Hair, Catherine Ann (2020) ***Development of community-based mariculture of sandfish, Holothuria scabra, in New Ireland Province, Papua New Guinea.*** **PhD Thesis, James Cook University.**

https://doi.org/10.25903/jft5%2Dwb40

Development of community-based mariculture of sandfish, *Holothuria scabra*, in New Ireland Province, Papua New Guinea

Thesis submitted by
Catherine Ann Hair (MSc)
February 2020

For the fulfilment of the degree of Doctor of Philosophy
James Cook University, Australia

Cover photo caption: Sam, of Limanak Island, holding a cultured sandfish juvenile (*Holothuria scabra*). Image used with permission.

Statement of access

I, the undersigned, author of this work, understand that James Cook University will make this thesis available for use within the University Library and, via the Australian Digital Theses network, for use elsewhere.

I understand that, as an unpublished work, a thesis has significant protection under the Copyright Act and I do not wish to place any further restriction on access to this work.

Catherine Ann Hair

8 February 2020

Statement of sources declaration

I, the undersigned, declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work or others has been acknowledged in the text and a list of references is given.

Catherine Ann Hair

8 February 2020

Electronic copy

I, the undersigned, the author of this work, declare that the electronic copy of this thesis provided to the James Cook University Library is an accurate copy of the print thesis submitted within the limits of the technology available.

Catherine Ann Hair

8 February 2020

Ethics and copyright

This research has been conducted under the James Cook University Human Research Ethics Committee approval numbers H4930 and H6897.

Catherine Ann Hair

8 February 2020

Acknowledgements

My sincere gratitude goes to Professor Paul Southgate, my primary advisor, who convinced me that this PhD was a good idea and then stuck with me through many ups and downs. Thank you for your confidence in me, your humour and, always, your wise and constructive guidance. Associate Professor Simon Foale ended up with a larger role than bargained for and I thank him most sincerely for guiding me through the intersecting worlds of anthropology, social science and fisheries. I appreciate the many in-depth conversations and his endless patience as I discovered the 'already known'.

My co-supervisor, Dr David Mills provided excellent support and advice to many aspects of this study. Valuable knowledge, inspiration and assistance also came from close colleagues; Dr Jeff Kinch, Dr Steven Purcell, Dr Georgi Robinson, Professor Paige West, Dr Mike Rimmer, Dr Chris Barlow and Dr Paul Nelson. A big thank-you to Dr Peter Wood for his 'above and beyond' contribution to the GIS aspects of this study. Thanks are also due to Jen Whan, Terry Miller and Susan Jacups at James Cook University, my fellow students, Duy and Ravinesh, and others at the Cairns JCU Postgraduate Centre. I would also like to acknowledge the valuable feedback obtained from anonymous reviewers of journal articles produced during this study and the final thesis.

I wish to acknowledge the Australian Centre for International Agricultural Research who funded the Papua New Guinea mariculture projects on which I was employed while completing this thesis.

This thesis could not have been completed without enormous support with field and hatchery work in New Ireland. A sincere thank you to Rowan McIntyre who was instrumental in early research efforts, he was a friend and source of fun during many hours of field work. To my Lavongai brother, John Aini, kalaro lui for your friendship, assistance, cultural guidance and a quiet haven at the Solwara Skul. Special thanks to Thane Militz for keeping things on track on many occasions. My gratitude is extended to all staff (past and present) of the Nago Island Mariculture and Research Facility for assistance with hatchery work, field experiments and gear construction, most especially Bitalen Peni, Nicholas Daniels, Esther Leini, Steven Namangan, Warren Pingo, Bradley Saesaria and Posolok Kanawi. A big thanks to Peter Minimulu and Jacob Wani for their personal and administrative support, and officers of the National Fisheries Authority in Port Moresby who facilitated aspects of my study.

I am very grateful for the assistance and hospitality of many people from the Limanak, Ungakum and Enuk communities. I cannot list everyone but make special mention of: Valentine Konga, Elizabeth and Barol, Esther and Robert Passingan, John and Judy Benga, Stanley and Nangkos (Limanak); Jackson Solo and family, Mandiu Junius and family, and Stanley (Ungakum); and Lembang, Sarah and Lesley Suri, Obed Piskaut, Esau, Pastor Samson and Vivianne (Enuk). Thank you all for welcoming me into your communities and teaching me so much about your culture, lives and livelihoods. You enabled this thesis and enriched me personally. Giro panaliu!

So many people have been a source of encouragement and support. I am forever grateful to my family: David, Fay, Robert, Karen, Mark, Sue and Lee, and my wonderful nieces and nephews. And to my friends, huge thanks to Bev, Bronwyn, Evizel, Hugh, Jackie, Jan, Julie, Kristi, Lydia, Mary, Phil, Richard and Sue. Thank-you all for motivation, laughs, meals, walks, and simply being there. A very special debt is owed to Sally, Neil and the girls; your thoughtfulness and generosity mean more than you know.

I dedicate this thesis to my parents, Gleeson and Aileen Hair, who have accompanied me in spirit on every step of this journey—to Dad, who would be elated to have a 'Dr' in the family, and to Mum who knew that education is never wasted.

Cathy

Statement of contributions by others

This study was conducted within the Australian Centre for International Agricultural Research projects FIS/2010/054 'Mariculture Development in New Ireland, Papua New Guinea' (for which James Cook University was the commissioned organisation) and FIS/2014/061 'Improving technical and institutional capacity to support development of mariculture based livelihoods and industry in New Ireland, Papua New Guinea' (for which the University of the Sunshine Coast was the commissioned organisation).

My advisors, Professor Paul Southgate, Associate Professor Simon Foale and Dr David Mills, provided academic, scientific, and editorial support.

Logistic support for fieldwork was provided by the National Fisheries Authority in Papua New Guinea, and in particular the NFA Nago Island Mariculture and Research Facility and National Fisheries College.

Specific co-author contributions for this thesis are outlined by chapter in the table below.

Chapter No	Details of publications	Nature and intellectual input of each author, including the candidate
1	Hair, C., Foale, S., Kinch, J., Yaman, L. and Southgate, P.C. (2016). Beyond boom, bust and ban: The sandfish (*Holothuria scabra*) fishery in the Tigak Islands, Papua New Guinea. **Regional Studies in Marine Science**, 5, 69–79.	**Hair C[1,2]** Project design, study execution, writing and editing. **Foale S[3]** Supervision, advice on project design, and editing. **Kinch J[4]** Editing **Yaman L[5]** Technical advice, editing **Southgate PC[1]** Supervision, advice on project design, and editing.
2	Hair, C., Foale, S., Kinch, J., Frijlink, S., Lindsay, D. and Southgate, P. C. (2019). Socioeconomic impacts of a sea cucumber fishery in Papua New Guinea: Is there an opportunity for mariculture? **Ocean and Coastal Management**, 179, 10 pp.	**Hair C[1,2]** Project design, study execution, writing and editing. **Foale S[3]** Supervision, advice on project design and editing. **Frijlink S[6]** Advice on project design and editing. **Kinch J[4]** Advice on project design and editing. **Lindsay D[7]** Data analyses. **Southgate PC[1]** Supervision, advice on project design and editing.

3	Hair, C., Mills, D., McIntyre, R. and Southgate, P.C. (2016). Optimising methods for community-based sea cucumber ranching: Experimental releases of cultured juvenile *Holothuria scabra* into seagrass meadows in Papua New Guinea. **Aquaculture Reports**, 3, 198–208.	**Hair C[1,2]** Project design, study execution, writing, analyses and editing. **Mills D[8,9]** Supervision, advice on project design and analyses, and editing. **McIntyre R[1]** Editing. **Lindsay D[7]** Data analyses **Southgate PC[1]** Supervision, advice on project design and editing.
4	Hair, C., Wood, P., Daniels, N. and Southgate, P.C. Preliminary assessment of geographic information system and remote sensing techniques to describe, assess and predict sea cucumber mariculture habitat (in preparation).	**Hair C[1,2]** Project design, study execution, writing, analyses and editing. **Wood P[10]** Satellite imagery preparation, unsupervised and supervised classifications, spectral analyses and editing. **Daniels N[11]** Editing. **Southgate PC[1]** Supervision, advice on project design and editing.
5	Hair, C., Militz, T., Daniels, N. and Southgate, P.C. (2020). Comparison of survival, growth and burying behavior of cultured and wild sandfish (*Holothuria scabra*) juveniles: Implications for ocean mariculture. **Aquaculture**, 526, 735355.	**Hair C[1,2]** Project design, study execution, writing and editing. **Militz T[1]** Statistical analyses and editing. **Daniels N[11]** Editing. **Southgate PC[1]** Supervision, advice on project design and editing.
6	Hair, C., Ram, R and Southgate, P.C. (2018). Is there a difference between bêche-de-mer processed from ocean-cultured and wild-harvested sandfish (*Holothuria scabra*)? **Aquaculture** 483 (Supplement C), 63–68.	**Hair C[1,2]** Project design, study execution, writing, analyses and editing. **Ram R[1]** Analyses of nutrients. **Southgate PC[1]** Supervision, advice on project design and editing.
7	Hair, C., Foale, S., Daniels, N., Minimulu, P., Aini, J. and Southgate, P.C. (2020). Social and economic challenges to community-based sea cucumber mariculture development in New Ireland Province, Papua New Guinea. **Marine Policy,** 17, 103940.	**Hair C[1,2]** Project design, study execution, writing and editing. **Foale S[3]** Supervision, advice on project design and editing. **Daniels N[11]** Editing. **Minimulu P[11]** Editing. **Aini J[12]** Editing **Southgate PC[1]** Supervision, advice on project design and editing.

Author affiliations

[1] Australian Centre for Pacific Islands Research and Faculty of Science and Engineering, University of the Sunshine Coast, Locked Bag 4, Maroochydore, Queensland 4558, Australia

[2] Centre for Sustainable Tropical Fisheries and Aquaculture, College of Science and Engineering, James Cook University, PO Box 6811, Cairns, Queensland 4870, Australia

[3] College of Arts, Society and Education, James Cook University, Townsville, Queensland 4811, Australia

[4] National Fisheries College, National Fisheries Authority, Kavieng, Papua New Guinea

[5] National Fisheries Authority, Port Moresby, Papua New Guinea

[6] Wildlife Conservation Society, PO Box 95, Kavieng, New Ireland Province, Papua New Guinea

[7] College of Public Health, Medical and Veterinary Sciences, James Cook University, Townsville, Queensland 4811, Australia

[8] WorldFish, Penang, Malaysia

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

[10] Great Barrier Reef Legacy, PO Box 128, Port Douglas, Queensland 4877, Australia

[11] Nago Island Mariculture and Research Facility, National Fisheries Authority, PO Box 239, Kavieng, New Ireland Province, Papua New Guinea

[12] Ailan Awareness, Kaselok, New Ireland Province, Papua New Guinea

Abstract

Sea cucumber, processed into its dried form of bêche-de-mer (BDM), is one of the oldest commercial marine commodities in the Pacific Islands region. High prices, low tech harvest and processing methods, strong demand in Asian markets, and well-developed supply chains make it an important economic livelihood for coastal communities in Papua New Guinea (PNG). Sea cucumber fisheries in the Pacific have historically followed boom and bust cycles and are very difficult to manage effectively to maintain sustainable yields. Depletion of sea cucumber stocks led the PNG National Fisheries Authority (NFA) to declare a nation-wide moratorium on the harvest of sea cucumber and sale of BDM from 2009 until 2017. The Tigak and Tsoi Islands in New Ireland Province, PNG, were the site of a commercial fishery for the high-value sea cucumber, sandfish (*Holothuria scabra* Jaeger), for a short period in the late 1980s before it was overfished. Despite no history of mariculture in the study area, sandfish represents a promising aquaculture candidate due to well-established hatchery production and ocean grow-out techniques. Sandfish sea ranching was proposed as a mariculture livelihood activity for Tigak and Tsoi communities; this involves releasing cultured juvenile sandfish (> 3 g) into unfenced areas of suitable habitat under community management, where they would be protected from fishing until they reach commercial size. The initial objective of this study was to assess the potential of sandfish sea ranching as a livelihood activity for Tigak and Tsoi Islands fishing communities. However, lifting of the moratorium during the study provided unexpected opportunities to assess the reopened fishery and the potential for sandfish mariculture alongside it. The focus of this study shifted as a result, to include assessment of social aspects of the sea cucumber fishery and the technical and social factors that may influence uptake of sandfish mariculture as a potential livelihood activity. Research was conducted in three collaborating partner communities; Limanak and Enuk in the Tigak Islands, and Ungakum in the Tsoi Islands.

The first two chapters draw on understandings of local culture and political economy, together with the results from the historic (pre-moratorium; 1988 to 2009), and the contemporary (post-moratorium; 2017) wild sea cucumber fishery, to examine how a livelihood based on sandfish culture could coexist with the wild fishery to increase benefits to coastal communities in PNG. Data presented in Chapter 1 confirmed that sandfish was the main target species in the early wild sea cucumber fishery but had been overfished. A history of disregard for fisheries regulations and poor-quality BDM processing was revealed. Chapter 2 presents socio-

economic data on income-earning activities, household income, expenditure, BDM quality, processing, gender roles, diet and attitude toward the fishery from Enuk, Limanak and Ungakum before, during and after the sea cucumber fishery re-opening in 2017. Fishing for sea cucumber and processing BDM replaced most other livelihoods and significantly increased mean weekly household income, which was spent on store-bought foods and assets. Sandfish remained a target species but the season lasted for less than two months before the NFA BDM quota was reached and the fishery closed. These two chapters indicated there was excellent potential for cultural compatibility of sandfish sea ranching due to its value, familiarity and preference among fishers, but raised concerns regarding unsustainable practices.

Research into technical aspects of sea ranching was conducted concurrently with the social research. Results from sea pen grow-out experiments are presented in Chapter 3. Cultured juvenile sandfish (≥ 3-g mean weight) were released into 100-m^2 sea pens, located within suitable seagrass habitat at four sites near the study communities. Newly-released juveniles were provided with nil, one or seven days' cage protection to investigate if short-term predator exclusion increased survival. Cage protection did not significantly affect survival at any site but there were significant differences in overall survival and mean sandfish weight between three sites where juveniles survived. Sandfish growth and sea pen biophysical parameters were monitored at regular intervals for up to 24 months after release. Multivariate analysis of biophysical factors clearly differentiated the sea pen habitats. One outstanding site, Limanak-1, had high survival and growth of sandfish and its habitat was characterised by higher coarse-grain fraction, seagrass epiphytes and chlorophyll-*a* sediment content, and low fine-grain fraction. Ungakum, a site with total mortality, had more predators and higher fine-grain fraction. Valuable qualitative data were obtained on the relationship between sandfish and habitat at the four sites. Chapter 4 presents a preliminary assessment of how geographic information systems (GIS) and remote sensing can assist in describing and predicting suitable sandfish mariculture sites. GIS is a valuable tool for aquaculture site selection but underutilised in sea cucumber mariculture. Spectral analyses of WorldView satellite imagery showed promise but were inadequate as stand-alone pre-assessment methods. However, based on these findings and the literature a three-stage GIS approach was proposed: (1) spatial multi-criteria evaluation based on parameters that influence sandfish survival and growth; (2) field data collection and liaison with stakeholders at promising sites; and (3) pilot trials with cultured juveniles at selected suitable sites, to gauge the risk of high predation and other unanticipated factors.

The success of mariculture activities involving the release of cultured marine invertebrates into the ocean is contingent on high survival and appropriate growth rates. However, physical, physiological or behavioural characteristics that differ from those of wild conspecifics, and may compromise the 'fitness' of cultured animals. These may be acquired through hatchery rearing, or as a result of stress induced by the release process. Chapter 5 investigated the influence of such factors on sandfish by comparing survival, growth and behaviour of release-size cultured juveniles to those of like-size wild conspecifics. After 85 days there was no significant difference in weight between cultured and wild sandfish juveniles. Burying behaviour of cultured and wild sandfish juveniles was observed over a 48-h period in natural habitat with or without seagrass. Cultured juveniles were found to be slower to bury in the substrate after release, less likely to be buried at most times, and more likely to be buried in substrate where seagrass was present; however, they became better synchronised with their wild counterparts after 30 h. Survival of cultured and wild sandfish was high in experiments (> 85%), but reduced burying by cultured individuals may increase the potential for predation because diel burying is the main predator avoidance strategy of sandfish juveniles. When combined with the results of Chapter 3, the findings indicate that protection of newly-released juveniles might only be advantageous where predation risk exists, and that seven days of protection may be inadequate. Minimising transportation stress and adhering to best practice release methods are key to successful ocean mariculture.

The quality of BDM from ocean-cultured (hatchery bred) sandfish was compared with that of like-size wild sandfish by processing both groups with identical methods in Chapter 6. The ratio of fresh whole to dried weight, and fresh body wall width, were significantly greater for wild individuals than cultured individuals. However, key determinants of BDM quality, including fresh gutted to dried weight ratio, dried to fresh length ratio, dried body wall width and BDM collagen content, were similar in both groups, indicating that BDM produced from ocean-cultured sandfish has similar recovery rate and quality as that from wild.

Development of mariculture livelihood activities also requires careful attention to the human dimension. Chapter 7 reports on a community trial sea ranch, in which a 5-hectare area was stocked with 5,000 cultured juvenile sandfish in order to: (1) generate data on their survival, growth and movement; and (2) to explore social aspects of community-based management and distribution of economic benefits. In 2018, during the sea cucumber fishing season, sandfish from the trial sea ranch were poached, terminating research at the site. Community attitudes

and responses to the 2018 season, mariculture research and the failure of the trial sea ranch were investigated. Widespread community approval of the trial sea ranch and respect for the fishing prohibition were reported. However, minor poaching within the ranch escalated because community-based management proved inadequate to sanction the poachers. The trial sea ranch failed due to internal factors (i.e., weak local leadership, community disunity), exacerbated by external pressures (i.e., increased buying pressure, higher prices, limited project oversight). Poor BDM quality and ineffective fisheries management remained concerning. Results of Chapters 2 and 7 are concerning, given that sea ranching success is predicated on adoption of sustainable harvest practices, improved BDM processing and strong community-based management.

