock assessments, are subject to commercial in confidence, the results and conclusions arising from this project are for the public domain; The report, project materials, and associated publications are intended for broad dissemination and promotion. All raw data (to the extent permitted by established contracts and agreements with fisheries managers and fishing sectors) will be available on the Tropical Data Hub.

References

AFMA (2017) Management of Coral Harvest in the Coral Sea Fishery, Aquarium Sector - Information to support a non-detrimental finding. Australian Government, Australian Fisheries Management Authority https://files.parksaustralia.gov.au/marine/submissions/DMP-000310_email_publish%202%20of%202.pdf

Albert JA, Olds AD, Albert S, Cruz-Trinidad A, Schwarz AM (2015) Reaping the reef: provisioning services from coral reefs in Solomon Islands. Marine Policy 62:244-251

Andrews JM, Gurney WS, Heath MR, Gallego A, O'Brien CM, Darby C, Tyldesley G (2006) Modelling the spatial demography of Atlantic cod (*Gadus morhua*) on the European continental shelf. Canadian Journal of Fisheries and Aquatic Sciences 63(5):1027-1048

Arrigoni R, Terraneo TI, Galli P, Benzoni F (2014a) Lobophylliidae (Cnidaria, Scleractinia) reshuffled: pervasive non-monophyly at genus level. Molecular Phylogenetics and Evolution 73:60-64

Arrigoni R, Richards Z, Chen C, Baird A, Benzoni F (2014b) Phylogenetic relationships and taxonomy of the coral genera *Australomussa* and *Parascolymia* (Scleractinia, Lobophylliidae). Contributions to Zoology 83(3):195-215

Arrigoni R, Kitano YF, Stolarski J, Hoeksema BW, Fukami H, Stefani F, Galli P, Montano S, Castoldi E, Benzoni F (2014c) A phylogeny reconstruction of the Dendrophylliidae (Cnidaria, Scleractinia) based on molecular and micromorphological criteria, and its ecological implications. Zoologica Scripta 43(6):661-688

Arrigoni R, Berumen ML, Stolarski J, Terraneo TI, Benzoni F (2019) Uncovering hidden coral diversity: a new cryptic lobophylliid scleractinian from the Indian Ocean. Cladistics 35(3):301-328

Arrigoni R, Benzoni F, Huang D, Fukami H, Chen CA, Berumen ML, Hoogenboom M, Thomson DP, Hoeksema BW, Budd AF, Zayasu Y (2016) When forms meet genes: revision of the scleractinian genera *Micromussa* and *Homophyllia* (Lobophylliidae) with a description of two new species and one new genus. Contributions to Zoology 85(4):387-422

Arvedlund M, Craggs J, Pecorelli J (2003) Coral culture—possible future trends and directions. pp 233-248 In: Cato JC, Brown CL (eds) Marine Ornamental Species: Collection, Culture, & Conservation. Iowa State Press, Iowa

Atkinson M, Kerrigan B, Roelfs A, Smith T (2008) Non-Detriment Finding for CITES-Listed Corals in the Queensland Coral Fishery. WG9-Aquatic Invertebrates Case Study. 28 pp www.cites.org/sites/default/files/ndf_material/WG9-CS4.pdf

Ayre DJ, Hughes TP (2004) Climate change, genotypic diversity and gene flow in reef-building corals. Ecology Letters 7(4):273-278

Babcock RC (1988) Age-structure, survivorship and fecundity in populations of massive corals. Proceedings of the 6th International Coral Reef Symposium 2:625-633

Bates D, Mächler M, Bolker BM, Walker SC (2015). Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software 67(1): 1–48

Baird AH, Guest JR, Willis BL (2009) Systematic and biogeographical patterns in the reproductive biology of scleractinian corals. Annual Review of Ecology, Evolution, and Systematics 40:551-571

Baird AH, Blakeway DR, Hurley TJ, Stoddart JA (2011) Seasonality of coral reproduction in the Dampier Archipelago, northern Western Australia. Marine Biology 158(2):275-285

Baird AH, Marshall PA (2002) Mortality, growth and reproduction in scleractinian corals following bleaching on the Great Barrier Reef. Marine Ecology Progress Series 237:133-141

Barton JA, Willis BL, Hutson KS (2017) Coral propagation: a review of techniques for ornamental trade and reef restoration. Reviews in Aquaculture 9(3):238-56

Benzoni F, Arrigoni R, Stefani F, Stolarski J (2012) Systematics of the coral genus *Craterastrea* (Cnidaria, Anthozoa, Scleractinia) and description of a new family through combined morphological and molecular analyses. Systematics and Biodiversity. 10(4):417-433

Bollati E, D'Angelo C, Alderdice R, Pratchett M, Ziegler M, Wiedenmann J (2020) Optical feedback loop involving dinoflagellate symbiont and scleractinian host drives colorful coral bleaching. Current Biology doi:10.1016/j.cub.2020.04.055

Bruckner AW (2000) New threat to coral reefs: trade in coral organisms. Issues in Science and Technology 17(1):63-68

Bruno JF, Valdivia A (2016) Coral reef degradation is not correlated with local human population density. Scientific Reports 6:29778.