This thesis presents the first evaluation of a range of social and technical factors affecting the development of a community-based sandfish mariculture livelihood in New Ireland Province, PNG. The broad and comprehensive approach generated sound baseline data and indicated priority areas for future research. Although no data were obtained from the community-scale sea ranch experiment, other technical investigations into survival, growth, optimal habitat, BDM value and the fitness of cultured sandfish all demonstrated significant potential. These results, and ongoing research in other countries, indicate that technical bottlenecks are unlikely to constrain community sandfish sea ranching success. Unfortunately, there were social barriers to community-based sea cucumber mariculture in New Ireland Province. It was concluded that further development of this livelihood and associated socio-economic benefits will be stymied until there is effective local control of the wild sea cucumber fishery. The findings presented in this thesis contribute to further development of sandfish mariculture in New Ireland Province should the requisite socio-economic conditions be met in the future. This research will also be of value to the development of sea cucumber mariculture elsewhere in the broader Indo-Pacific region.

Table of contents

List of figures

List of tables

List of appendices

Chapter 1
The sandfish, *Holothuria scabra,* fishery in the Tigak Islands, New Ireland Province, Papua New Guinea[1]

1.1 Introduction

Sea cucumbers (holothurians) have been collected and processed into bêche-de-mer or trepang as a culinary delicacy, medicinal food and aphrodisiac for Asian (predominantly Chinese) consumers for at least 400 years (Conand and Byrne 1993, Schwerdtner Máñez and Ferse 2010). Bêche-de-mer (referred to as BDM throughout this thesis) is the dried body wall of the sea cucumber, prepared by boiling, gutting, and boiling again before either sun drying or smoke curing (Purcell 2014a). The ease of processing using simple equipment and the non-perishable nature of the final product suits BDM for collection from remote coastal and island localities (Conand 1990, Preston 1993). It is an important marine resource in the Pacific Islands region (Kinch et al. 2008a) where commodification of sea cucumber occurred in the early 1800s. Traders followed the first explorers into the region—after delivering convicts, settlers and supplies, ships were filled with sandalwood and BDM for trading in China on their return sea journeys (Ward 1972, Dalzell et al. 1996, Conand 2018). Despite this long history, the bulk of BDM originated from Asia until the 1980s when Pacific Island sources (including PNG) started supplying higher volumes to the major export markets of Hong Kong and Singapore (van Eys 1986, Schwerdtner Máñez and Ferse 2010). Worldwide, about 60 species of sea cucumber are valued as BDM (Purcell et al. 2012a) and over 30 species are traded as BDM in the Western Pacific (Kinch et al. 2008a, Purcell et al. 2018b).

The history of the sea cucumber fishery in PNG has been described by several authors (Shelley 1981, Conand 1990, Lokani 1990, Kailola 1995, Kinch et al. 2008b, Govan 2017, Kinch 2020). Pre-commercial exploitation is generally regarded as negligible because few people in PNG consumed sea cucumber (Lokani 1990, Preston 1993). The earliest commercial records are from 1878 (Conand and Byrne 1993, Kailola 1995) and BDM was the fifth most important export from PNG in 1903 at 83 tonnes (t) (Shelley 1981). Thereafter, exports rose and fell due to competition from other commodities, variable prices and overfishing. Macroeconomic

---

[1] Data from this chapter were published as: Hair, C., Foale, S., Kinch, J., Yaman, L. and Southgate, P.C. (2016). Beyond boom, bust and ban: The sandfish (*Holothuria scabra*) fishery in the Tigak Islands, Papua New Guinea. *Regional Studies in Marine Science*, 5, 69–79. https://doi.org/10.1016/j.rsma.2016.02.001

factors such as the Sino-Japanese war, Chinese trade barriers and World War II (WWII) slowed trade after 1930 (Lokani 1990, Preston 1993, Dalzell et al. 1996). The post-WWII industry was rebuilt by Asian businessmen who trained local people how to process BDM and purchased small quantities for consumption and to send home. The PNG export market from the 1960s to the mid-1980s was small, at less than 20 t annually, but in 1986 it jumped to over 100 t (Fig. 1.1) (Kailola 1995, Kinch et al. 2008b, NFA database). By the mid-2000s, PNG was the third largest supplier of BDM to Hong Kong (van Eys 1986, Kinch et al. 2008b).

Sea cucumber fisheries in PNG, as elsewhere in the Pacific, have historically followed boom and bust cycles with periods of heavy exploitation (boom) followed by a rest period (bust) where populations may recover to a degree. Bust periods can be due to lack of access to stocks, resource depletion, poor recruitment, or socio-economic events (Ward 1972, Conand 1990, Preston 1993, Dalzell et al. 1996, Friedman et al. 2011). However, despite some years of slightly lower exports than others (Fig. 1.1), the PNG sea cucumber fishery had been in a boom since the late 1980s. This growth is generally attributed to the removal of trade barriers to the Chinese market and a rising middle class in China which meant BDM were no longer the sole preserve of the very wealthy (Fabinyi 2012). Increased exploitation was assisted by spatial expansion and improved harvest efficiency, accompanied by greater demand for lower value and newly commercialised sea cucumber species (Kinch et al. 2008b, Schwerdtner Máñez and Ferse 2010, Anderson et al. 2011, Branch et al. 2013, Eriksson et al. 2015).

Due to reported low stocks of all commercially valuable sea cucumbers, the PNG National Fisheries Authority (NFA) imposed a 3-year moratorium on their harvest in 2009 (Carleton et al. 2013, Barclay et al. 2016, Kinch 2020). The moratorium was lifted in early 2017, after a period of seven and a half years, equivalent to seven annual fishing seasons. The sea cucumber fishery opened for brief seasons in 2017 and 2018, during fieldwork for this thesis.

For sea cucumbers, data on a fishery's progress through boom and bust cycles is usually sketchy—early export records often aggregate different species as generic 'bêche-de-mer', surveys of unfished commercial populations are rare, while exploitation of new stocks can proceed undocumented due to the speed of discovery and extraction (Kailola 1995, Dalzell et al. 1996, Eriksson et al. 2015). Pre-boom and boom periods are often described with apocryphal tales of huge and abundant sea cucumbers, which can be difficult to verify.

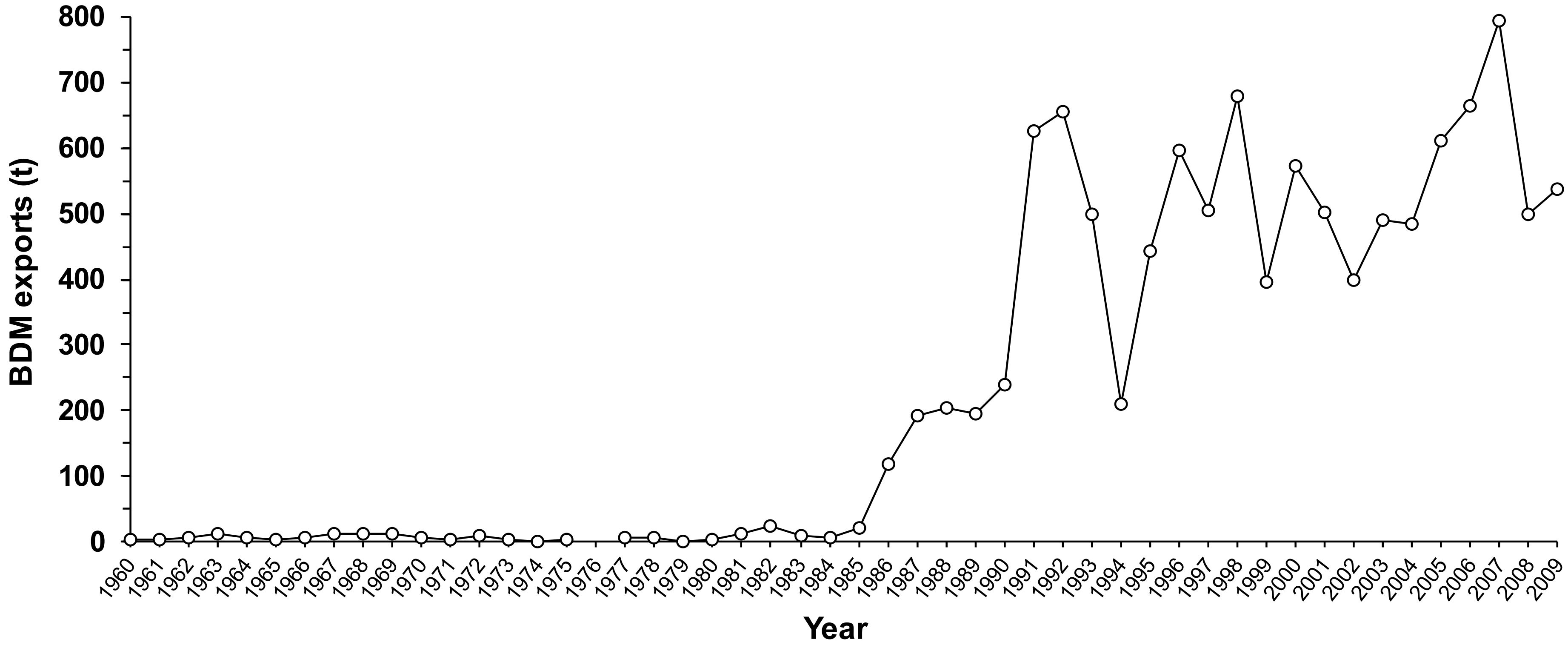


Figure 1.1 **PNG BDM exports (t) from 1960 up to the moratorium in 2009 (after Kinch et al. 2008b, additional data from the NFA database).**

By contrast, the history of the commercial fishery for sandfish (*Holothuria scabra*) in the Tigak and Tsoi Islands of New Ireland Province in PNG is comparatively well documented from its beginning in the 1980s to the present time. Fortuitously, sandfish is also the most promising tropical sea cucumber candidate for mariculture[2] (Raison 2008, Purcell et al. 2012b, Robinson 2013). This chapter details the recorded and recollected history of sandfish exploitation in this area. It also speculates on the next phase of this fishery, when it reopens after an extended moratorium on sea cucumber harvesting. The potential for sandfish mariculture to be integrated into a future fishery management framework is considered.

1.2 Methods

Information on the history of the Tigak Islands sandfish fishery was sourced from journal articles and 'grey' literature (e.g., reports, surveys, reviews and consultancy reports). Two databases also provided data on PNG BDM: (1) the National Provincial Fisheries Database (NPFD), which collected data on BDM purchases in Kavieng in 1994 and 1995; and (2) the PNG NFA database, which contains BDM export records for New Ireland Province from 1994 up to the moratorium in 2009.

Anecdotal information on sandfish exploitation and the BDM trade was obtained from semi-structured interviews of community members from Limanak in the Tigak Islands (n = 13 interviews, comprising 19 respondents: 14 males and 5 females, aged from 18–70 years), conducted between November 2013 and May 2014. Interview questions covered aspects such as traditional fisheries management, marine tenure, past sea cucumber fishing practices, and attitudes to the moratorium (Appendix 1). Conversations with older community members (during and outside interviews) also investigated the early history of the fishery. In addition, interviews were conducted in 2015 with former Kavieng BDM exporters and buyers (collectively referred to as traders, except when referring specifically to export licence holders), who purchased BDM prior to the moratorium (n = 3 traders). Interview questions for traders were focused on BDM species, supply, processing quality, also with an emphasis on sandfish.

[2] Aquaculture is the farming of aquatic animals and plants. Mariculture is aquaculture that is undertaken in marine environments

1.3 Sandfish biology and BDM processing

Sandfish, *Holothuria scabra* (Jaeger) (Fig. 1.2), is a commercial aspidochirotid sea cucumber that has been well studied (Hamel et al. 2001 and references therein), not least because of its importance as BDM in artisanal and commercial fisheries in the tropical Indo-Pacific region and potential as a mariculture commodity (Raison 2008, Purcell et al. 2012b). Sandfish are deposit feeders and bury during part of the day (Hamel et al. 2001, Purcell 2010b). They inhabit low energy environments behind fringing reefs or on coastal sandflats associated with seagrass and mangroves, and are tolerant of a wide range of environmental conditions (Purcell et al. 2012a). Post-larval juveniles recruit to seagrass blades before adopting a benthic lifestyle as deposit feeders in muddy-sand substrates (Mercier et al. 2000b). As they grow, sandfish often move to deeper, bare habitat (up to 20-m depth) (Mercier et al. 2000b, Purcell et al. 2012a), although large individuals also occupy shallow habitats in lightly exploited populations (Hasan 2005). Sandfish are generally regarded as site-attached and slow moving (Hamel et al. 2001, Purcell and Kirby 2006, Lee et al. 2018a). These characteristics, combined with their high value, have led to severe population declines over much of their range. Sandfish were listed as an endangered species on the IUCN Red List in 2010 (Hamel et al. 2013).

Figure 1.2 Live sandfish, *Holothuria scabra.*

Sandfish have separate sexes that are indistinguishable externally except during spawning (Hamel et al. 2001). Being broadcast spawners, they are vulnerable to the allee effect, whereby low population densities reduce the chance of successful reproduction (Bartley and Bell 2008, Friedman et al. 2011). Size at first sexual maturity appears to vary between locations (Hamel et al. 2001, Purcell et al. 2012a). Conand (1990) reported the weight of 184 g for mature sandfish in New Caledonia, but smaller individuals have been observed spawning in other places (Olavides et al. 2011, Hair et al. 2016). The feeding and burying habits of sea cucumbers, including sandfish, have been shown to bioturbate and oxygenate sediments, recycle nutrients, increase seagrass growth and dissolve calcium carbonate, thereby promoting productive ecosystems (Uthicke 1999, Hamel et al. 2001, Wolkenhauer et al. 2010, Schneider et al. 2011, Purcell et al. 2016b, Lee et al. 2018b).

Sandfish have many calcareous ossicles in their skin, which must be removed to produce high-quality BDM (Purcell 2014a, Ram 2018). After gutting and boiling fresh sandfish (Fig. 1.3a), the outer skin layer skin is broken down using one of three methods: (1) burying them in a sandpit overnight; (2) soaking them in seawater overnight; or (3) treating them with papaya (pawpaw) leaves (Purcell 2014a, Fig. 1.3b). Once skin decomposition has occurred, the ossicles are scraped or scrubbed off with a brush until the product is dark in colour and there are no visible chalky deposits (Fig. 1.3c). It is then boiled again and dried to produce BDM (Fig 1.3d). Large-sized and well-processed sandfish are classed as first grade BDM, while smaller sized and poorly processed individuals attract lower grading and reduced value.

1.4 The Tigak Islands' sandfish fishery

1.4.1 Background

New Ireland Province lies within the Bismarck Archipelago in the western Pacific Ocean, part of the Islands Region of PNG that includes Manus Province to the west and New Britain to the south. The Tigak Islands comprise a group of raised limestone or sand islands situated between the larger land masses of mainland New Ireland and New Hanover (Fig. 1.4). Many of the Tigak Islands are fringed by mangroves, with dense tropical forest further inland, while abundant coconut palms are still present on islands that were once planted for copra production (Wright et al. 1983). The islands are bordered by coral reefs and interspersed in a mostly sandy lagoon floor of about 20-m depth (Lokani 1996b). Eight of the Tigak Islands sit within Balgai Bay, a protected, mangrove-lined embayment at the north-west tip of New Ireland (Fig. 1.4). Sheltered nearshore zones of this area harbour extensive and species-rich seagrass meadows adjacent to sandy seafloor, habitats that once supported abundant stocks of sandfish (Lokani 1996b). Another historically important sandfish producing area was the Tsoi Islands, which extend from the Tigak Islands along the northern edge of New Hanover (Fig. 1.4).

Figure 1.3 Selected processing steps for sandfish BDM production in the village setting: (a) first boil of the fresh, gutted sandfish; (b) use of papaya leaves to break down the calcareous skin layer of boiled sandfish; (c) removing the outer skin layer; and (d) sandfish BDM.