Budd, A. F., Fukami, H., Smith, N. D., & Knowlton, N. (2012). Taxonomic classification of the reef coral family Mussidae (Cnidaria: Anthozoa: Scleractinia). *Zoological Journal of the Linnean Society*, *166*(3), 465-529.

Buddemeier RW, Fautin DG (1993) Coral bleaching as an adaptive mechanism. Bioscience 43(5):320–326

Burt JA, Paparella F, Al-Mansoori N, Al-Mansoori A, Al-Jailani H. Causes and consequences of the 2017 coral bleaching event in the southern Persian/Arabian Gulf. Coral Reefs 38(4):567-589

Camp EF, Schoepf V, Mumby PJ, Hardtke LA, Rodolfo-Metalpa R, Smith DJ, Suggett DJ (2018) The future of coral reefs subject to rapid climate change: lessons from natural extreme environments. Frontiers in Marine Science 5:4

Cartwright I, Harriott V, Willock A (2002) A Report to the Chair Great Barrier Reef Marine Park Authority on The Coral Collection Fishery.

Chou LM, Toh TC, Toh KB, Ng CS, Cabaitan P, Tun K, Goh E, Afiq-Rosli L, Taira D, Du RC, Loke HX (2016) Differential response of coral assemblages to thermal stress underscores the complexity in predicting bleaching susceptibility. PloS ONE 11(7):e0159755

Craggs J, Guest JR, Davis M, Simmons J, Dashti E, Sweet M (2017) Inducing broadcast coral spawning *ex situ*: Closed system mesocosm design and husbandry protocol. Ecology and Evolution 7(24):11066-11078

Dandan SS, Falter JL, Lowe RJ, McCulloch MT (2015) Resilience of coral calcification to extreme temperature variations in the Kimberley region, northwest Australia. Coral Reefs 34(4):1151-63

Darus RF, Zamani NP, Solihin DD (2016) *Acanthophyllia deshayesiana* (Michelin, 1850) coral species is not synonym with *Cynarina lacrymalis* (Milne Edwards & Haime, 1848). Indonesian Journal of Marine Sciences 21(3)107-116

De'ath G, Fabricius KE, Sweatman H, Puotinen M (2012) The 27–year decline of coral cover on the Great Barrier Reef and its causes. Proceedings of the National Academy of Sciences 109(44):17995-17999

Dee LE, Horii SS, Thornhill DJ (2014) Conservation and management of ornamental coral reef wildlife: successes, shortcomings, and future directions. Biological Conservation 169:225-237

DEEDI (2012) Annual status report 2011, Queensland Coral Fishery. State of Queensland, Department of Employment, Economic Development and Innovation. 16pp www.daf.qld.gov.au/__data/assets/pdf_file/0010/76978/ASR_QCF2011.pdf

Delbeek JC (2001) Coral farming: past, present and future trends. Aquarium Sciences and Conservation 3(1-3):171-181

Depczynski M, Gilmour JP, Ridgway T, Barnes H, Heyward AJ, Holmes TH, Moore JA, Radford BT, Thomson DP, Tinkler P, Wilson SK (2013) Bleaching, coral mortality and subsequent survivorship on a West Australian fringing reef. Coral Reefs 32:233-238

DOF (2013) Proposed harvest strategy for the take of cites listed species (hard coral, giant clams and seahorses) by the Western Australian Marine Aquarium Fish Managed Fishery. Department of Fisheries, Government of Western Australia. 11pp www.environment.gov.au/system/files/pages/184b5421-9828-4536-8f42-70c5bb73cf87/files/application-2013.pdf

Donnelly R (2013) Stewardship Action Plan 2013 – Mitigating ecological risk in a changing climate. Pro-vison Reef Incorporated. Lotsa Printing, Cairns. 32pp www.provisionreef.org.au/wp-content/uploads/2013/08/SAP_II-7-8-2013-web.pdf

Dornelas M, Madin JS, Baird AH, Connolly SR (2017) Allometric growth in reef-building corals. Proceedings of the Royal Society B: Biological Sciences 284(1851):20170053

DPIR (2019a) Ecological Risk Assessment of the NT Aquarium Fishery - A report to the Australian Government on the environmental risk assessment requirements set out in Wildlife Trade Operation approvals for Northern Territory fisheries under *Environment Protection and Biodiversity Conservation Act* 1999 approvals. Northern Territory Government, Department of Primary Industry and Resources, 60pp