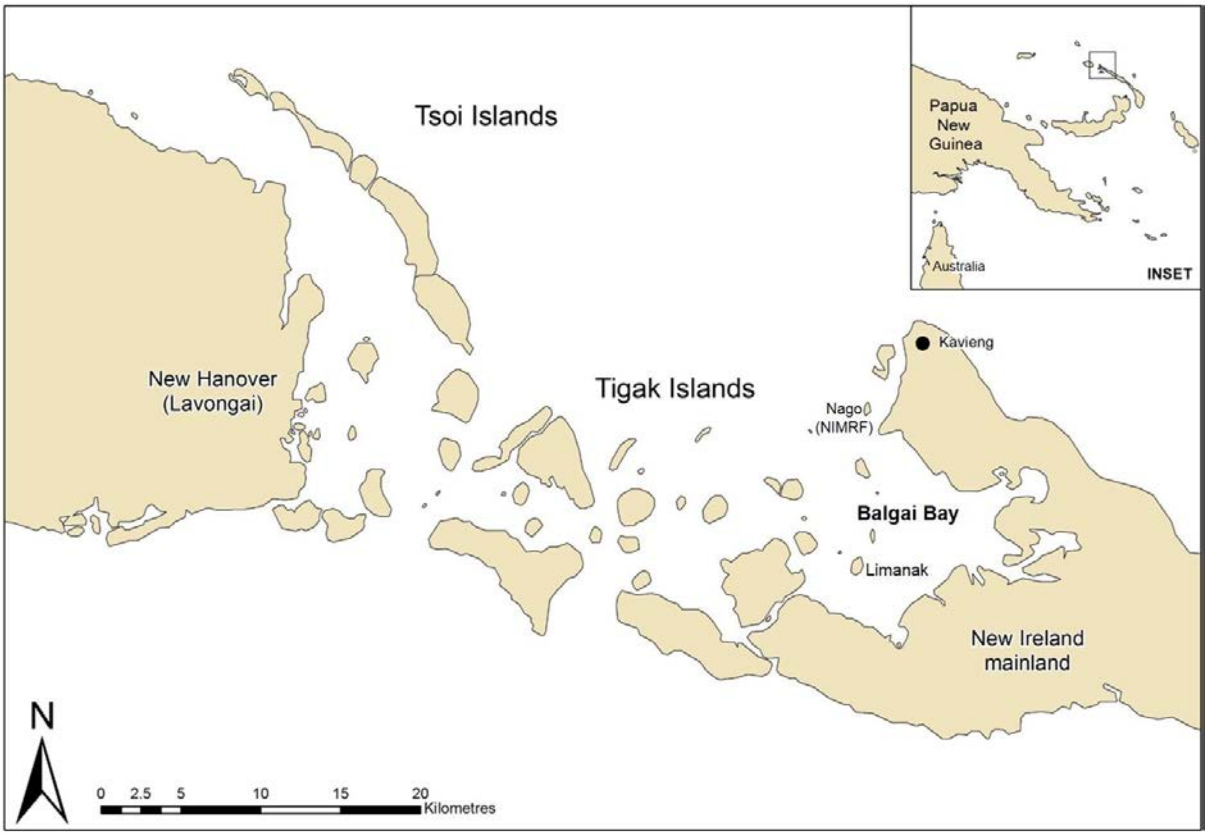


Figure 1.4 **Map of north-western New Ireland Province showing the Tigak and Tsoi islands, and the location of Limanak Island.**

The well-documented history of the Tigak Islands' sea cucumber fishery can be attributed to a number of factors: (1) sea cucumber research carried out in the 1980s at a fisheries research station in Kavieng (Department of Fisheries and Marine Resources, the predecessor of the NFA); (2) a National Provincial Fisheries Database (NPFD) that collected data on the BDM trade in the mid-1990s; and (3) the Coastal Fisheries Management and Development Project (CFMDP) that undertook sea cucumber stock surveys and collected socio-economic data between 2004 and 2007. Furthermore, current research into community-based mariculture of sandfish is being carried out at the NFA's first marine hatchery, the Nago Island Mariculture and Research Facility (NIMRF), which began operation in 2012. NIMRF is located on Nago Island in the Tigak Islands, near the provincial capital of Kavieng (Fig. 1.4). The facility produces cultured sandfish juveniles for experimental research and community grow-out trials (Southgate et al. 2012, Militz et al. 2018). Socio-economic research into traditional sea cucumber fishing and potential mariculture activities was undertaken with three partner communities in the Tigak and Tsoi Islands. One of these, the source of interview data presented in this chapter, is a community spread across three islands in Balgai Bay; Limanak, Limellon and Nusailas (referred to as Limanak) (Fig. 1.5). Their traditional fishing area encompasses all three islands and the adjacent bay margins (Fig. 1.5). Limanak was a copra plantation after WWII, before being handed over to the inhabitants of Nusailas Island, who claimed ownership and who then repopulated the island. In 2016, the Limanak population had grown to around 250.

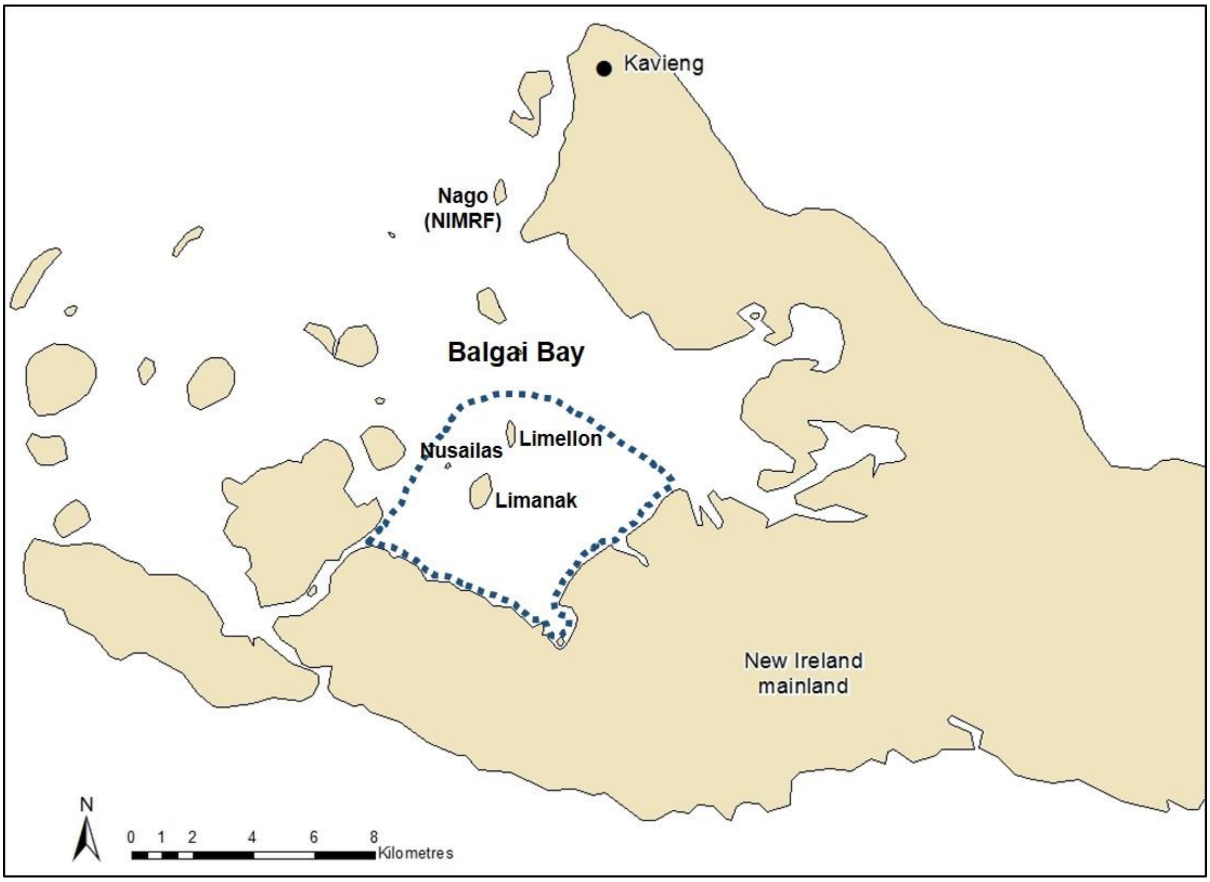


Figure 1.5 Balgai Bay and the three islands of the 'Limanak' community. The approximate extent of their traditional fishing area is indicated by the dashed line.

1.4.2 History of sandfish exploitation

Sandfish may have been a subsistence item in New Ireland Province in times of famine or bad weather (Kailola 1995, interview data) but is generally regarded as an unimportant part of the local diet (Wright et al. 1983, Lokani 1990, Conand and Byrne 1993, Kinch et al. 2008b). Local language species' names can inform on the importance of a commodity (Foale 1998, Cohen et al. 2014). The generic local name for sea cucumbers in both Tigak and Tsoi islands is *pula.* In Tigak language, *kono* means sand and some people refer to sandfish as *pula-kono*, but this name may also refer more generally to all species found on sandy seafloors, including golden sandfish (*Holothuria lessoni*), brown sandfish (*Bohadschia vitiensis*) and chalkfish (*Bohadschia marmorata*). There are also older local names linked to the extra step required to process sandfish into BDM, i.e., removal of the chalky skin layer. For example, *pula-buta* alludes to the resemblance of the discarded outer skin to ash (*buta* means 'ash' in Tigak). The expression *pula-brush* in the Tigak Islands and the Tsoi equivalent of *pula-sok* refer to the processing step of brushing and scraping off the calcareous skin layer. Interview respondents insist these are traditional names related to their subsistence use, but it is unclear whether they were in use prior to the BDM trade.

Sea cucumbers were probably first fished commercially around the Tigak Islands from the mid- to late-1800s (Lokani 1996b). Trading ships undoubtedly passed through the Bismarck Archipelago because nearby Manus Province was a commercial source of mother-of-pearl, tortoiseshell and BDM in that period (Carrier and Carrier 1989), while sandalwood and BDM traders plied the western Pacific Ocean during the 1840s (Cheyne 1852). Ward (1972) mentions a ship prospecting for BDM along the New Ireland coast in the 1830s and another gathering BDM in New Hanover in the 1840s. Later, Chinese traders may have taken sea cucumbers for home consumption and exported small quantities of BDM. The pre-WWII BDM industry ceased when New Ireland was occupied by the Japanese in early 1942 (Lindholm 1978, Wright et al. 1983, Conand 1990). New Ireland Province is absent from the PNG BDM export data records in the 1970s, although a 1977 Kavieng fishery was mentioned by Lindholm (1978). Local informants claim that Asian traders targeted sandfish in the Tigak area in the early 1980s. Strangely, Wright et al. (1983) did not report on a local BDM industry at that time, despite noting that 26 commercial sea cucumber species occurred in New Ireland Province and that teatfish (*Holothuria fuscogilva* or *H. whitmaei*) was found throughout the Tigak Islands. The comprehensive review of Kailola (1995) made tantalising mention of missing Tigak Islands sea cucumber surveys from the 1970s and 1980s, which would have represented relatively virgin stocks. Local fishers assert that Limanak fishing grounds always held sandfish and that their sea cucumber stocks persisted when other areas became depleted (interview data).

The first commercial records from New Ireland Province appear in 1988 when the Danasa company established centralised processing of sandfish on Limellon Island (Kailola 1995, Lokani 1996b). Centralised BDM processing is not as profitable to individual fishers but a benefit of the Limellon operation was the controlled monitoring of fishery data from one place rather than from scattered landing places and sale points. From mid-1989, individual processing became more common. Present day interview respondents who recall those times refer to the Danasa operation as a 'factory', where the initial processing steps were carried out by hired labour before partially processed sea cucumbers were transferred to Kavieng for drying. Danasa concentrated solely on sandfish, which were boiled in large metal tubs, with reports of two men stirring up to 500 sandfish at a time with long wooden paddles. Women brushed off the outer skin the following day. According to Limanak sources, men, women and children harvested sandfish in their thousands by gleaning in shallow water. There were not enough canoes, so people would walk or swim from Limanak to Limellon with their catch. Sandfish were reputedly 'as long as your arm' and so numerous that 'you couldn't walk without stepping on them' (interview data). While it is common for memories of past times to be exaggerated (e.g., prestige bias where catches are recalled as bigger than they were, Lyle et al. 2002), in this case hard data supports these early recollections (Pauly 1995).

Sandfish were crucial to the development of the BDM trade in the Tigak Islands in the early days of the fishery. Lokani (1996b) reported a catch rate from 150–300 sandfish per person per day in the first seven months of the fishery. Conservative estimates indicate that sandfish of an average 2.35 kg live weight produced 'Super-grade' BDM (Table 1.1), and some sandfish measured more than 50 cm (Lokani 1996b). A-Grade BDM was produced from sandfish of more than 1.5-kg live weight (Table 1.1), 16-cm dried length or 42-cm live length. The New Ireland Province BDM trade expanded from one species (sandfish) in 1988 to a total of five species in 1989, at least 12 species in 1991, and between 18-20 species from 1998 to 2009 (Fig. 1.6) (Lokani 1996b, NFA database). The proportion of sandfish (by weight) in the catch declined from 100% in 1988 to 93% in 1989, and then to 12% in 1990. Sandfish were considered to be overfished by 1992 based on the smaller lengths of live sea cucumbers (mean 17 cm, range 12–22 cm) and increased proportions of lower grade BDM (Lokani 1996b). In 2006, the mean live length of surveyed sandfish stocks in New Ireland Province had fallen to 13 cm (6–20-cm range) (Kaly et al. 2007).

Table 1.1 Mean weight of different sandfish grades in 1988–99 (after Lokani 1996b).

BDM grade	Mean dried individual weight (g)	Estimated mean individual live weight* (g)
Super	117.4	2,350
A	83.7	1,680
B	55.7	1,110
C	27.9	560
D	17.45	350

* *Lokani (1996b) reported 95% weight loss during processing.*

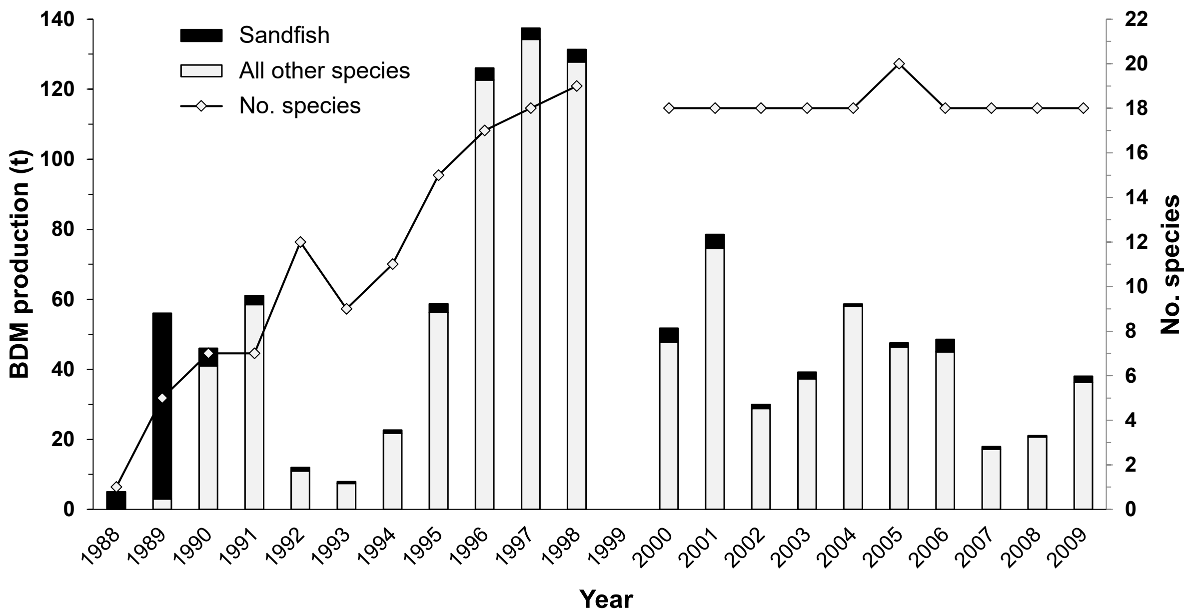


Figure 1.6 New Ireland Province BDM production quantity (t) and species diversity from 1988 to 2009 (black bar = sandfish, grey bar = all other sea cucumber species, line = no. species). The New Ireland Province sea cucumber fishery was closed in 1999. Sources: Lokani (1996b) (1988-1992); NFA database (1993–2009).

In 1988 all sea cucumber catches came from the Tigak Islands, but by 1990 the fishery had expanded to exploit other areas in the province (Lokani 1996b, NFA 2007). Between 1994 and 2009, Sandfish made up between 2–8% of provincial BDM exports (NFA database) (Fig. 1.6). The Tigak (including adjacent mainland villages) and Tsoi Islands (including New Hanover) continued to be the major suppliers, contributing 83% of the New Ireland Province sandfish catch (Hair and Aini 1995, 1996). Data from the NPFD show that fishers from 86 villages sold sandfish in 1995, although some originated from 'unspecified villages'. CFMDP also found that the Tigak and Tsoi island groups dominated BDM exports in 1998 accounting for 45% and 28% of the total, respectively (NFA 2007), and it is reasonable to assume that most sandfish originated from those areas. In 2006, a calculated annual catch rate of 15 t of sandfish (wet weight) was reported from the Tsoi Islands, although most surveyed individuals were of small or medium size (Friedman et al. 2008a). BDM traders confirmed that sandfish, when it was offered for sale, mostly originated from the Tigak and Tsoi Islands. The NFA database records do not show the village of origin.

Both official records and interview data indicate that the Tigak Islands' sandfish stocks rapidly tracked a 'text-book' decline (Lokani 1996b, Schwerdtner Máñez and Ferse 2010, Anderson et al. 2011). Large sandfish were first exhausted by gleaning in shallow water, then by diving in deeper waters and then smaller sandfish were collected from any depth. Next, large and small sized individuals of medium- and low-value species were harvested until eventually all commercial sea cucumber stocks were depleted. Similar fisheries based on intense but short-lived sandfish exploitation have been reported from Mua Island in Milne Bay Province from 1987-1990 (Kinch 2002) and from Western Province near Daru in 1992–1993 (Kailola 1995), the former of these was also a centralised operation.

1.4.3 Value of the sandfish fishery

Sandfish currently commands the highest price for tropical BDM in Asian markets (Purcell 2014b, Purcell et al. 2018b); however, prior to the 1970s it was 'unimportant' (Hamel et al. 2001) and classed as a medium-value species in the Pacific Islands region in the late-1980s (McElroy 1990). This early regional disinterest set PNG apart in 1989 with sandfish as the main target species (Conand and Byrne 1993). In 1989, about 136.5 t of sandfish BDM was exported from PNG, comprising 70% of PNG's exports. Over 50 t originated from New Ireland Province, the largest supplier after Milne Bay Province (Lokani 1990, Lokani 1996b). A key factor for increased engagement in the sea cucumber fishery and BDM trade in the Tigak Islands was the increased value of sandfish around this time as prices declined for a staple cash crop, copra (Lokani 1996b). The earliest known prices for sandfish were PNG kina (PGK) 0.02-0.10 per piece[3] from 1988–1992, for all grades (Lokani 1996b, interview data).

Sandfish was the most lucrative sea cucumber species in Kavieng from 2001-2005 (Kaly 2005); high-grade sandfish BDM fetched the best prices (PGK 66, PGK 42 and < PGK 30 per kg for A, B and lower grades[4], respectively). Only dragonfish (*Stichopus horrens)*, a newly commercialised species, was more valuable than C-Grade sandfish. Although only small quantities of sandfish were being sold, Limanak fishers recall receiving up to PGK 100 per kg BDM[5] in 2009, prior to the moratorium, a value confirmed by former traders. Interview respondents related that, in the rush to exploit as much sea cucumber as possible leading up to the 2009 closure, traders waited on the beach at Limanak to purchase partially processed sea cucumbers. New Ireland Province reported export tonnage and value of sandfish BDM from 2000 up until the moratorium in 2009 are shown in Figure 1.7; during that time it ranged from a minimum of around 1% (e.g., in 2008) to a maximum of 17% (e.g., in 2001) of PNG's total export amount and value.

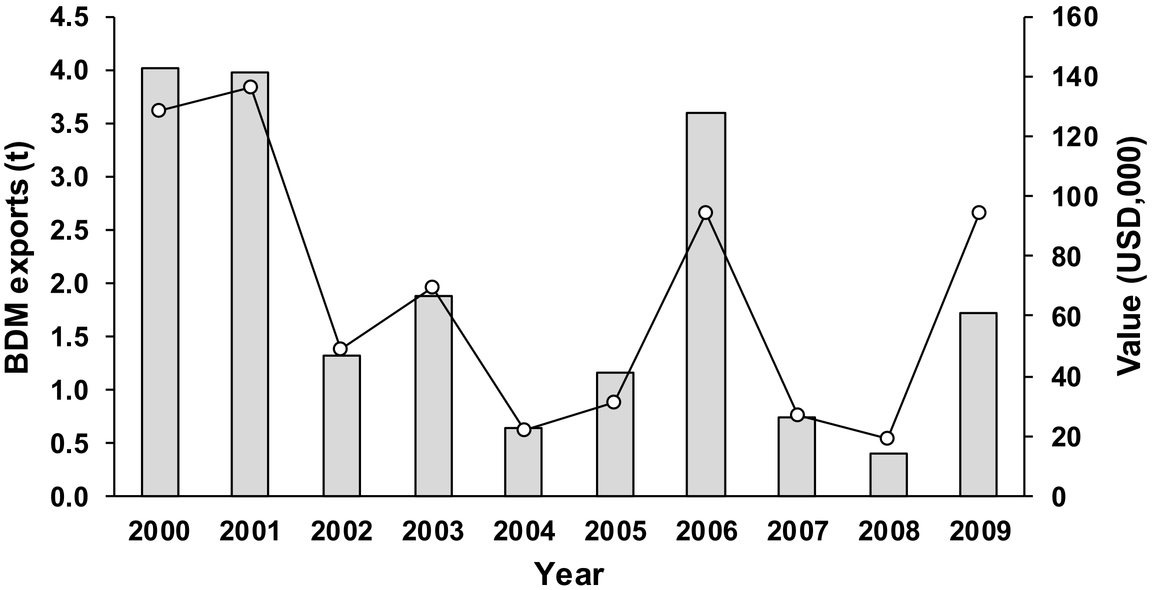


Figure 1.7 Total New Ireland Province sandfish BDM exports from 2000 to 2009 (bar = tonnes BDM, line = USD 1,000 export value). Source: NFA database.

---

[3] At that time, this was less than United States Dollar (USD) 0.10 per piece.
[4] Approximately USD 20, USD 12, and < USD 9 per kg for A, B and lower grades, respectively.
[5] Approximately USD 30 per kg.

During interviews, many fishers complained that BDM prices were better in other provinces. In 1994, sandfish BDM prices in Manus Province were triple those in Kavieng (Hair and Aini 1995, Polon 2004). NFA database records for 2000–2009 show that New Ireland Province sandfish BDM prices were 6–36% less than the national average in 7 out of 10 years, the same price in one year and about 15% higher in 2 years, including 2009. The difference in value could be due to product grade (size and quality), inaccurate data or some other reason (e.g., greater competition). Fishers also claimed that Kavieng traders did not pay higher prices for well-processed BDM. Traders countered that they invariably reprocessed the BDM to bring the product up to export standard (see also Barclay et al. 2016). They maintain that fishers residing near to Kavieng (e.g., Tigak Islands) sold incompletely processed BDM on a daily basis in order to obtain immediate cash, while BDM from more distant locations (such as the Tsoi Islands) was well dried to reduce the risk of spoilage.

1.4.4 Management of the fishery

BDM is a highly valued commodity in the Pacific Islands region, where income-generating opportunities for coastal communities are scarce. Management of sea cucumber fisheries is notoriously difficult for many reasons, including numerous and widely scattered landing places, wide reach of traders and poorly resourced regulators (Anderson et al. 2011, Carleton et al. 2013, Barclay et al. 2016). Consequently, overexploitation is very common (Kinch et al. 2008a).

The need for regulation in New Ireland Province was first recognised when localised overfishing of sandfish occurred in 1989 and the issue was raised again in the mid-1990s (Lokani 1996a). In 1996, the NFA implemented a sea cucumber management plan, with a total allowable catch (TAC) of 80 t for the province, and sandfish size limits of 8-cm dry and 20-cm live (Kinch et al. 2008b). The use of lights or underwater breathing apparatus to harvest sea cucumbers were also banned. Lokani (1996a) further recommended capping the number of traders. A proactive New Ireland Provincial government also created a Provincial BDM Management Plan in 1997 with regulatory measures that included licensing restrictions. Overfishing of the TAC by 57 t and 51 t in 1997 and 1998, respectively, triggered closure of the 1999 fishing season in New Ireland Province (NFA 2000).

The NFA drafted its first National Beche-de-mer Fishery Management Plan (referred to as the BDM Plan throughout this thesis) in 2000 (Polon 2004). It divided TACs into high- and low-value groups (i.e., 25 t of high-value species including sandfish, and 55 t of low-value species for New Ireland Province), and introduced a compulsory closed season from 1 October to 15 January each year, although a provincial fishery could be closed earlier if their TAC was exceeded (Polon 2004, Kinch et al. 2008b). An increased minimum size limit was introduced for sandfish; 10-cm dry and 22-cm live. To put this minimum size limit in historical context, it equated to a live sea cucumber less than 500 g in weight that would have been classed as D-Grade in the late 1980s and considered not worth collecting in the 1970s (Lindholm 1978, Lokani 1996b).

Many sources, including sea cucumber fishers themselves, suggest that government fisheries regulations were not well known or respected at the village level. Fishing at night with lights was commonplace and size limits were generally disregarded (NFA 2000, Kinch et al. 2008b). Provincial Fisheries officers warned fishers that their sea cucumber resources were threatened by unsustainable and illegal fishing practices (interview data). However, with no fear of apprehension and no penalties for infringement, these and other rules were often flouted by both fishers and traders. For example, both licensed and unlicensed traders in Kavieng purchased undersized BDM in the 1990s and 2000s (NFA 2000, NFA database, interview data). A sign of low sea cucumber stocks was the failure of New Ireland Province to reach its TAC quota for several years prior to 2007 (NFA 2007). Reduced fishing effort, including a resting period to allow immature sandfish to reach spawning size, were recommended in 2006 following sea cucumber surveys in the Tsoi Islands (Friedman et al. 2008a).

Despite the existence of various targeted management measures (Friedman et al. 2008b, Carleton et al. 2013), the inability to police them often force the regulatory agencies of Pacific nations to suspend all fishing and trade of sea cucumbers (Purcell et al. 2013). Population surveys in the 2000s indicated severe overfishing of all commercial sea cucumber species in PNG (Skewes et al. 2002, NFA 2007, Friedman et al. 2008a, Kinch et al. 2008b). In addition, sampling of BDM exports by the NFA revealed that undersized BDM made up a large proportion of shipments. To avoid the risk of total stock collapse, the NFA imposed a 3-year moratorium in 2009. The purpose of this closure was to allow recovery of the sea cucumber stocks to levels where they could be managed sustainably. From 2010, the NFA conducted annual sea cucumber surveys in eight PNG provinces, including New Ireland, to track recovery of sea cucumber stocks. When surveys in 2012 and 2015 indicated limited stock recovery, the moratorium was extended on both occasions. The ban on fishing was eventually lifted in 2017;

the first post-moratorium sea cucumber season was declared open on April 1, 2017. The socio-economic impacts of the reopened fishery became key components of this thesis.

As discussed above, shallow-water, high-value invertebrate fisheries in the Pacific, such as those for sea cucumber, are very difficult to manage effectively to maintain sustainable harvests. Even when previously overexploited stocks appear to show recovery, they can be quickly and easily overfished again (Friedman et al. 2011, Carleton et al. 2013, Baker-Médard and Ohl 2019). This is compounded by the apparent unwillingness of fishers and traders (and sometimes government policy makers) to support practices of sustainable harvesting (Pakoa et al. 2013). Through the drafting of a revised BDM Plan (NFA 2016), the PNG NFA was determined to avoid a relapse to unsustainable sea cucumber fishing, as experienced elsewhere in the Pacific Islands region (e.g., Tonga, see Carleton et al. 2013, Pakoa et al. 2013). The potential for sustainable mariculture activities provides an additional management option, although they should not replace a precautionary approach to management and adherence to responsible fisheries practices (Purcell 2010a).

1.4.5 Potential for sandfish mariculture

Mariculture of sea cucumbers is a relatively new industry (Lovatelli et al. 2004), but hatchery production of the high-value temperate species, *Apostichopus japonicus,* in China has overtaken wild harvests (Chen 2004, Eriksson and Clarke 2015, Ru et al. 2019). Progress in tropical sea cucumber aquaculture has lagged behind that in temperate areas, but sandfish has been identified as a promising candidate for culture (Battaglene 1999, Purcell et al. 2012b, Robinson 2013) and significant research into the development of this species has occurred in recent decades (James 1996, Battaglene et al. 1999, Purcell et al. 2012b). Routine hatchery production of small juveniles is well established (Agudo 2007, Duy 2010, Militz et al. 2018), and technical advances are occurring rapidly (Mercier and Hamel 2013, Duy et al. 2016). Strategies for release and grow-out in the wild and monitoring the success of juvenile sandfish releases are also improving (Purcell 2004, Purcell 2012, Rougier et al. 2013, Ceccarelli et al. 2018).

In general, mariculture initiatives in the Pacific have a poor track record and this low success rate is associated with many factors, including high costs, market access, species choice, inadequate planning and lack of community consultation (Pomeroy et al. 2006, Hambrey et al. 2011, Krause et al. 2015). The possibility of genetic problems caused by translocation or inbreeding, disease risk, ecosystem impacts, conflict with wild fishery management, and a range of negative community effects have also been raised (Eriksson 2012, Pakoa et al. 2012). However, sea cucumber has advantages over many other potential mariculture commodities; there is a strong international market, and it can be developed in an environmentally benign and culturally compatible way using appropriate and affordable technology (see references in Hair et al. 2012). From an ecological standpoint, sandfish appear to have few drawbacks—they feed low on the food chain, do not require supplemental feeding and may provide ecosystem benefits. Nor are sandfish likely to require intensive husbandry once they are released into the wild, although early juvenile stages are vulnerable to predation and may require protection in some areas (Rougier et al. 2013, Eeckhaut et al. 2020). Nowland et al. (2017) reported that PNG sandfish populations exhibit a panmictic stock structure, therefore movement of broodstock and cultured juveniles within PNG for mariculture purposes is not likely to be a contentious issue as suggested for other countries (Uthicke and Purcell 2004). There is also evidence from other sandfish-producing countries, such as Madagascar, Vietnam and the Philippines, to indicate that cultured sandfish can achieve harvestable size in an appropriate time frame (with a cropping cycle of less than two years) (Duy 2012, Robinson 2013, Juinio-Meñez et al. 2017). Sea ranching is a mariculture activity where cultured juveniles are released into an unenclosed oceanic environment in a ‘put, grow, and take’ operation (Bartley and Bell 2008). It is important to note that mariculture can also be conducted in land-based facilities (e.g., seawater ponds and tanks); however, in the context of this thesis, only oceanic mariculture is considered. Sandfish released into suitable habitat are unlikely to move far in the first 2 years (Purcell and Kirby 2006, Lee et al. 2018a), which is an advantage in community-based sea ranching. Finally, since sandfish become sexually mature well before they reach harvestable size, ranched or farmed[6] individuals will contribute to spawning biomass (Hair et al. 2011, Olavides et al. 2011, Juinio-Meñez et al. 2013).

Sea cucumber mariculture is not a cure-all for wild harvest problems, but if integrated within a sound management framework it could enhance biological and social outcomes (Bell et al. 2008). The NFA has recognised this potential in the post-moratorium revised BDM Plan (NFA 2016). In addition to stricter regulatory measures for fishers and traders, and TACs based on annual stock assessments for each maritime province, the revised plan promotes joint management of sea cucumber resources with communities through provinces and local level governments. Notably, the revised BDM Plan included a new section on ‘Mariculture,

[6] In the context of this thesis, farming refers to rearing cultured sandfish in enclosures, such as sea pens.

Aquaculture, Ranching and Stock Enhancement' to incorporate sea cucumber mariculture activities. Routine provision of juveniles for sea ranching of sandfish in communities with suitable habitat could be used as a management tool by levelling peaks and troughs in supply. Sellers and traders may benefit from reduced variability in cultured sandfish size and quantity, compared to that from wild fisheries (Agudo 2012). Increased certainty regarding harvest quantities may create an atmosphere where controlled and equitable distribution can occur. With further decentralisation of regulatory control, more effective community-based fisheries management of both wild and ranched sandfish stocks may ensue. This concept is explored in more detail in this thesis.

1.4.6 Socio-economic aspects of sandfish mariculture

Unlike Asia, the Pacific Islands region (including PNG) has few examples of traditional community-based mariculture to draw on (Hambrey et al. 2011), but interest and capacity in sea cucumber culture is growing (Jimmy et al. 2012, Ram et al. 2016a). Familiarity with the BDM trade, coupled with the technical advantages outlined above, has fuelled interest in community-based mariculture of sandfish (with emphasis on sea ranching) in PNG. In PNG, New Ireland Province stands to benefit in the first instance as it is a historically significant BDM source and three local communities are collaborating with NIMRF in mariculture research (Southgate et al. 2012). The diversity and dynamism in marine tenure regimes across PNG preclude a 'one-size-fits-all' mariculture model (Johannes 1982, Ruddle et al. 1992, Hyndman 1993, Macintyre and Foale 2007, Aswani et al. 2017). It is also difficult to predict how fishers who traditionally targeted wild sandfish will adapt to this activity until mariculture operations can be trialed in the field. There is a lack of data on the socio-economic aspects of sandfish mariculture and more research is needed in this area. However, community consultation has been integrated into the sandfish mariculture research phase in an attempt to bridge the 'people-policy gap' that can constrain aquaculture development (Krause et al. 2015). Research with partner communities (described in this thesis) and lessons learned from sandfish mariculture elsewhere also provide an excellent head start (Lovatelli et al. 2004). Certainly, equitable distribution of benefits in the community and adoption of sustainable management measures are desirable outcomes, and must be nurtured together with good governance of the fishery at all levels (Barclay et al. 2016, Eriksson et al. 2019).

The relationship between sandfish farmers and fishers, BDM traders and product quality is of the highest priority; the future must encompass motivations and incentives for high-quality BDM. The following factors underpin this objective:

1. The retail value of sandfish BDM in China, per kilogram and per piece, increases exponentially with length for BDM over 10 cm (Purcell 2014b, Purcell et al. 2018b).
2. Sea cucumber fishers receive on average 65% of the export price at the point of sale (higher than many other commodities). This percentage increases with higher value species and higher grades within species, hence good quality BDM from large sandfish is worth proportionately more of the export value (Kinch et al. 2008b).
3. Value of the final BDM can be reduced by 10–50% through negligence during processing (Ram et al. 2014).

There may also be a possibility for fishers and sandfish farmers close to urban centres to add value with novel sea cucumber processing and packaging techniques (Purcell et al. 2014a, Ram and Southgate 2014). Education is therefore essential to encourage fishers to forego immediate and frequent income from small, badly processed sandfish in exchange for substantially higher returns from larger, well-processed product. To this end, price differentials may act as a management tool as long as traders offer prices that are commensurate with high-quality BDM. This will require a major behavioural change in all stakeholders but a more consistent supply through mariculture may provide the impetus for this shift. Closer examination of earning and expenditure patterns, value placed on labour and the motivation for financial reward in PNG sea cucumber fishers is still needed (e.g., see Curry and Koczberski 2012, Barclay and Kinch 2013, Curry et al. 2015).

Evaluating the success of sandfish sea ranching will require appropriate monitoring (Bell et al. 2008). Data collection programs that differentiate sea ranch production from wild catches of sandfish are needed to document initial and ongoing production from mariculture. Income generated from mariculture activities and a measure of improvements in BDM processing should be collected from sandfish fishers and farmers and BDM traders. It is also important to assess social outcomes such as the formation of village cooperatives or associations, enhanced environmental awareness, adoption of targeted local level government (LLG) management of this resource, efforts to ensure equitable distribution of benefits, and so on.

As pointed out by Dalzell et al. (1996), the impressive catches of tuna in the Pacific have far less social and economic impact on the lives of residents than the more modest coastal zone landings. In PNG, sea cucumber was a major cash earner prior to the 2009 moratorium, supporting up to 200,000 PNG villagers (Polon 2004, Kinch et al. 2008b) providing approximately PGK 100 per person per year, i.e., as much as 30% of annual villager income. In the year prior to the closure, the New Ireland Province sea cucumber fishery was worth over PGK 2 million (> PGK 257,000 for sandfish alone)[7]. It is a national priority to enable the people of PNG to sustainably exploit this valuable resource into the future. This will require improved management of the fishery but there now also exists potential to increase harvests through mariculture.

1.5 Thesis overview

When sea cucumber stocks in PNG were deemed sufficiently recovered for NFA to reopen the sea cucumber fishery, mariculture of sandfish was considered an exciting opportunity for PNG coastal communities to move beyond the ‘boom, bust and ban’ paradigm for this lucrative yet fragile resource. At this juncture, reliable hatchery methods for tropical sea cucumbers was limited to sandfish, a commercial species that has supported significant fisheries in PNG in the past. Ironically, the same characteristics that predisposed sandfish to overexploitation in the wild fishery (i.e., high unit value, relatively sessile, site attached, shallow depth preference) suit them to sea ranching.

The original objective of this study was to focus on development of community-based sandfish mariculture in the Kavieng area of PNG. However, lifting of the sea cucumber fishery moratorium changed the focus of this study from purely assessing sandfish mariculture potential, to include assessment of social aspects of the sea cucumber fishery and the technical and social factors that may influence uptake of sandfish mariculture as a livelihood activity. These were addressed in the following six research chapters:

Chapter 2 Social and economic impacts of the re-opening (and subsequent closure) of a sea cucumber fishery in New Ireland, Papua New Guinea: lessons for mariculture development;

[7] Approx. USD 761,700 (USD 98,000 for sandfish) (NFA database).