DPIR (2019b) Northern Territory Aquarium Fishery re-assessment Report, September 2019, Northern Territory Government Department of Primary Industry and Resources, 13pp www.environment.gov.au/system/files/consultations/6469a408-431f-44a3-b1e3-4a711a9a84e4/files/nt-aquarium-re-assessment-2019.pdf

DPIRD (2018) Ecosystem-Based Fisheries Management (EBFM): Risk Assessment of the Marine Aquarium Fish Managed Fishery 2014. Fisheries Management Paper No. 293, September 2018, Department of Primary Industries and Regional Development, Perth, Western Australia. 73pp

Dayton PK (1998) Reversal of the burden of proof in fisheries management. Science 279(5352):821-822

Evans RD, Wilson SK, Fisher R, Ryan NM, Babcock R, Blakeway D, Bond T, Dorji P, Dufois F, Fearns P, Lowe RJ (2020) Early recovery dynamics of turbid coral reefs after recurring bleaching events. Journal of Environmental Management. 268:110666

Fabricius KE, De'Ath G, Puotinen ML, Done T, Cooper TF, Burgess SC (2008). Disturbance gradients on inshore and offshore coral reefs caused by a severe tropical cyclone. Limnology and Oceanography 53(2):690-704

Fadlallah YH (1983). Sexual reproduction, development and larval biology in scleractinian corals. Coral Reefs 2(3):129-150

Fan T, Lin K, Kuo F, Soong K, Liu L, Fang L (2006) Diel patterns of larval release by five brooding scleractinian corals. Marine Ecology Progress Series 321:133–142

Fernandes L, Day JC, Lewis A, Slegers S, Kerrigan B, Breen D, Cameron D, Jago B, Hall J, Lowe D, Innes J, Tanzer J, Chadwick V, Thompson L, Gorman K, Simmons M, Barnett B, Sampson K, De'ath G, Mapstone B, Marsh M, Possingham H, Ball I, Ward T, Dobbs K, Aumend J, Slater D, Stapleton K (2005) Establishing representative no-take areas in the Great Barrier Reef: Large-scale implementation of theory on marine protected areas. Conservation Biology 19(6):1733–1744

Ferse SC, Knittweis L, Krause G, Maddusila A, Glaser M (2012) Livelihoods of ornamental coral fishermen in South Sulawesi/Indonesia: implications for management. Coastal Management. 40(5):525-555

Fisk DA (1983) Free-living corals: distributions according to plant cover, sediments, hydrodynamics, depth and biological factors. Marine Biology 74(3):287-294

Fitzpatrick M, Graham N, Rihan DJ, Reid DG (2011) The burden of proof in co-management and results-based management: the elephant on the deck! ICES Journal of Marine Science 68(8):1656-1662

Fletcher WJ (2005) The application of qualitative risk assessment methodology to prioritize issues for fisheries management. ICES Journal of Marine Science. 62(8):1576-1587

Foster T, Heyward AJ, Gilmour JP (2018). Split spawning realigns coral reproduction with optimal environmental windows. Nature Communications 9(1):1-8

Fujita R, Thornhill DJ, Karr K, Cooper CH, Dee LE (2014) Assessing and managing data-limited ornamental fisheries in coral reefs. Fish and Fisheries 15(4):661-675

Garrabou J, Sala E, Linares C, Ledoux JB, Montero-Serra I, Dominici JM, Kipson S, Teixidó N, Cebrian E, Kersting DK, Harmelin JG (2017). Re-shifting the ecological baseline for the overexploited Mediterranean red coral. Scientific Reports 7:42404

Gilmour JP, Cook KL, Ryan NM, Puotinen ML, Green RH, Shedrawi G, Hobbs JP, Thomson DP, Babcock RC, Buckee J, Foster T (2019) The state of Western Australia's coral reefs. Coral Reefs 38(4):651-667

Glynn PW, Colley SB, Maté JL, Baums IB, Feingold JS, Cortés J, Guzmán HM, Afflerbach JC, Brandtneris VW, Ault JS (2012) Reef coral reproduction in the equatorial eastern Pacific: Costa Rica, Panamá, and the Galápagos Islands (Ecuador). VII. Siderastreidae, *Psammocora stellata* and *Psammocora profundacella*. Marine Biology 159(9):1917-1932

Grafeld S, Oleson KL, Teneva L, Kittinger JN (2017) Follow that fish: Uncovering the hidden blue economy in coral reef fisheries. PLoS One 12(8):e0182104

Grottoli AG, Warner ME, Levas SJ, Aschaffenburg MD, Schoepf V, McGinley M, Baumann J, Matsui Y (2014) The cumulative impact of annual coral bleaching can turn some coral species winners into losers. Global Change Biology 20(12):3823-33

Guest JR, Baird AH, Maynard JA, Muttaqin E, Edwards AJ et al. (2012) Contrasting patterns of coral bleaching susceptibility in 2010 suggest an adaptive response to thermal stress. PLoS ONE 7: e33353

Hall VR, Hughes TP (1996) Reproductive strategies of modular organisms: comparative studies of reef-building corals. Ecology 77(3):950-963

Harriott VJ (1999). Coral growth in subtropical eastern Australia. Coral Reefs 18:281–291

Harriott V (2001) The sustainability of Queensland's coral harvest fishery: CRC Reef Research Centre Technical Report No. 40. CRC Reef Research Centre. Townsville, Australia

Harriott VJ (2003) Can corals be harvested sustainably? AMBIO: A Journal of the Human Environment 32(2):130-134

Heaven, C. (2018). *Queensland Fisheries Summary*. Brisbane: Department of Agriculture and Fisheries, 62 pp.

Hobday AJ, Alexander LV, Perkins SE, Smale DA, Straub SC, Oliver EC, Benthuysen JA, Burrows MT, Donat MG, Feng M, Holbrook NJ (2016) A hierarchical approach to defining marine heatwaves. Progress in Oceanography 141:227-238

Hoeksema BW, Cairns S (2020a) World List of Scleractinia. Lobophylliidae Dai & Horng, 2009. World Register of Marine Species www.marinespecies.org/aphia.php?p=taxdetails&id=739007

Hoeksema BW, Cairns S (2020b) World List of Scleractinia. *Trachyphyllia geoffroyi* (Audouin, 1826). World Register of Marine Species. www.marinespecies.org/aphia.php?p=taxdetails&id=207495

Hoeksema BW, Cairns S (2020c). World List of Scleractinia. *Acanthophyllia deshayesiana* (Michelin, 1850). World Register of Marine Species. www.marinespecies.org/aphia.php?p=taxdetails&id=289315

Hoey AS, Pratchett MS, Cvitanovic C (2011) High macroalgal cover and low coral recruitment undermines the potential resilience of the world's southernmost coral reef assemblages. PLoS One 6(10):

Hoey AS, Howells E, Johansen JL, Hobbs JPA, Messmer V, McCowan DM, Wilson SK, Pratchett MS (2016) Recent advances in understanding the effects of climate change on coral reefs. Diversity 8(2):12

Huang D, Licuanan WY, Baird AH, Fukami H (2011) Cleaning up the'Bigmessidae': Molecular phylogeny of scleractinian corals from Faviidae, Merulinidae, Pectiniidae and Trachyphylliidae. BMC Evolutionary Biology. 11(1):37.

Huang D, Benzoni F, Arrigoni R, Baird AH, Berumen ML, Bouwmeester J, Chou LM, Fukami H, Licuanan WY, Lovell ER, Meier R (2014) Towards a phylogenetic classification of reef corals: the Indo-Pacific genera *Merulina*, *Goniastrea* and *Scapophyllia* (Scleractinia, Merulinidae). Zoologica Scripta 43(5):531-548

Huang D, Arrigoni R, Benzoni F, Fukami H, Knowlton N, Smith ND, Stolarski J, Chou LM, Budd AF (2016) Taxonomic classification of the reef coral family Lobophylliidae (Cnidaria: Anthozoa: Scleractinia). Zoological Journal of the Linnean Society 178(3):436-481.

Hughes L (2003) Climate change and Australia: trends, projections and impacts. Austral Ecology 28(4):423-43

Hughes TP, Barnes ML, Bellwood DR, Cinner JE, Cumming GS, Jackson JB, Kleypas J, Van De Leemput IA, Lough JM, Morrison TH, Palumbi SR (2017a) Coral reefs in the Anthropocene. Nature 546(7656):82-90

Hughes TP, Kerry JT, Álvarez-Noriega M, Álvarez-Romero JG, Anderson KD, Baird AH, Babcock RC, Beger M, Bellwood DR, Berkelmans R, Bridge TC (2017b) Global warming and recurrent mass bleaching of corals. Nature 543(7645):373-377

Hughes TP, Anderson KD, Connolly SR, Heron SF, Kerry JT, Lough JM, Baird AH, Baum JK, Berumen ML, Bridge TC, Claar DC, Eakin CM, Gilmour JP, Graham NAJ, Harrison H, Hobbs JPA, Hoey AS, Hoogenboom M, Lowe RJ, McCulloch MT, Pandolfi JM, Pratchett MS, Schoepf V, Torda G, Wilson SK (2018a) Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science 359(6371):80–83