Chapter 3 Optimising methods for community-based sandfish sea ranching: Experimental releases of cultured sandfish juveniles into seagrass meadows in PNG;

Chapter 4 Preliminary assessment of geographic information system and remote sensing techniques to describe and predict mariculture habitat for sandfish;

Chapter 5 Comparison of survival, growth and behaviour of cultured and wild sandfish juveniles;

Chapter 6 Comparison of quality of bêche-de-mer processed from ocean-cultured and wild-harvested sandfish; and

Chapter 7 Social and economic challenges to community-based sea cucumber mariculture development.

The final chapter is a General Discussion that summarises the main outputs of the research and discusses the major technical and social barriers to successful community-based sandfish mariculture in the study area, together with recommendations for the way forward.

The data chapters listed above are presented in a Thesis-by-Publication format. Each chapter represents an independent study that has either been published or is being prepared for submission at the time of writing. On this basis, there may be some repetition of content between chapters, although minor changes have been made to improve the flow of the thesis and to minimise repetition. The status of each chapter at the time of thesis submission is indicated using footnotes associated with chapter titles.

Chapter 2
Socio-economic changes associated with the post-moratorium sea cucumber fishery in New Ireland communities[8]

2.1 Introduction

2.1.1 Fisheries livelihoods

Small-scale fisheries provide many benefits to island and coastal communities in developing nations including food security and improved nutrition (Kawarazuka and Béné 2010, Mills et al. 2011b), although the link to poverty alleviation is more complex (Béné et al. 2016). Cash generated from the sale of seafood and marine export commodities is commonly used to purchase food, as well as clothes, housing, household goods, schooling, health needs and cultural obligations (Foale 2005, Curry et al. 2015, Fabinyi et al. 2017). In maritime regions of Papua New Guinea (PNG), growing human populations and an intensifying engagement with markets have placed pressure on marine resources (Kronen et al. 2010, Barclay and Kinch 2013) as greater income is sought from a shrinking resource base. Further, many islands have limited arable land area and low soil fertility, increasing their reliance on small-scale fisheries for subsistence and livelihoods.

Commodified marine resources such as sea cucumber, processed into BDM support important livelihood opportunities in the Indo-Pacific region. As outlined in Chapter 1, sea cucumber fisheries are prone to boom-and-bust cycles where heavy fishing precedes depletion (Anderson et al. 2011). However, lucrative returns, escalating demand from Asian markets and well-developed market chains incentivise fishers to continue harvesting depleted stocks (Friedman et al. 2008a, Kinch et al. 2008a, Eriksson et al. 2015, Purcell et al. 2017). Furthermore, negative social impacts and failure to produce long-term benefits or to increase community well-being have also been reported for sea cucumber fisheries (Christensen 2011, Rasmussen 2015, Barclay et al. 2016). Alternative sources of food and cash are urgently needed to reduce fishing pressure and to maintain ecosystem services and food security in the Pacific Islands region (Bell et al. 2009, Kronen et al. 2010). Worldwide, there is increasing research interest in

---

[8] Data from this chapter were published as: Hair, C., Foale, S., Kinch, J., Frijlink, S., Lindsay, D. and Southgate, P.C. (2019). Socioeconomic impacts of a sea cucumber fishery in Papua New Guinea: Is there an opportunity for mariculture? *Ocean and Coastal Management*, 179, 104826. https://doi.org/10.1016/j.ocecoaman.2019.104826

sustainable livelihood opportunities based on mariculture of the high-value sea cucumber species, sandfish (*Holothuria scabra*) (Jimmy et al. 2012, Purcell et al. 2012b, Robinson 2013, Juinio-Meñez et al. 2017). In this chapter, this research focus is developed using data from three New Ireland Province island communities that engage in the wild sea cucumber fishery.

2.1.2 New Ireland Province and the sea cucumber fishery

New Ireland Province is located in northern PNG, and consists of two large islands, New Ireland and Lavongai (also known as New Hanover), plus many smaller islands. The capital Kavieng is located on the northwest tip of New Ireland (Fig. 1.4). Production and sale of BDM has been an important activity in the study area since the late 1980s, targeting sandfish until they were overfished and the fishery expanded to include other species (Lokani 1996b, Friedman et al. 2008a, Chapter 1).

Severe depletion of wild sea cucumber stocks nationwide led the PNG National Fisheries Authority (NFA) to impose a moratorium on fishing sea cucumber and selling BDM in September 2009. Communities that relied heavily on BDM for income were forced to pursue alternative livelihoods, with most effort shifting to other forms of fishing (Barclay et al. 2016, Purdy et al. 2017, Vieira et al. 2017). The moratorium was in place for more than seven years and reopened on 1 April 2017, despite the NFA surveys indicating that populations of many sea cucumber species had not fully recovered (Hair et al. 2018). Resumption of the fishery had been eagerly anticipated by New Ireland Province fishers; sea cucumbers were conspicuous again in nearshore fishing grounds and BDM prices had increased greatly during the moratorium. A feature of NFA's revised BDM Plan (Barclay et al. 2016, NFA 2016, Chapter 1) was an annual open season that would run from April to September or until a pre-set provincial total allowable catch (TAC) of BDM was reached, which would be assessed from traders' purchase records in real time. In this first post-moratorium season, the TAC for New Ireland Province was 43 tonnes (t). This TAC was attained in less than two months of intensive fishing, and was actually exceeded by at least 36 t because of the failure to monitor BDM purchases in real time (Hair et al. 2018). More than 20 sea cucumber species were harvested in New Ireland Province during the 2017 fishing season.

The reopening of the sea cucumber fishery provided an opportunity to describe and quantify its importance and value to New Ireland fishing communities. Changes in income source, income, spending patterns, diet and fishers' attitudes are compared over three periods: before, during and after the 2017 sea cucumber fishery. Drawing on survey results and current understandings of local culture and political economy, this chapter concludes with an appraisal of the potential contribution a sea cucumber mariculture-based livelihood might make to the well-being of coastal communities and how best to successfully integrate this with the existing wild fishery.

2.2 Methods

2.2.1 Ethical statement

This study was carried out under James Cook University Human Research Ethics Committee approval H4930. All interviewees gave consent to participate, verbal consent was usually sought because of low levels of literacy. Prior to being interviewed, each respondent was informed of the purpose of the interview, the confidentiality of information provided and the right to omit questions or end the interview at any stage.

2.2.2 Description of the study area

The study area lies within the Tigak and Tsoi Islands, east of the New Ireland mainland (Fig. 2.1). These islands are raised limestone or sand atolls, featuring fringing reefs, sandy seafloors with coral bommies, seagrass meadows in sheltered areas and extensive mangroves on the islands and the nearby mainland areas. Most communities in this area are heavily reliant on marine resources for food and income but also engage other activities to meet subsistence and cash needs. Customary marine tenure in this area gives equal rights to all community members to harvest in their respective traditional fishing grounds (Otto 1998, and confirmed in subsequent interviews with fishers). Outsiders are generally permitted to fish for subsistence needs but not for high-value commodities such as sea cucumber, trochus, lobster and mangrove crab (Foale et al. 2011). Many islands in the study area have former coconut plantations and copra production is undertaken by clans with entitlement to a 'block' of land.

The study was conducted in three communities: Enuk and Limanak in the Tigak Islands; and Ungakum in the Tsoi Islands (Fig. 2.1). All three communities were involved with the BDM trade in the boom period of the late 1980s, up until the time the moratorium was declared in 2009. Limanak and Enuk fishers sold sandfish to a processing company on nearby Limellon Island as described in Chapter 1, while middlemen on Enuk also bought fresh sandfish from Ungakum fishers. These communities were selected because they are involved in mariculture research using sandfish juveniles produced at the NFA Nago Island Mariculture and Research

Facility (NIMRF) (Militz et al. 2018). Although no commercial mariculture operations have commenced under this program, two trial ‘sea ranches’, stocked with cultured sandfish juveniles from NIMRF, had been established at Limanak and Ungakum.

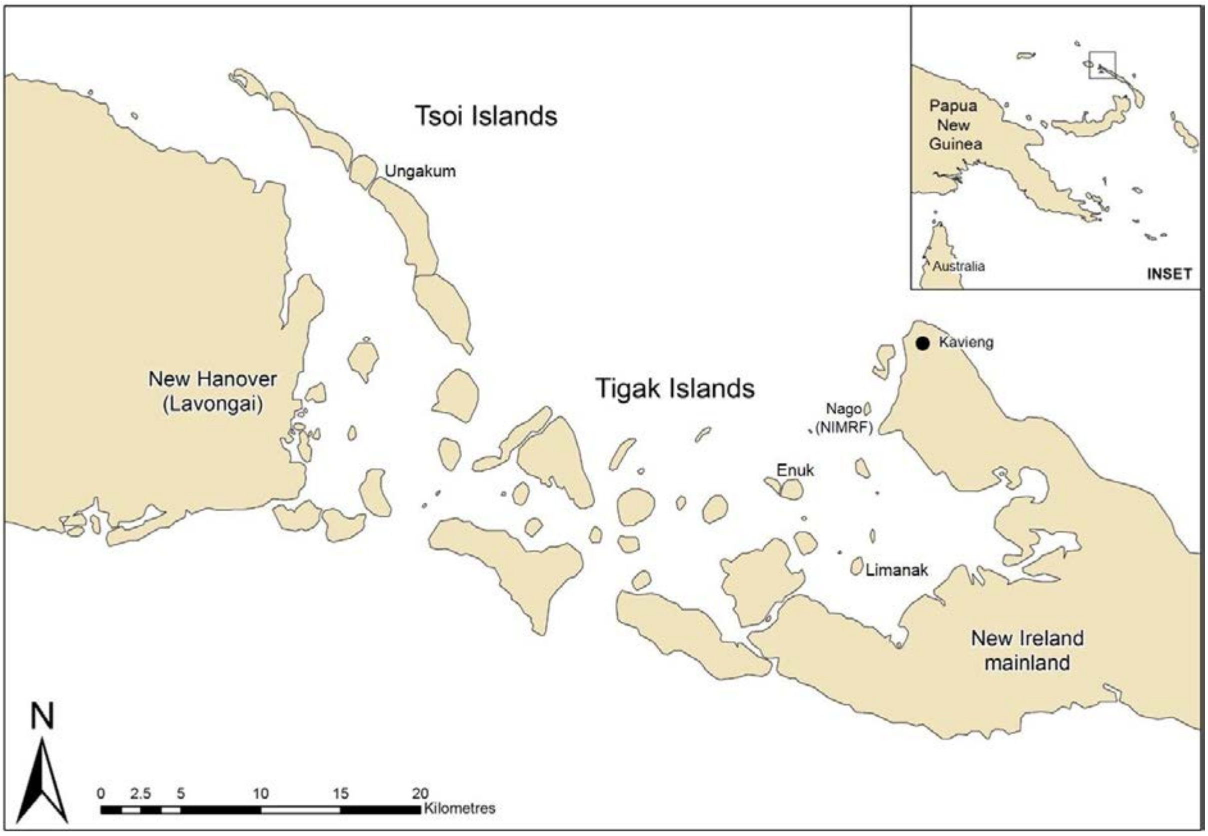


Figure 2.1 Map showing the location of Enuk, Limanak and Ungakum communities involved in the study and the provincial capital, Kavieng.

The population of each community fluctuates but at the time of the study was between 250 to 300 residents, as estimated from available information. Lawless and Frijlink (2016) provide estimates but census figures were not available for all communities, nor were village officials able to provide accurate numbers of residents. Proximity to Kavieng by boat is approximately 15 min from Enuk and Limanak, and 1–1.5 h from Ungakum. Formal employment is generally low in the area but a resort near Enuk employs some residents from that island.

The level of community-based fisheries management (CBFM) relating to sea cucumber ranged from minimal (Enuk) to well-developed (Ungakum). Enuk had no formal community management in place when the 2017 sea cucumber season commenced. Both Ungakum and Limanak had management plans in place, facilitated by a local conservation non-government organisation (NGO). Ungakum had established a Marine Management Committee and developed their first marine resource management plan in the mid-2000s. In 2016 the plan was revised (WCS 2016b), incorporating new regulations regarding sea cucumber harvest. At Limanak, a resource management committee was formed and a Fisheries Management Plan was ratified in 2016 (WCS 2016a). Their plan did not include specific sea cucumber management measures, but the committee informally banned all fishing in nearshore areas and prohibited non-residents from sea cucumber collection, even if they had relatives on the island. The Limanak population was reputed to double during sea cucumber open seasons before the moratorium, when outsiders, mostly relatives and in-laws, migrated to the island to participate in the fishery (interview data). This was a source of conflict with many of the permanent residents, giving rise to attempts to control outsider fishing in the 2017 season.

2.2.3 Survey and sampling design

2.2.3.1 Socio-economic data collection from partner communities

A mixed-methods approach was used, incorporating: oral, semi-quantitative socio-economic surveys of households; semi-structured interviews with key informants (KIs); informal conversations with fishers and other community members; and participant observation.

Data were collected over a 2.5-year period that encompassed three periods: during the moratorium, leading up to the 2017 fishery re-opening (*Pre-fishery* period); the sea cucumber open season from 1 April to 26 May, 2017 (*Fishery* period); and several months into the sea cucumber closed season, September 2017 (*Post-fishery* period) (Table 2.1).

Table 2.1 Survey period dates and number of household (HH) surveys conducted in each community in each Fishery period.

	Enuk		**Limanak**		**Ungakum**	
Survey period	Date	No. HH	Date	No. HH	Date	No. HH
Pre-fishery	March 2017	55	April 2015	40	Dec 2014	40
Fishery	May 2017	45	April 2017	45	April 2017	35
Post-fishery	Sept 2017	53	Sept 2017	47	Sept 2017	36

Household socio-economic surveys were done in the *Pre-fishery*, *Fishery* and *Post-fishery* periods. For each survey, a team of two to five enumerators worked in each study community for up to two days. Attempts were made to survey the household head/s (male or female, or both) of every household. If neither were available on the first attempt, the house was revisited. A minimum of 35 households per community in each survey period was accepted as comprising an acceptable proportion of households in each community (see Lawless and Frijlink 2016) (Table 2.1). Interviews were conducted in *Tokpisin*, a National *lingua franca*. Enumerators were accompanied by local assistants, who translated questions into local language (Tigak *Tokples*) and provided clarification when required.

Pre-fishery period data included information on demography, assets, income, income source/s, fishing activity and diet. *Fishery* period data included demography, income, income source/s, expenditure (with initial BDM income), fishing activity, gender roles and diet. *Post-fishery* period data included income, income source/s, expenditure (with 2017 season BDM income), fishing activity, diet and attitude towards the 2017 sea cucumber fishing season (Appendix 2).

Interviews were held with key informants (KIs) during *Pre-fishery* and *Fishery* periods, to probe more deeply into aspects of the sea cucumber fishery during pre-moratorium times (with an emphasis on sandfish) and the broader impacts of the 2017 fishery and trade (Table 2.2). *Pre-fishery* KI interviews included those referred to in Chapter 1 (*section 1.2,* Appendix 1). Enumerators also recorded observations and information gleaned from discussions with community members. After each survey or interview, respondents were invited to volunteer information or ask questions. Information from all sources was examined for key themes (Bernard 2006).

Table 2.2 Number of key informant interviews conducted, total number of people interviewed and male-female numbers, in each study community.

	Enuk	Limanak*	Ungakum
No interviews	6	17	8
Total number interviewed	9	25	12
Male:female	6:3	16:9	8:4

* *Note the larger number of Limanak interviews due to their greater involvement during the early stages of research (see Chapter 1).*

2.2.3.2 Data collection from BDM traders

Pre-fishery period interview data from former New Ireland Province BDM-traders (*section 1.2*) were used in this chapter. In addition, at the conclusion of the 2017 sea cucumber season, export data from the New Ireland Province BDM exporters (NFA database) was aggregated and summarised for type, quality and value of BDM for the study communities and province.

2.2.4 Data analysis

Weekly income from all sources and from seafood sales were compared for the three fishery periods for each community. A generalised least square (GLS) analysis was used for total income (data were log+1 transformed prior to analysis to normalise values). A binomial logistic regression was used for seafood sales income where 0 denoted nil income and 1 denoted income from this source. Differences in diet and income-earning activities were analysed for each community in the *Fishery* and *Post-fishery* periods only. The proportion of imported food items consumed was analysed with GLS, while the number of non-BDM related income sources was analysed with a Poisson GLM. Results of all analyses were considered significant at $p < 0.05$. GLS and GLM coefficient values are presented to indicate goodness of fit between the actual and the fitted values of the dependent variable. Descriptive statistics are presented for responses to gender roles and attitude toward aspects of the fishery.

2.3 Results

2.3.1 Income and income-earning activities

Reported household weekly income from sale of BDM was divided by three because fishers sold BDM they had stockpiled for three weeks due to a 20-day delay in issuing of exporter licences. Respondents who did not divulge their income in *Pre-fishery* surveys (n = 15 households) were omitted from analyses, as were households that had collected but not yet sold BDM in *Fishery* period interviews (n = 8 households). If households provided an income range instead of an exact amount, the lower value was used (n = 10 households over all survey periods).

Average weekly household income (in PNG kina, PGK[9]) in all communities was significantly higher in the *Fishery* period (F = 91.981, $p < 0.001$; Fig. 2.2). Limanak had higher weekly income than Ungakum and Enuk (F = 8.99, $p < 0.001$). Increases in average household income during the *Fishery* period were due to BDM sales, which surpassed income from other income sources in all communities: average weekly BDM earnings for Enuk, Limanak and Ungakum

[9] During the study, PGK 1 equalled approximately USD 0.31.

was PGK 140, PGK 580 and PGK 405, respectively, comprising 82%, 94% and 99% of the total average weekly income for each community. Across sites, weekly household income from BDM sales ranged from PGK 16–2,700, with the greatest change observed in the lower income bracket, which rose more than the high-incomes bracket (Fig. 2.2). Analyses revealed that Enuk's *Post-fishery* period income remained relatively high compared to the other communities (interaction coefficient value of -2.70, $p < 0.001$ compared to Limanak, -1.53, $p < 0.05$ compared to Ungakum). Across all communities, more households reported nil income in the *Pre-* and *Post-fishery* periods (31% and 23%, respectively) compared to one household (< 1%) in the *Fishery* period (discounting households that were in the process of selling BDM when interviews were held).