Hughes TP, Kerry JT, Baird AH, Connolly SR, Dietzel A, Eakin CM, Heron SF, Hoey AS, Hoogenboom MO, Liu G, McWilliam MJ, Pears RJ, Pratchett MS, Skirving WJ, Stella JS, Torda G (2018b) Global warming transforms coral reef assemblages. Nature 556(7702):492–496

Hughes TP, Kerry JT, Baird AH, Connolly SR, Chase TJ, Dietzel A, Hill T, Hoey AS, Hoogenboom MO, Jacobson M, Kerswell A, Madin JS, Mieog A, Paley AS, Pratchett MS, Torda G, Woods RM (2019) Global warming impairs stock–recruitment dynamics of corals. Nature 568(7752):387-90

Johns KA, Osborne KO, Logan M (2014) Contrasting rates of coral recovery and reassembly in coral communities on the Great Barrier Reef. Coral Reefs 33(3):553-563

Jones AM (2011) Raiding the coral nurseries? Diversity 3(3):466-482.

Kaplan EL, Meier P (1958) Nonparametric estimation from incomplete observations. Journal of the American Statistical Association 53:457–481

Kitahara MV, Fukami H, Benzoni F, Huang D (2016) The New Systematics of Scleractinia: Integrating Molecular and Morphological Evidence. In: Goffredo S., Dubinsky Z. (eds) The Cnidaria, Past, Present and Future. Springer, Cham

Leggat WP, Camp EF, Suggett DJ, Heron SF, Fordyce AJ, Gardner S, Deakin L, Turner M, Beeching LJ, Kuzhiumparambil U, Eakin CM (2019) Rapid coral decay is associated with marine heatwave mortality events on reefs. Current Biology 29(16):2723-30

Longenecker K, Bolick H, Langston R (2015) Estimating sustainable live-coral harvest at Kamiali wildlife management area, Papua New Guinea. PLoS One 10(10):e0140026

Loya Y, Sakai K, Yamazato K, Nakano Y, Sambali H, Van Woesik R (2001) Coral bleaching: the winners and the losers. Ecology Letters 4(2):122-131

Madin JS, Hoogenboom MO, Connolly SR, Darling ES, Falster DS, Huang D, Keith SA, Mizerek T, Pandolfi JM, Putnam HM, Baird AH (2016) A trait-based approach to advance coral reef science. Trends in Ecology and Evolution 31(6):419-428

Madin JS, Baird AH, Bridge TC, Connolly SR, Zawada KJ, Dornelas M (2018) Cumulative effects of cyclones and bleaching on coral cover and species richness at Lizard Island. Marine Ecology Progress Series 604:263-268

Marshall PA, Baird AH (2000) Bleaching of corals on the Great Barrier Reef: differential susceptibilities among taxa. Coral Reefs 19(2):155-163

McClanahan TR, Baird AH, Marshall PA, Toscano MA (2004) Comparing bleaching and mortality responses of hard corals between southern Kenya and the Great Barrier Reef, Australia. Marine Pollution Bulletin 48(3-4):327-35

McCormack C (2005) Ecological Assessment of the Queensland Coral Fishery - A report to the Australian Government Department of the Environment and Heritage on the ecologically sustainable management of the Queensland Coral Fishery. Queensland Governement Department of of Primary Industries and Fisheries. 13pp

Meesters EH, Wesseling I, Bak RP (1996) Partial mortality in three species of reef-building corals and the relation with colony morphology. Bulletin of Marine Science 58(3):838-852.

Mellin C, Matthews S, Anthony KR, Brown SC, Caley MJ, Johns KA, Osborne K, Puotinen M, Thompson A, Wolff NH, Fordham DA (2019) Spatial resilience of the Great Barrier Reef under cumulative disturbance impacts. Global Change Biology 25(7):2431-2445.

Moberg F, Folke C (1999) Ecological goods and services of coral reef ecosystems. Ecological Economics 29(2):215-233

Montero-Serra I, Garrabou J, Doak DF, Ledoux JB, Linares C (2019) Marine protected areas enhance structural complexity but do not buffer the consequences of ocean warming for an overexploited precious coral. Journal of Applied Ecology 56(5):1063-1074

Moustaka M, Mohring MB, Holmes T, Evans RD, Thomson D, Nutt C, Stoddart J, Wilson SK (2019) Cross-shelf heterogeneity of coral assemblages in Northwest Australia. Diversity 11:15

Myers RA, Worm B (2005) Extinction, survival or recovery of large predatory fishes. Philosophical Transactions of the Royal Society B: Biological Sciences. 360(1453):13-20

Nietzer S, Moeller M, Kitamura M, Schupp PJ (2018). Coral larvae every day: *Leptastrea purpurea*, a brooding species that could accelerate coral research. Frontiers in Marine Science 5:466

Noreen AM, Harrison PL, Van Oppen MJ (2009) Genetic diversity and connectivity in a brooding reef coral at the limit of its distribution. Proceedings of the Royal Society B: Biological Sciences 276(1675):3927-3935