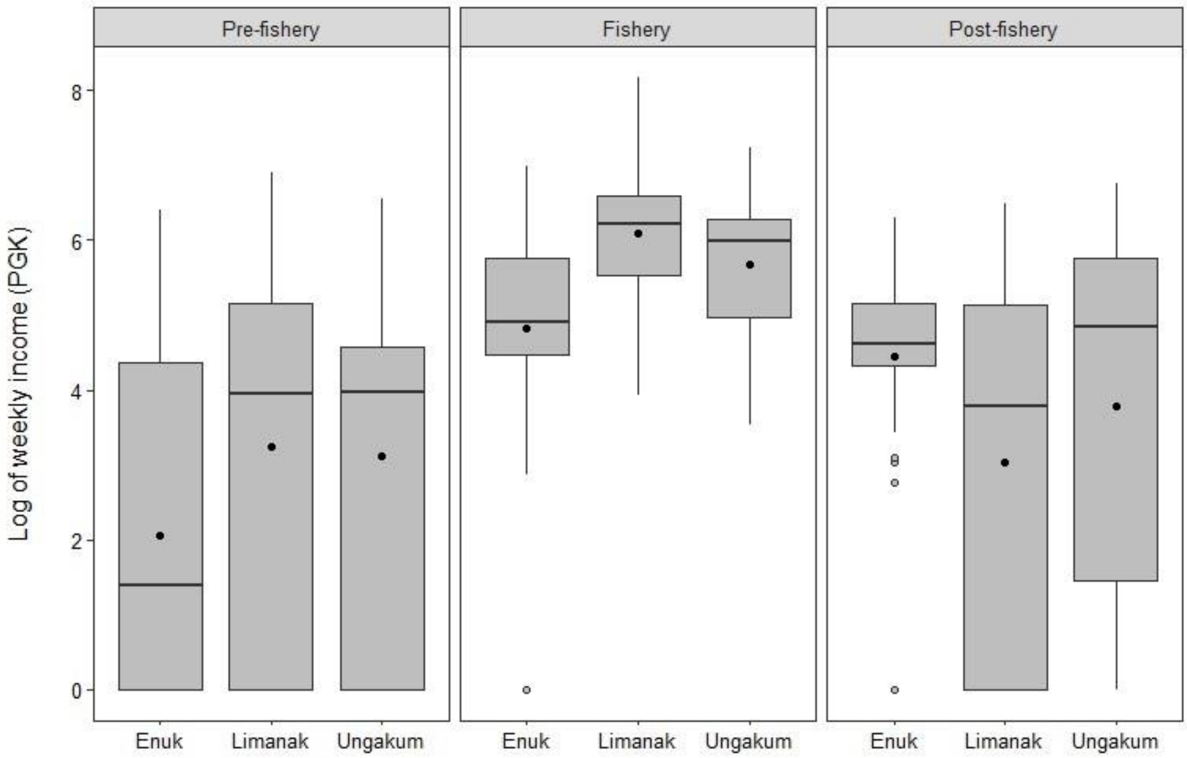


Figure 2.2 Box plots of log-transformed average household weekly income (PGK) per community for *Pre-fishery*, *Fishery* and *Post-fishery* periods. Closed circle = mean; horizontal line = median; grey bars = 25th and 75th percentiles; whiskers = 5th and 95th percentiles; open circle = outlier.

Seafood and copra sales were the most common income sources in *Pre-* and *Post-fishery* periods (Fig. 2.3) but copra production ceased and seafood fishing effort decreased during the *Fishery* period (Fig. 2.4). Significantly fewer households earned any income from seafood sales during the *Fishery* period (coefficient value 2.68, $p < 0.001$); most fish caught during this period were for subsistence purposes, and there were anecdotal reports of price increases and reduced supply in the Kavieng market. Many other income-earning and subsistence activities ceased or were curtailed during the *Fishery* period—sea cucumber were collected every day except Sunday (C. Hair, unpublished data). There were significantly more non-BDM income sources in the *Post-fishery* than the *Fishery* period (coefficient value 1.17, $p < 0.001$) but this also varied between communities with Enuk having a significantly greater diversity of income sources than Limanak and Ungakum (also note relatively higher *Post-fishery* income in Enuk, Fig. 2.2). Non-BDM income sources were diverse and included salaried work, village industries such as selling cooked food and sewing, sale of market produce, handicrafts, trades and petrol sales. Waged employees did not quit their jobs to fish for sea cucumber during the open season but many participated in the fishery in their free time.

It must be noted that some sources of income were under-reported during the *Fishery* period. For example, betelnut sales and boat transport did not cease but these sources were not always mentioned in surveys, possibly because of the collective focus on BDM.

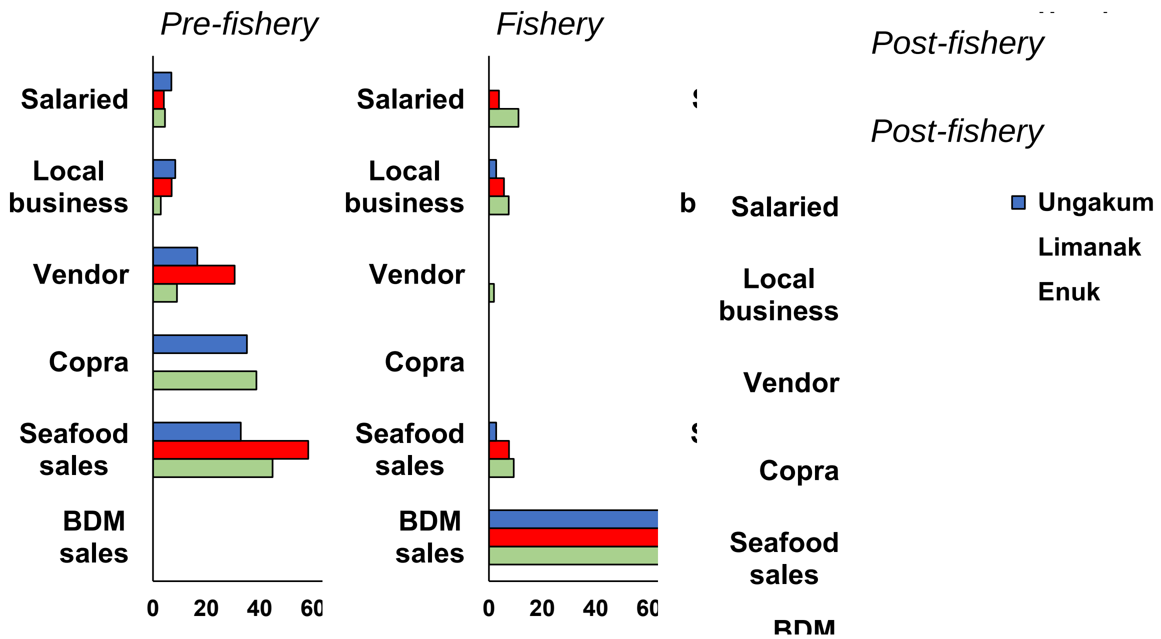


Figure 2.3 Selected income source as a proportion (%) of all income sources for Enuk (green), Limanak (red) and Ungakum (blue) during *Pre-fishery*, *Fishery* and *Post-fishery* periods.

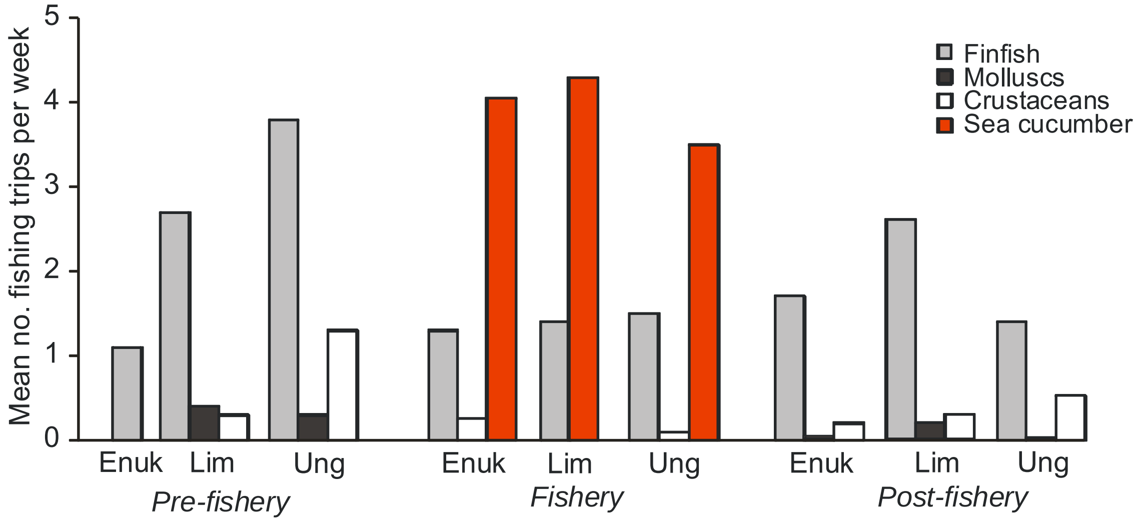


Figure 2.4 Fishing effort (mean number of fishing trips per week) for marine resource groups in each community during *Pre-fishery*, *Fishery* and *Post-fishery* periods.

2.3.2 Expenditure

Data on expenditure were collected during *Fishery* and *Post-fishery* surveys only: household heads were asked specifically how they used income from BDM sales. *Fishery* period surveys recorded expenditure of initial BDM earnings and *Post-fishery* period surveys recorded expenditure of earnings from the entire 2017 season, although the amount spent on each item was not recorded.

The most common expenditure reported for initial BDM earnings (i.e., *Fishery* period surveys) was purchase of store-bought food and clothes, reported by at least 50% of households in each community (Fig. 2.5). Many households also spent BDM income on school items, homewares, fishing gear and electronics. A high proportion of households reported some unspent income, which was partly due to surveys being done soon after such large amounts of cash were earned and would likely be lower if surveys had been conducted later (cf. Foale 2005, Christensen 2011).

Fishery and *Post-fishery* 24-h total diet recall (Kennedy et al. 2011) confirmed the substantial expenditure on store-bought food in the *Fishery* period (Appendix 3). Store-bought foods also included food cooked and sold in the community using store-bought ingredients (e.g., buns and fried pastries). Locally sourced food came from produce markets, gardens, the bush or ocean, or was gifted. Households consumed a significantly higher proportion of store-bought food when the fishery was open ($F = 102.44$, $p < 0.001$).

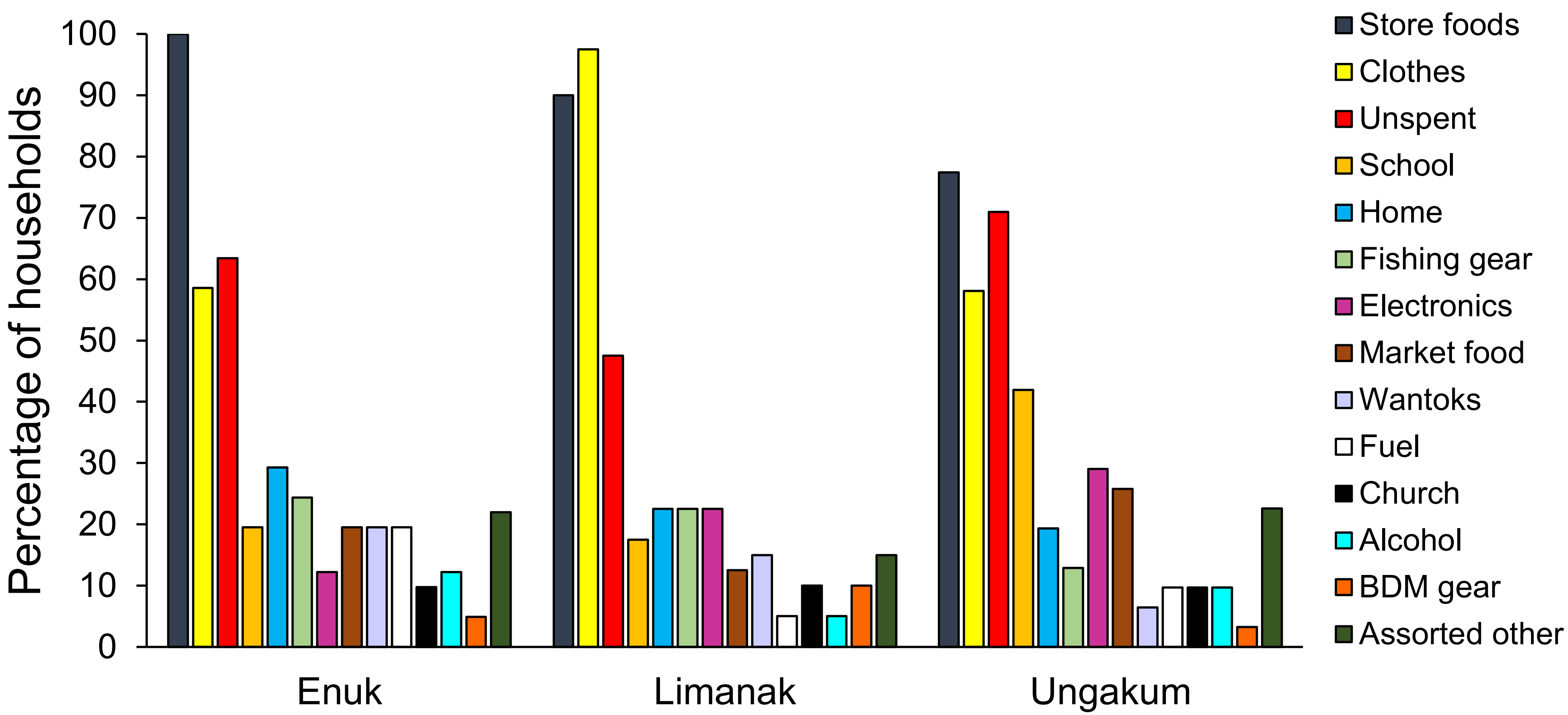


Figure 2.5 **Percentage of households in each community that reported expenditure on selected items using income from initial BDM sales.**

Rice was consumed by more than 95% of households and tinned fish was the most common protein (58% of households) during the *Fishery* period. Rice consumption frequency decreased slightly in the *Post-fishery* period, being consumed by 75% of households. Note that this figure is still high, but the quantity of rice consumed by households probably decreased because consumption of tubers, plantains, and sago increased during this period (Appendix 3). Likewise, the number of households eating fresh fish increased in the *Post-fishery* period, while consumption of tinned fish decreased (Appendix 3).

A recurring theme from KI interviews was that large, lump sums of money earned from BDM sales allowed people to purchase expensive items that are beyond their means during periods of ‘normal’ income earning. As such, BDM expenditure patterns (as reported in the *Post-fishery* period) were typified by asset purchases and items associated with house improvements. Assets were defined as durable and discretionary items, divided into: (1) minor assets: items of value up to PGK 200 (excluding clothing); and (2) major assets: items of value greater than PGK 200. More than 75% of households bought assets with BDM income (Table 2.2). The most commonly purchased minor assets were dive torches and snorkelling gear that were used for sea cucumber collection as well as other fishing, followed by homewares and tools. The most commonly purchased major assets were solar power cells and lights, mobile phones, electronic equipment and fishing equipment such as nets. Some households invested in alternative income-earning business, e.g., drums of fuel or canteen items to sell in the village. Almost half of all households spent money on house construction (Table 2.3), with roofing iron, walling, and chainsaw hire reported. Three respondents completed new permanent houses with BDM earnings.

Most households reported that decisions regarding expenditure were made jointly by male and female (68%, 72%, and 63% in Enuk, Limanak and Ungakum respectively). Men were solely responsible for decisions in 18% of households. When a woman was solely responsible for expenditure decisions (14% of households), she was usually unmarried or the fisher.

Table 2.2 Number (*n*) and percentage of households (HH) who purchased selected assets with income from BDM sales.

Asset category	Enuk (52 HH) n (%)	Limanak (43 HH) n (%)	Ungakum (35 HH) n (%)	Total (130 HH) n (%)
Major assets				
Solar kit (light, panel, inverter)	20 (38%)	26 (60%)	14 (40%)	60 (46%)
Phone	11 (21%)	13 (30%)	5 (14%)	29 (22%)
Electronic goods (screen, radio, speaker)	4 (8%)	8 (19%)	4 (11%)	16 (12%)
Major fishing gear (e.g., net, canoe, eskie)	1 (2%)	8 (19%)	3 (9%)	12 (9%)
Generator	3 (6%)	2 (5%)		5 (4%)
Chainsaw		3 (7%)	1 (3%)	4 (3%)
Fuel drum		2 (5%)	2 (6%)	4 (3%)
Power tools		1 (2%)	2 (6%)	3 (2%)
Outboard engine		2 (5%)		2 (2%)
Business investment capital			1 (3%)	1 (1%)
Minor assets				
Minor fishing gear (e.g., torch, mask, fins, handline, spearguns)	21 (40%)	28 (65%)	14 (40%)	63 (48%)
Homewares (e.g., mattresses, plates)	4 (8%)	10 (23%)	7 (20%)	21 (16%)
Tools/hardware	9 (17%)	4 (9%)	6 (17%)	19 (15%)
Parts (generator, chainsaw, outboard)	7 (13%)	4 (9%)	3 (9%)	14 (11%)
Boat repair	1 (2%)			1 (1%)
Nil assets				
No asset purchases	14 (27%)	9 (21%)	7 (20%)	30 (23%)

Table 2.3 Number and percentage of households from each community who reported expenditure of BDM income on house improvement.

Home improvement category	Enuk	Limanak	Ungakum	All communities
Purchase of materials for house	12 (23%)	28 (59%)	10 (28%)	49 (37%)
Completed a new house		1 (2%)	2 (6%)	3 (2%)
Repair/extension to existing house	3 (6%)	1 (2%)	4 (11%)	8 (6%)
Reported saving for new house	3 (6%)	1 (2%)		4 (3%)
Total any home improvement	***18 (35%)***	***31 (65%)***	***16 (45%)***	***65 (48%)***
No home improvement	35 (65%)	16 (35%)	20 (55%)	71 (52%)

2.3.3 Community attitude towards the 2017 sea cucumber season

Household surveys and KI interviews elicited views about personal satisfaction and perceived benefits and disadvantages of the 2017 fishing season. Also, what practices fishers would like to change in future seasons. Respondents were overwhelmingly of the opinion that the sea cucumber season had benefited them personally (96%, 98% and 100% from Enuk, Limanak and Ungakum, respectively), either through direct participation in the fishery, or indirectly by receiving benefits from participants in terms of gifts and increased local business. Only three respondents felt they did not benefit from the fishery.

Satisfaction with the 2017 season was also high (77%, 66% and 81% of respondents from Enuk, Limanak and Ungakum, respectively). High income was the primary reason (90% of responses) but social benefits related to a prospering community were also mentioned. All key informants confirmed the positive benefits from the fishery; e.g., young men were kept busy, money was earnt to meet daily and long-term needs, standards of living improved, and debts were repaid. Dissatisfied respondents (13%, 30%, and 17% of respondents from Enuk, Limanak, Ungakum, respectively) were unhappy with trade issues (49%), fisheries management (40%) or social problems (5%). Enuk fishers reported more dissatisfaction with the amount of BDM that was rejected because it was undersized or badly processed, underpayment and delays in selling due to late issuance of licences (83%, compared to 29% and 38% for Limanak and Ungakum, respectively). Limanak fishers reported more fishery management issues (e.g., short season, failed CBFM) than the other two communities. Negative aspects were noise and disturbance from drunks but problems such as domestic violence were not reported, purportedly due to the surplus of money, which mitigated this conflict. KIs from Limanak and Ungakum mentioned problems with fishers harvesting sea cucumber in protected areas and bemoaned the neglect of gardens and community work. There were also complaints about the irresponsible disposal of rotten sea cucumber and rejected BDM, mostly from Enuk.

Regarding what practices fishers said they would change, the most common was to improve income management (37% of all responses), followed by improving fishing (29%) and processing (21%) methods in order to maximise income. There were some differences among communities: more than half of households in Enuk wanted to improve fishing and processing practices; more Limanak households wanted to improve resource management; and Ungakum had the highest proportion who wanted to improve their income management (Fig. 2.6).

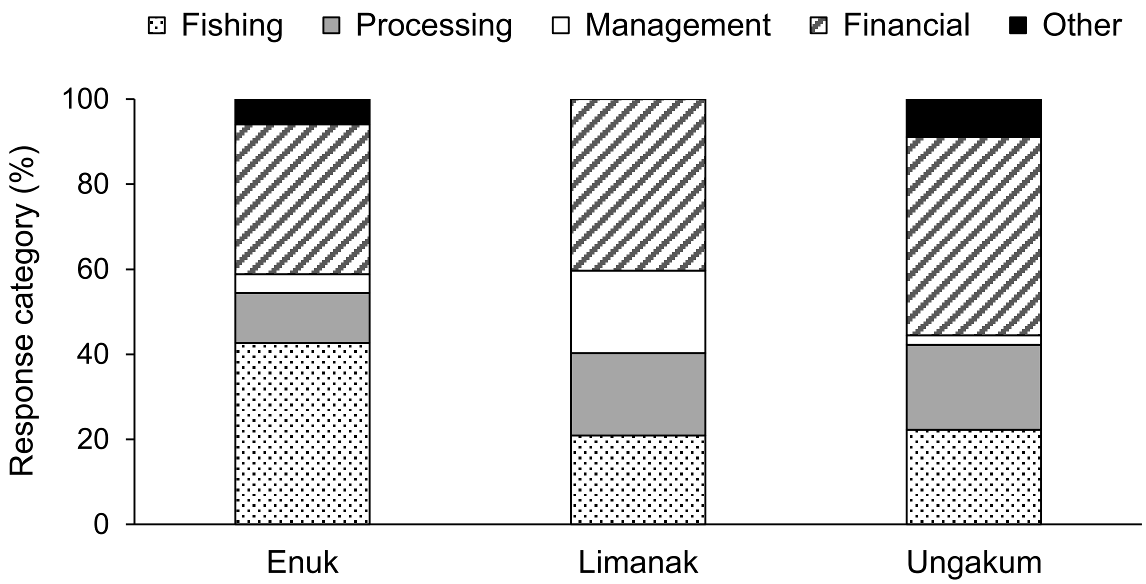


Figure 2.6 Percentage of household responses per community for each category of desired changes to practices associated with the sea cucumber fishery and BDM trade.

Post-fishery household surveys and KI interviews probed into outsider fishing of sea cucumbers, this being a recurring theme in *Pre-fishery* and *Fishery* surveys. Two common types of outsiders were identified: (1) 'Poachers': fishers who reside outside the community and enter community fishing grounds without permission to harvest sea cucumber; and (2) 'Insider-outsiders': fishers who temporarily relocate to the village during the open season for the purpose of harvesting sea cucumber. Insider-outsiders were ex-residents or people who had connections to the community through relatives (*wantoks*) or marriage (*tambus*).

During the *Fishery* period, Enuk respondents mostly reported poaching on islands within their fishing grounds or were unaware of outsiders (Fig. 2.7). There were few concerns raised in *Pre-fishery* surveys and minimal effort made to stop poaching, possibly due to the difficulty of enforcement on uninhabited islands. Two households, however, imposed informal 'tambu' zones (i.e., banned all fishing) in the sea adjacent to their houses. Limanak predominantly reported insider-outsiders (Fig. 2.7), also an issue of concern before the moratorium. Ungakum reported roughly equal numbers in all categories and were the only community to mention outsiders with reciprocal rights (some nearby New Hanover villages are permitted to access Ungakum fishing grounds due to a trading relationship). Outsider fishing in Ungakum was not raised in *Pre-fishery* KI interviews and was of minor concern in *Post-fishery* surveys.

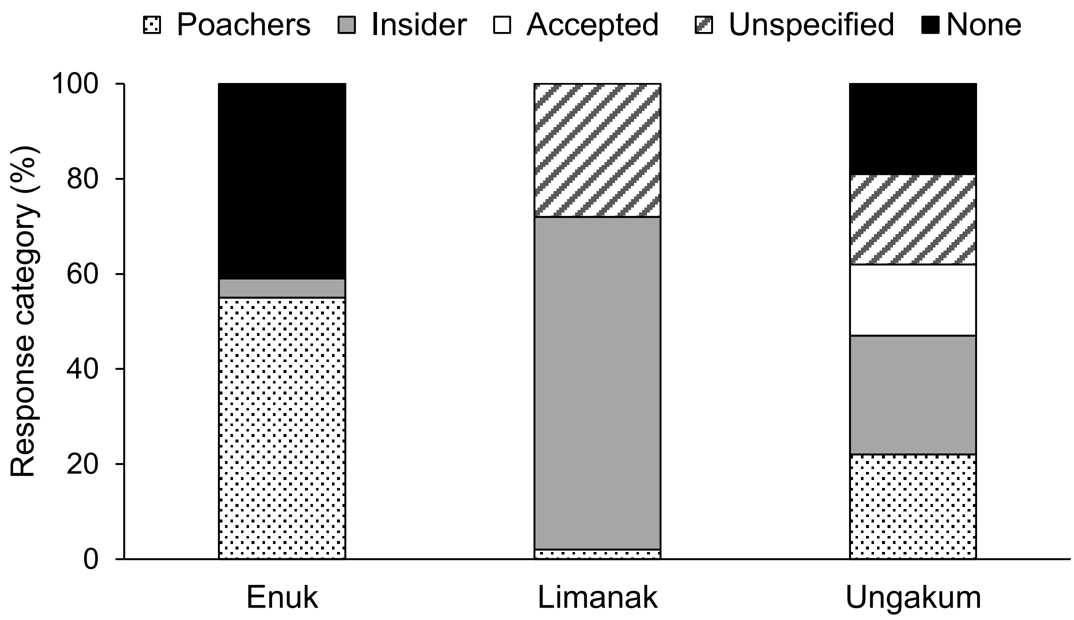


Figure 2.7 Percentage of household responses per community for each category of 'outsider fishing'.

2.3.4 New Ireland Province BDM exports

New Ireland Province traders purchased 68 t of BDM, valued at PGK 4.2 million (approximately USD 1.26 million) from thousands of fishers in New Ireland Province villages during the 2017 open season. Based on recorded village of origin, fishers from Enuk sold 1,886 kg of BDM earning PGK 101,700; fishers from Limanak sold 2,943 kg of BDM earning PGK 171,000; and fishers from Ungakum sold 1,458 kg of BDM earning PGK 100,640. Prices received for sandfish BDM were higher than for non-sandfish BDM (Fig. 2.8) with Limanak recording the highest mean price. Proportionally more sandfish BDM was sold by Ungakum fishers (52% compared to 9 and 17% for Enuk and Limanak, respectively). Traders complained about the quantity of undersized and badly processed BDM offered for sale in the 2017 season, echoing complaints from *Pre-fishery* interviews (Chapter 1).

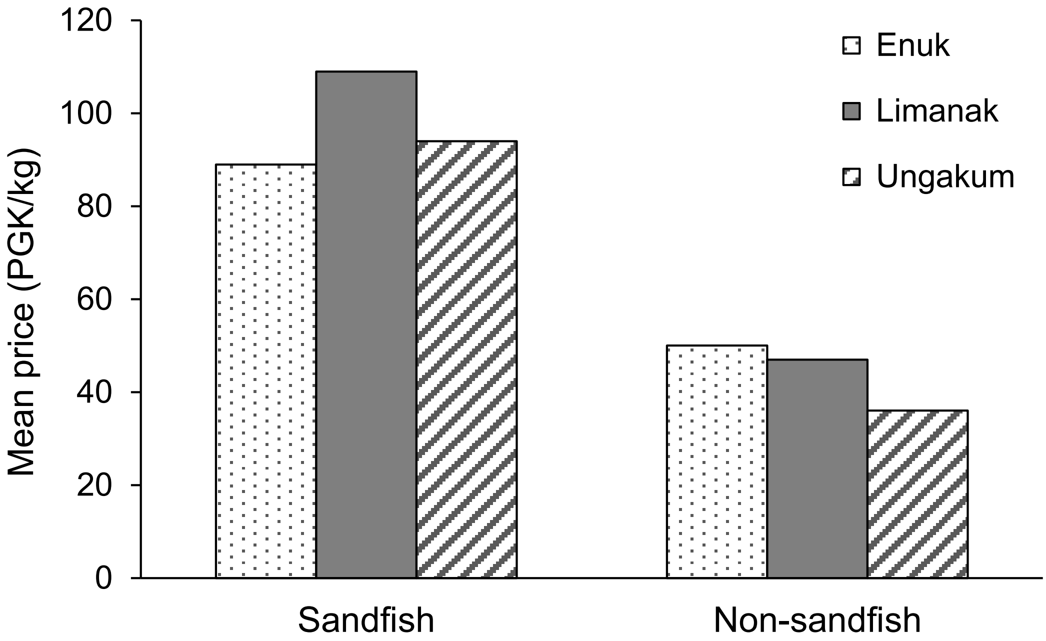


Figure 2.8 Mean price (PGK/kg) received for sandfish BDM and non-sandfish BDM by Enuk, Limanak and Ungakum fishers.

2.4 Discussion

2.4.1 The 2017 sea cucumber fishery and BDM trade

Following the extended moratorium, sea cucumber stocks were partially restored in shallow, nearshore waters in New Ireland Province. The re-opening of the fishery with high BDM prices created a bonanza, dominating community life at the expense of other subsistence and income-earning activities. A large cross-section of the community participated in the fishery (Hair et al. 2018). However, much undersized and poorly processed BDM received lower prices or was rejected outright, reducing returns for fishers. Income results need to be viewed with caution due to not sampling the exact same households in each fishery period, and some risk that the observed changes may be due to changes in the sample characteristics. Nonetheless, the two-month sea cucumber fishing season injected more than PGK 4 million into New Ireland Province households, with more than PGK 370,000 earned in the three study communities over the course of the season. This study estimated average weekly household income across the three communities to be PGK 413 during the fishing season. This compares favourably with the minimum weekly wage for salaried workers in PNG of around PGK 140[10] and the official weekly income of PGK 111[11], while noting that more than 40% of the population live on less than PGK 30 per week.

Few studies have directly quantified the income of sea cucumber fishers in the Pacific Islands region (but see Ramofafia 2004, Purcell et al. 2018a, Kinch 2020). However, numerous sources suggest that communities endure financial hardship when the fishery is closed, due to fewer and less lucrative alternative livelihoods (Foale 2005, Kinch et al. 2007, Christensen 2011, Barclay et al. 2016, Kinch 2020). Purdy et al. (2017) found that New Ireland Province households compensated for lost BDM income by increasing seafood sales and were not financially disadvantaged by the sea cucumber moratorium (noting that their income baseline was from a depleted pre-moratorium fishery). Conversely, Vieira et al. (2017) reported that income from marine resources in the Louisiade Archipelago of Milne Bay Province fell by 92% when the sea cucumber moratorium was introduced, and increased seafood and sharkfin sales did not make up the shortfall. The present study quantified the significantly higher incomes resulting from the 2017 post-moratorium sea cucumber season in three New Ireland Province communities—many fishers claimed to have earned more money than they had ever seen before. Barclay et al. (2016) suggested that sea cucumber wealth was disproportionately held by young men and resulted in few long-term benefits to the community. Results of this chapter, however, suggest that benefits were somewhat better distributed and satisfaction with the fishery was high across different genders and age groups. Concurrent sea cucumber fishery monitoring also reported that a wide cross-section of the community participated in the New Ireland Province fishery (Hair et al. 2018). Further, most fishers believed that their standard of living was improved by making changes to their diet, clothes, material possessions and housing. Initial spending was unsurprisingly on store-bought foods. The consumption of rice and tinned fish supplanted garden food and fresh fish during the *Fishery* period, highlighting a desire for these foods when income is adequate and less time available for sourcing and preparing 'traditional' foods owing to heightened fishing activity (Saweri 2001, Christensen 2011, Fabinyi et al. 2017, Kinch 2020).

---

[10] https://tradingeconomics.com/papua-new-guinea (accessed 2/2/2019)
[11] Based on per capita income of USD 1,790 (PGK 5,774) http://www.pg.undp.org/content/papua_new_guinea (accessed 2/2/2019)

As the season progressed and more money was earned, durable assets were purchased, such as gear for general fishing activities (e.g., nets, outboard engines), capital for non-fishing businesses (e.g., fuel sales, canteens) and house construction. The desire for a permanent house is an increasingly high priority in modern Melanesian society (Macintyre and Foale 2004, Smith 2018) and was a recurrent theme in this study. It requires significant capital but is long-lasting, has practical benefits (e.g., rainwater collection from iron roofing), while signalling prestige and modernity. Revenue derived from the fishery enabled many fishers to undertake full or partial construction of a permanent house. Conversely, some fishers spent their income on consumable items and recreation (cf. Barclay et al. 2016), while others claimed they were caught off-guard by the brevity of the season, restricting their capacity to purchase assets. Alcohol consumption and drunken anti-social behaviour were widely reported (despite the difficulty of obtaining unbiased reports, see Foale 2005). Other social problems, such as domestic conflict and gambling (Barclay et al. 2016) were not reported or observed (also see Kinch 2020).

2.4.2 Sandfish: A premium marine resource

In contrast to most marine resources harvested for subsistence and artisanal purposes in the community, sea cucumbers are usually exported. It is one of the 'readily profitable' but easily depleted fisheries identified by Barclay and Kinch (2013). While artisanal seafood fishing remains an important livelihood for many community members (Purdy et al. 2017, this chapter), financial returns are restricted by proximity to markets (in the absence of refrigeration), plus fluctuating prices owing to local supply and demand. BDM, on the other hand, is non-perishable, has a guaranteed immediate sale and high value (described by one KI as 'fast money'). The commodification of sea cucumber has also resulted in communities exerting stronger proprietary rights to this resource (see Otto 1998, Kinch 2020).

Among traded sea cucumber species, sandfish 'punches above its weight' in income generation. It requires a more complicated and lengthy processing method (Purcell 2014a, Ram 2018), but remains the most valuable tropical species fetching an average retail price of USD 369 per kg in China in 2016, with exponentially higher prices for larger individuals (Purcell et al. 2018b). The premium position of sandfish in the study area is confirmed by past harvest levels (Lokani 1996b, Friedman et al. 2008a, Chapter 1), fishers' declared preference (interview data) and targeted fishing for this species in the 2017 season (Hair et al. 2018).

2.4.3 *Wild sea cucumber fishery and community-based mariculture*

This study contributes to understanding the value of the wild sea cucumber fishery in New Ireland Province and provides important information for management. The inherent and intractable difficulties in the sustainable management of wild sea cucumber fisheries due to high demand, ease of harvest and various biological characteristics are well known (Uthicke et al. 2009, Anderson et al. 2011, Purcell et al. 2014b, Eriksson et al. 2015). Even though the moratorium did effect a partial recovery prior to the 2017 season (Hair et al. 2018), further recovery may be jeopardised if the fishing practices reported for the 2017 season, including exceeding the TAC and harvesting undersized animals, continue in future seasons (Carleton et al. 2013, Pakoa et al. 2013). As suggested in Chapter 1, sandfish sea ranching has potential to co-exist with the wild fishery as a complementary and more sustainable mode of exploitation (Purcell et al. 2012b). The socio-economic parameters described in this study can instruct the development of mariculture-based livelihoods and also provide a baseline for future comparisons.