Okubo N, Motokawa T, Omori M (2007) When fragmented coral spawn? Effect of size and timing on survivorship and fecundity of fragmentation in *Acropora formosa*. Marine Biology 151(1):353-563

Oliver EC, Donat MG, Burrows MT, Moore PJ, Smale DA, Alexander LV, Benthuysen JA, Feng M, Gupta AS, Hobday AJ, Holbrook NJ (2018) Longer and more frequent marine heatwaves over the past century. Nature Communications 9:1324

Oliver J, Babcock R (1992) Aspects of the fertilization ecology of broadcast spawning corals: sperm dilution effects and *in situ* measurements of fertilization.The Biological Bulletin 183(3):409-417

Oliver J, McGinnity P (1985) Commercial coral collecting on the Great Barrier Reef. Proceedings of the Fifth International Coral Reef Congress 5: 563-568

Pisapia C, Sweet M, Sweatman H, Pratchett MS (2015) Geographically conserved rates of background mortality among common reef-building corals in Lhaviyani Atoll, Maldives, versus northern Great Barrier Reef, Australia. Marine Biology 162(8):1579-1586

Pratchett MS, Messmer V (2017) *Determining amount of substrate that is trimmed from stony corals in the Specialty Coral quota category*. FRDC Report (project no. 2016/051). James Cook University, Townsville, 21pp http://frdc.com.au/Archived-Reports/FRDC%20Projects/2016-051-DLD.pdf

Pratchett MS, McCowan D, Maynard JA, Heron SF (2013) Changes in bleaching susceptibility among corals subject to ocean warming and recurrent bleaching in Moorea, French Polynesia. PLoS ONE 8(7):e70443

Pratchett MS, Caballes C, Rivera-Posada JA, Sweatman HPA (2014). Limits to understanding and managing outbreaks of crown-of-thorns starfish (*Acanthaster* spp.). Oceanography and Marine Biology: An Annual Review 52:133-200

Pratchett MS, Anderson KD, Hoogenboom MO, Widman E, Baird AH, Pandolfi JM, Edmunds PJ (2015) Spatial, temporal and taxonomic variation in coral growth: implications for the structure and function of coral reef ecosystems. Oceanography and Marine Biology: An Annual Review 53:215-295

Pratchett MS, Baird AH, Bauman AG, Burt JA (2017) Abundance and composition of juvenile corals reveals divergent trajectories for coral assemblages across the United Arab Emirates. Marine Pollution Bulletin 114(2):1031-1035

Pratchett MS, Caballes CF, Newman SJ, Wilson SK, Messmer V, Pratchett DJ (2020) Bleaching susceptibility of aquarium corals collected across northern Australia. Coral Reefs 39:663-673

QDAF (2017) Guidelines for Implementing the Queensland Harvest Strategy Policy. Queensland Department of Agriculture and Fisheries, 14pp www.publications.qld.gov.au/dataset/5cffe911-e6c1-4851-b05b-f8a6d2210ed5/resource/bb2468d1-5b62-4a61-b17e-2c1497fa933b/fs_download/queensland-harvest-strategy-guidelines.pdf

QDAF (2019) Queensland fisheries summary report: Catch and effort data for Queensland's Commercial Fisheries. Updated data for the 2018/19 Financial Year. Queensland Department of Agriculture and Fisheries, 29pp www.daf.qld.gov.au/__data/assets/pdf_file/0004/1423831/Queensland-Fisheries-Summary-Report.pdf

R Core Team (2020) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/

Rapuano H, Brickner I, Shlesinger T, Meroz-Fine E, Tamir R, Loya Y (2017). Reproductive strategies of the coral *Turbinaria reniformis* in the northern Gulf of Aqaba (Red Sea). Scientific Reports 7:42670

Rhyne A, Rotjan R, Bruckner A, Tlusty M (2009) Crawling to collapse: Ecologically unsound ornamental invertebrate fisheries. PLoS One 4(12):e8413

Rhyne AL, Tlusty MF, Kaufman L (2012) Long-term trends of coral imports into the United States indicate future opportunities for ecosystem and societal benefits. Conservation Letters 5(6):478-485

Rhyne AL, Tlusty MF, Kaufman L (2014) Is sustainable exploitation of coral reefs possible? A view from the standpoint of the marine aquarium trade. Current Opinion in Environmental Sustainability 7:101-107

Richmond RH, Hunter Cl (1990) Reproduction and recruitment of corals: comparisons among the Caribbean, the Tropical Pacific, and the Red Sea. Marine Ecology Progress Series 60:185–203

Roelofs A (2018) *Ecological Risk Assessment of the Queensland Coral Fishery 2013*, Queensland Department of Agriculture and Fisheries, Brisbane, Australia.

Schmidt-Roach S, Lundgren P, Miller KJ, Gerlach G, Noreen AM, Andreakis N (2013) Assessing hidden species diversity in the coral *Pocillopora damicornis* from Eastern Australia. Coral Reefs 32(1):161-172

Schmidt-Roach S, Miller KJ, Lundgren P, Andreakis N (2014) With eyes wide open: a revision of species within and closely related to the *Pocillopora damicornis* species complex (Scleractinia; Pocilloporidae) using morphology and genetics. Zoological Journal of the Linnean Society. 170(1):1-33

Siebeck UE, Marshall NJ, Klüter A, Hoegh-Guldberg O (2006) Monitoring coral bleaching using a colour reference card. Coral Reefs 25(3):453-60

Skirving WJ, Heron SF, Marsh BL, Liu G, De La Cour JL, Geiger EF, Eakin CM (2019) The relentless march of mass coral bleaching: a global perspective of changing heat stress. Coral reefs 38(4):547-557

Spalding M, Burke L, Wood SA, Ashpole J, Hutchison J, Zu Ermgassen P (2017) Mapping the global value and distribution of coral reef tourism. Marine Policy 82:104-113

Stefani F, Benzoni F, Yang SY, Pichon M, Galli P, Chen CA (2011) Comparison of morphological and genetic analyses reveals cryptic divergence and morphological plasticity in *Stylophora* (Cnidaria, Scleractinia). Coral Reefs 30(4):1033-1049

Szmant-Froelich A, Reutter M, Riggs L (1985). Sexual reproduction of *Favia fragum*(Esper): Lunar patterns of gametogenesis, embryogenesis and planulation in Puerto Rico. Bulletin of Marine Science 37(3):880–892

Tan CH, Pratchett MS, Bay LK, Graham EM, Baird AH (2018). *Biennium horribile*: very high mortality in the reef coral *Acropora millepora* on the Great Barrier Reef in 2009 and 2010. Marine Ecology Progress Series 604:133-142.

Torda G, Sambrook K, Cross P, Sato Y, Bourne DG, Lukoschek V, Hill T, Jorda GT, Moya A, Willis BL (2018). Decadal erosion of coral assemblages by multiple disturbances in the Palm Islands, central Great Barrier Reef. Scientific Reports 8(1):11885

Torstrom SM, Pangle KL, Swanson BJ (2014) Shedding subspecies: the influence of genetics on reptile subspecies taxonomy. Molecular Phylogenetics and Evolution. 76:134-143

Torrejon-Magallanes J (2020) sizeMat: Estimate Size at Sexual Maturity. *R package, version 1.1.1 [https://CRAN. R-project. org/package= sizeMat]*.

Vargas-Angel B, Huntington B, Brainard RE, Venegas R, Oliver T, Barkley H, Cohen A (2019) El Nino-associated catastrophic coral mortality at Jarvis Island, central Equatorial Pacific. Coral Reefs. 38(4):731–741

Veron JJ, Pichon MM (1980) Scleractinia of Eastern Australia. Part III: Families Agariciidae, Siderastreidae, Fungiidae, Oculinidae, Merulinudae, Mussidae, Pectiniidae, Caryophylliidae, Dendrophylliidae. Australian Institute of Marine Science, Townsville

Victor BC (2015) How many coral reef fish species are there? Cryptic diversity and the new molecular taxonomy. Pp 76-88 In: Mora C (ed) Ecology of fishes on coral reefs. Cambridge University Press, Cambridge

Wear SL (2016) Missing the boat: Critical threats to coral reefs are neglected at global scale. Marine Policy 74:153-157

Willis BL, Babcock RC, Harrison PL, Oliver JK (1985) Patterns in the mass spawning on the Great Barrier Reef from 1981 to 1984. Proceedings of the Fifth International Coral Reef Symposium, Tahiti, 4:343–348

Wilson JR, Harrison PL (2003) Spawning patterns of scleractinian corals at the Solitary Islands-a high latitude coral community in eastern Australia. Marine Ecology Progress Series 260, 115-123.

Wolstenholme J, Dinesen Z, Alderslade P (1997) Hard corals of the Darwin Region, Northern Territory. pp 381-398. In: Hanley JR, Caswell G, Megirian D, Larson HK (eds) Proceedings of the Sixth International Marine Biological Workshop. The Marine Flora and Fauna of Darwin Harbour, Northern Territory, Australia. Museums and Art Galleries of the Northern Territory and the Australian Marine Sciences Association.

Wolstenholme J, Nozawa Y, Byrne M, Burke W (2018) Timing of mass spawning in corals: potential influence of the coincidence of lunar factors and associated changes in atmospheric pressure from northern and southern hemisphere case studies. Invertebrate Reproduction & Development 62(2):98-108

Wood E, Malsch K, Miller J (2012) International trade in hard corals: review of management, sustainability and trends. Proceedings 12th International Coral Reef Symposium 1:9-13

FRDC FINAL REPORT CHECKLIST

Project Title:	Vulnerability of commercially harvested corals to fisheries exploitation versus environmental pressures		
Principal Investigators:	**Morgan Pratchett, Ciemon Caballes, Vanessa Messmer, Shaun Wilson, Anthony Roelofs, Mark Grubert, Russell Kelley and Stephen Newman**		
Project Number:	2014/029		
Description:	The objectives and outcomes of this project were three-fold. Firstly, we established the abundance and turnover of select, commercially important coral species in areas of concentrated fishing across northern Australia. Improved understanding of the biology and ecology of harvested corals is fundamental to establishing baselines and sustainable harvest levels. Secondly, we helped to refine species-level taxonomy for commonly harvested coral species, using genetic analyses, to better establish what is being harvested and where. Genetic analyses on corals collected from different jurisdictions helped to reveal which species are very widespread, and therefore more resilient, versus those that are geographically restricted, and therefore warrant specific management attention. Thirdly, we explored species-specific vulnerability to extrinsic pressures on coral stocks, related to environmental change. Climate induced coral bleaching if the foremost threat to coral species and could undermine the sustainability of ongoing coral harvesting independent of fishery effort or take.		
Published Date:	XX/XX/XXXX (if applicable)	Year:	2020
ISBN:	XXXXX (if applicable)	ISSN:	XXXXXXXXXXXXX (if applicable)
Key Words:	Aquarium fisheries; coral reefs; Scleractinia; Western Australian Marine Aquarium Fish Managed Fishery (MAFMF); Northern Territory Aquarium Fishery (NTAF); Queensland Coral Fishery (QCF).		

Please use this checklist to self-assess your report before submitting to FRDC. Checklist should accompany the report.

	Is it included (Y/N)	Comments
Foreword (optional)	Y	
Acknowledgments	Y	
Abbreviations	Y	
Executive Summary		
– What the report is about	Y	
– Background – why project was undertaken	Y	

– Aims/objectives – what you wanted to achieve at the beginning	Y	
– Methodology – outline how you did the project	Y	
– Results/key findings – this should outline what you found or key results	Y	
– Implications for relevant stakeholders	Y	
– Recommendations	Y	
Introduction	Y	
Objectives	Y	
Methodology	Y	
Results	Y	
Discussion	Combined with Results	
Conclusion	Y	
Implications	Y	
Recommendations	Y	
Further development	Y	
Extension and Adoption	Y	
Project coverage	Y	
Glossary	N - NA	
Project materials developed	Y	
Appendices	Y	
EXTENSION		
Extension plan developed?	Y	
Extension undertaken?	Y	
If extension was undertaken, who was it undertaken with and was it successful? (Detail answer in comments section)	Y	Extensive extension was undertaken through the course of this project, both with fisheries managers and compliance offices, but also the major licensees in each jurisdiction. That said there is always scope for more extension, and while we want to deliver this report now (and

		thereby avoid any further delays in the delivery of this FRDC project) there are firm plans for further research and extension through the course of this year, as long as Covid-19 restrictions are eased sufficiently to allow the progress of these plans (as outlined below).
If No, then is further extension necessary? With who? How? (detail answer in comments section)		While there has been extensive extension (as evidence by the direct contributions of relevant fisheries managers in WA, NT and Queensland) to the preparation of this report) we do plan to follow up the research reported herein, with two key research components. i) Final workshop with WA licensees (originally planned for May 2020) to communicate all findings and explicitly discuss the results of genetic sampling. These results have been directly communicated to the two major licence holders, who are now embarking on dedicated sampling to provide necessary samples of corals to confirm the identity of corals that are nominally regarded as *H. australis* and *M. lordhowensis* Moreover, we will complete sequencing of all existing samples to resolve genetic structure of widespread species. ii) A notable gap in the *in situ* sampling of major focal coral species relates to apparent absence of both *H. australis* and *M. lordhowensis*, because we did not sample in areas where these corals are most abundant (inshore southern GBR). This information is however critical to the impending (2020/21) ERA and NDF/WTO applications for the QCF. To redress this dedicated sampling trip are now planned for July/ August 2020 (or as soon as possible thereafter), and we are going to trial a whole range of different methods (including ROVs recently acquired by Cairns Marine) to get information on the size and abundance of these aforementioned coral species in relevant locations and habitats. The findings and outcomes of these activities will be incorporated into journal articles directly arising from this research (to make all information readily accessible to key stakeholders and decision-makers), though we are also happy to update this report (if required) as soon as we have the necessary information.