Alternative livelihoods in developing countries work best with a familiar resource, strong financial incentives, cultural compatibility, low investment and realistic time and labour demands (e.g., Stevenson and Irz 2009, Slater et al. 2013, Curry et al. 2015, Steenbergen et al. 2017a). Research from PNG (Chapter 1, this chapter) and elsewhere (Juinio-Meñez et al. 2012a, Robinson and Pascal 2012) suggests that sandfish mariculture is well-positioned to meet these criteria. From a technical perspective, community-based sea ranching is a simple and low-cost mariculture intervention: cultured juveniles are released into an unenclosed area that is designated as the community 'sea ranch'; they are protected until they reach commercial size (≥ 400 g)[12]; then they can be harvested, processed and sold (Purcell et al. 2012b). Key to the success of this activity is the community having sole, exclusive access rights to the ranch and selecting suitable habitat to maximise retention of individuals within sea ranch bounds, given their naturally low dispersal rates (Purcell and Kirby 2006, Lee et al. 2018a). Survival and growth vary with juvenile release size and habitat quality (Purcell and Simutoga 2008, Tsiresy et al. 2011, Kumara and Dissanayake 2017, Ceccarelli et al. 2018, Chapter 3), and small juveniles may require protection against early mortality (Dance et al. 2003, Lavitra et al. 2015,

[12] Weight for a commercial sandfish varies between countries. Based on the PNG minimum legal length of 22 cm, length-weight data collected in the study area (Chapter 6), and regional length-weight estimates (e.g., Feary et al. 2015, Lee et al. 2018a), a 400-g sandfish is regarded as minimum commercial size throughout this thesis.

Chapters 3 and 5). However, sandfish mortality decreases as they grow and with no need for supplementary feeding, inputs from the community during grow-out to commercial size are minimal. In socio-economic terms, benefits from a sea ranch must exceed the costs of creating and maintaining it, and opportunity costs must also be considered if fishing grounds are lost through establishment of a ranch. Finally, sandfish sea ranching is unlikely to sustain ongoing individual high incomes but is more likely to contribute to a portfolio of livelihoods, a strategy shown to increase income security and resilience (Allison and Ellis 2001, Mills et al. 2011b). The salient issues around sea cucumber mariculture are, therefore, likely to be in the human dimension: social acceptance and adoption, sensible and effective community-based management, and equitable distribution of both costs and benefits (Krause et al. 2015).

Development and enforcement of sound management measures are equally important for sandfish mariculture as for the wild fishery (Purcell et al. 2012b). These include measures to ensure that optimal value is extracted from the resource by harvesting larger sandfish (Purcell et al. 2018b) and that benefits are equitably distributed. Results from the 2017 sea cucumber fishery season raise concerns for the former. In New Ireland Province, poor BDM processing and harvest of undersized sea cucumbers constrained profits for fishers. A lack of awareness underpinned these problems, highlighting an urgent need for information on sustainable harvesting and improved processing practices. These difficulties were exacerbated by the influx of inexperienced fishers with substandard processing skills, in addition to informed, experienced fishers seeking a fast (low-value) sale. Traders reported similar problems during pre-moratorium times (see Chapter 1). The persistence of these practices in 2017 suggests that fishers were focused more on catch volume than optimal prices, a version of 'race to fish' behaviour (Gordon 1954).

Under a sea ranching scenario, it would be expected that community leaders will regulate who has harvest rights, when the ranch can be accessed, and which animals can be harvested. It is reasonable to assume that harvest will be restricted to community members. Sea ranch harvest frequency might be 'never' (i.e., aimed at producing spill-over into outside open areas), 'annual', 'random' (e.g., fundraising events) or 'year-round', all of which require control of access. Issues experienced with outsider fishing in the 2017 wild fishery will therefore affect sea ranch operations, especially if wild sea cucumber catches dwindle and sandfish become depleted, as in the past (Hair et al. 2018, Chapter 1). Sea ranches should therefore be located close to villages and additional security measures introduced (Juinio-Meñez et al. 2012a, Robinson and Pascal 2012). Although Purdy et al. (2017) recorded an increase in Tigak Island households enforcing access rights to community fishing grounds in 2014, effective CBFM will be harder to enforce for the much higher value sea cucumber fishery (Sulu et al. 2015, Barclay et al. 2019). Among other things, the capacity to enforce management measures depends on proximity to town, past experiences, local politics and relationships with neighbouring communities (Otto 1998, Allison and Ellis 2001, Foale et al. 2011, this chapter). The unique circumstances of any community engaging in mariculture must be considered in deciding how to mitigate against poaching. Equitable distribution of benefits from communally cultured sandfish must be carefully managed to establish trust in sea ranching as a community activity and to maintain support for the operation. Furthermore, just as the large individual incomes obtained in the 2017 wild fishery are likely to decline in future fishing seasons, sandfish ranchers must also be realistic about financial returns from this activity.

There are obvious ways in which stocking of cultured sea cucumber juveniles into suitable habitat under community control might deliver benefits. Regular releases of juveniles can buffer the effects of irregular recruitment events and overfishing, enabling a predictable harvest and sustaining a regular income stream. In New Ireland Province, men and women fish for sea cucumber, although there are often gender differences in harvest method, habitats fished, species harvested and income (Friedman et al. 2008a, Lawless and Frijlink 2016, Purcell et al. 2016a, Purcell et al. 2018a). Sandfish mariculture may produce a more egalitarian system if sea ranches are located close to villages in accessible waters (noting high participation by women and the elderly in the 2017 sea cucumber fishing season). Depending on how fisheries regulations are framed, communities might avoid the race to fish, instead harvesting when it can provide most benefit to them (Purcell et al. 2018b, Chapter 1). Options include a quota system for individuals or family groups (sensu Preston 1992) or harvest for whole-of-community benefit. The success of any model, however, relies on the ability to control access to the ranch and a commitment to extract maximum benefit through sale of large, well-processed BDM. Unfortunately, these were not features of the 2017 wild fishery.

Various models of community or corporate sea cucumber mariculture operate in other countries. In the Maldives, northern Australia and Madagascar, private hatcheries produce juvenile sandfish that support community livelihoods in addition to supplying commercial grow-out operations (Bowman 2012, James 2012, Robinson and Pascal 2012). In the former, sandfish are either purchased back from individual farmers or resource-owners are paid for their role in the production process. In Vietnam, farmers purchase sandfish juveniles from private hatcheries, then rear them to commercial size in ex-shrimp ponds (Duy 2012). In the Philippines, sea ranches are leased and managed by a community group, juveniles supplied by public sector hatcheries, and profits distributed to those who work the lease (Juinio-Meñez et al. 2012a). In some places, failed mariculture ventures have left communities cautious about involvement in sea cucumber aquaculture (Hambrey et al. 2011, Slater et al. 2013, von Essen et al. 2013) In PNG, routine hatchery production of juvenile sandfish for mariculture research occurs at NIMRF. Production and distribution are the responsibility of the NFA and there is currently no commercial imperative, although this may change in the future should production be scaled up, if cost recovery is sought or if the private sector becomes involved. However, success of this activity in PNG relies on the capacity for 'communities' to function as cohesive social, political and economic units – a goal which may be elusive.

2.5 Conclusions

The 2017 sea cucumber fishing season made a significant financial contribution to coastal communities in New Ireland Province, and has the potential to do so in future seasons, particularly if management practices are improved (Barclay et al. 2016, Hair et al. 2018). The importance of sandfish in the study area has been highlighted, but the prognosis for wild stocks of this species is dire, given its history of over-exploitation (Hamel et al. 2013, Hair et al. 2018, Chapter 1). Accordingly, the opportunity to farm sandfish to obtain a modest, consistent income is considered here, but successful uptake will depend on adoption of approaches that optimise financial returns through sound, effective management. This study suggested a more responsible attitude to spending the large earnings from BDM, which had a positive impact on village life with relatively few negative consequences. However, careless processing, fishing of undersized sea cucumber and ineffectual CBFM remain issues of concern. Although community sandfish mariculture can be economically successful (Klückow et al. 2017), it does have risks, and many externally-supported projects fail (Barclay and Kinch 2013, von Essen et al. 2013); however, sandfish sea ranching has an added advantage in closely mimicking a very high-value wild fishery. Continuing research is aimed at developing a viable model for sandfish mariculture in PNG through resolving technical bottlenecks while addressing the social barriers that limit community uptake of sea ranching. Some of these aspects are investigated in later chapters of this thesis.

Chapter 3
Optimising methods for sea ranching of sandfish in seagrass meadows: release methods and habitat selection[13]

3.1 Introduction

As outlined in Chapter 1, community-based sandfish sea ranching has potential as a sustainable livelihood activity in Papua New Guinea (PNG), particularly if the sea cucumber fishery continues to open annually and fishing effort remains high as observed in the first two post-moratorium sea cucumber seasons (Hair et al. 2018, Chapters 2 and 7). In the context of this thesis, this low-technology mariculture activity involves release of juveniles into nearshore ocean environments under traditional marine tenure in a 'put, grow, and take' operation. However, its successful development depends on resolving a number of technical and social constraints (Eriksson et al. 2012, Purcell et al. 2012b). In terms of production, it is crucial to maximise the number of cultured sandfish juveniles that reach commercial size in the shortest time. The greatest mortality in release of cultured juveniles occurs immediately following liberation (Dance et al. 2003, Purcell and Simutoga 2008, Lavitra et al. 2009). Mortality is inversely related to the size of the released juvenile (Purcell and Simutoga 2008) but small juveniles are cheaper to produce and transport (Raison 2008). Case studies report variable and often low survival of sandfish juveniles after release into the sea (Purcell et al. 2012b), for example: 20–30% in sea ranches (Juinio-Meñez et al. 2012c, Juinio-Meñez et al. 2013) and 0–65% in sea pens in the Philippines (Juinio-Meñez et al. 2017); 0–80% in pens and sea farms in Madagascar (Robinson and Pascal 2012, Rougier et al. 2013); 20–40% in small sea pens in Fiji (Hair et al. 2011); 14% from field releases in northern Australia (Taylor et al. 2016); and less than 15% in lagoonal sea ranches in the Maldives (James 2012). Purcell et al. (2012b) suggested 10–20% survival of 3–10-g juveniles as a benchmark in sea ranching operations.

Reasons for poor recovery of sea cucumber juveniles in ocean-based mariculture include predation, transport stress, freshwater inundation, being washed away by strong currents, climbing or floating escape from enclosures and extreme weather (Purcell 2004, Robinson and

---

[13] Data from this chapter were published as: Hair, C., Mills, D., McIntyre, R. and Southgate, P.C. (2016). Optimising methods for community-based sea cucumber ranching: Experimental releases of cultured juvenile *Holothuria scabra* into seagrass meadows in Papua New Guinea. *Aquaculture Reports*, 3, 198–208. https://doi.org/10.1016/j.aqrep.2016.03.004

Pascal 2012, Uekusa et al. 2012, Hamel et al. 2019). Predation is most frequently cited as the major cause of juvenile mortality (Bell et al. 2005, Lavitra et al. 2009, Robinson and Pascal 2012, Yu et al. 2015). Sea cucumber predators include fish, crustaceans, sea stars and gastropods (Kropp 1982, Francour 1997, Dance et al. 2003, Zamora and Jeffs 2013). Of these, fish and crustaceans have been most problematic to mariculture activities (Lavitra et al. 2009, Eeckhaut et al. 2020). Measures adopted to minimise predation commonly fall into four categories: (1) release of larger juveniles; (2) improved methods of release; (3) removal of predators; and (4) protection from predators. Size at release is inversely related to the risk of predation (Bell et al. 2005, Purcell and Simutoga 2008). The minimum recommended release size of 3 g for sandfish was made after observing total mortality among 1-g juveniles in an experimental release (Purcell and Simutoga 2008) and this standard has been adopted in other studies in the Indo-Pacific region (e.g., Juinio-Meñez et al. 2013, Taylor et al. 2016, Ceccarelli et al. 2018, this study). Alternatively, large-size sea cucumbers can be released in mariculture operations to minimise predation; e.g., juvenile *Apostichopus japonicus* > 5 cm (Chen 2004, Zhang et al. 2015), and 15–30-g sandfish (Rougier et al. 2013, Eeckhaut et al. 2020). However, survival of 0–5-g juveniles was not significantly different to that of 15–20-g juveniles in an ocean farming situation where predators were not abundant (Lavitra et al. 2015).

Attention to the time and manner of release, e.g., handling, transport, release site habitat, and liberation protocol including adequate on-site acclimation, can also improve survival (Purcell 2004, Rougier et al. 2013, Zamora and Jeffs 2015). For example, sand conditioning (acclimation to sand prior to release) of hatchery bred juveniles led to increased burying activity (i.e., predator avoidance) in the first hour after release (Juinio-Meñez et al. 2012a). Dance et al. (2003) suggested releasing juveniles at night when fish predators are less active, however, Robinson and Pascal (2012) reported heavy predation by crabs during night releases. Removal of predators can also improve survival. Higher survival of juvenile sea cucumbers (40–85%) has been reported from ponds where predators are removed prior to stocking (e.g., Agudo 2012, Duy 2012, Yu et al. 2015). Also, culling of crabs from sandfish farming enclosures significantly reduced loss from predation (Lavitra et al. 2009, Rougier et al. 2013). However, in extensive, open sea ranches, predators will be less easily controlled by hunting.

Some success in reducing predation of juvenile sea cucumbers released into the sea has been demonstrated with the use of cages to exclude large predators (Dance et al. 2003, Purcell 2004). In some Madagascan sea farms, predation can be so intense that 15-g cultured juveniles are reared in covered nursery pens until they reach about 50 g in size (Robinson and Pascal 2009, Rougier et al. 2013). The benefit of caging newly released juveniles may extend beyond simple predator exclusion if naïve, hatchery-produced juveniles are provided a chance to acclimate to the wild and normalise behaviours such as seeking shelter, predator avoidance and feeding (Purcell 2004, Purcell 2010b, Palomar-Abesamis et al. 2017). In the case of sandfish, protection from predators until their normal diel burying regime is established may be advantageous.

Ocean mariculture success also relies on releasing cultured sea cucumber into optimal habitat where there will be high survival and strong growth (Plotieau et al. 2013, Zamora and Jeffs 2013, Zhang et al. 2015, Juinio-Meñez et al. 2017, Ceccarelli et al. 2018). This presents a substantial challenge because cultured juveniles of 3–15 g are released into the sea with the aim of harvest at commercial size (≥ 400 g) between one and two years later. High initial survival is desirable, but grow-out habitat must also support growth at different life stages that have shifting requirements (Hines et al. 2008, Ceccarelli et al. 2018). Observations and field studies of juvenile sandfish in the wild and in captivity indicate that sparse to medium seagrass habitats with muddy-sandy substrate of moderate penetrability and low in organic matter, minimum 20 centimetres (cm) depth at low tide, minimal freshwater input and populated by varied invertebrate fauna, are favourable for juvenile sandfish (Mercier et al. 1999, 2000b, Shiell 2004, Purcell and Simutoga 2008, Lavitra et al. 2010, Tsiresy et al. 2011, Altamirano et al. 2017, Ceccarelli et al. 2018). There is also a growing body of literature relating to mineral and organic characteristics of the sediment that promote juvenile sea cucumber growth. The roles of benthic microalgae, organic matter, microorganisms (e.g., bacteria), grain size and so on, are now being studied in more detail (Lavitra et al. 2010, Slater and Jeffs 2010, Plotieau et al. 2014a, Plotieau et al. 2014b, Robinson et al. 2015, Robinson et al. 2019). However, the exact nature of ideal habitat remains unknown and this limits the development of optimal sandfish ocean mariculture methods.

This chapter investigated whether short-term protection from predation would improve survival of cultured sandfish juveniles released into a range of seagrass habitats available in partner communities, where trial sea ranching was proposed. Longer-term data on the biophysical properties of these habitats, and sandfish growth characteristics were also collected. These are important inputs for economic modelling of sea ranching viability. Establishment of trial sea ranches for sandfish in New Ireland communities require careful consideration; knowledge of optimal habitat is important because sea ranches are costly to stock, the associated research is labour-intensive and time-consuming, and there are social implications, such as inflated expectations and potential for conflict within communities.

3.2 Materials and methods

3.2.1 Study area

The study sites were adjacent to island communities collaborating in sandfish sea ranching trials, i.e., Enuk, Limanak and Ungakum (Fig. 2.1). All communities had sandfish fisheries in their fishing grounds, as described in Chapter 2.

3.2.2 Experimental sea pens

Circular experimental sea pens of 100 m^2 area were installed at four village locations; two sea pens at Limanak (Limanak-1 and Limanak-2), and one each at Enuk and Ungakum (Fig. 3.1). Sea pens were constructed from rigid plastic mesh (3-mm pore size) held in place with wooden stakes and not covered. They were designed to retain sea cucumbers within natural habitat while predation, water exchange and food supply occurred as they would outside the pen (Purcell et al. 2012b). Escape by 3-g juveniles was minimised by digging the base of the pen mesh 15 cm into the substrate to prevent them from burying underneath, while 30 cm of mesh wall extended above the substrate, the upper inside edge of which was painted with a 10-cm strip of antifoul to discourage climbing (Purcell and Simutoga 2008). The large pen size was chosen in order to facilitate monitoring over an extended period until sandfish reached adult size. Pens of larger area and low profile are less prone to cage effects (Miller and Gaylord 2007). Pens were installed in areas that retained water at low tide, with minimum depths of ~20 cm, except Limanak-2, which was slightly shallower (~10 cm at extreme low tides).

Pens were intentionally positioned within sites that differed from each other in habitat characteristics, but all fulfilled the optimal release criteria of Purcell and Simutoga (2008) with respect to depth, substrate and seagrass presence/species type. The Limanak-1 site was characterised by patchy *Cymodocea rotundata* and *Enhalus acoroides* seagrass, and Limanak-2 was more sandy with patches of sparse *C. rotundata*, *Thalassia hemprichii* and *Halodule uninervis*. The Enuk sea pen enclosed sparse but homogeneous *E. acoroides* and the Ungakum sea pen had a large patch of *E. acoroides* in sandy substrate. Enuk and Ungakum sea pens were located in channels between two islands. Wild sandfish were observed at all sea pen sites.

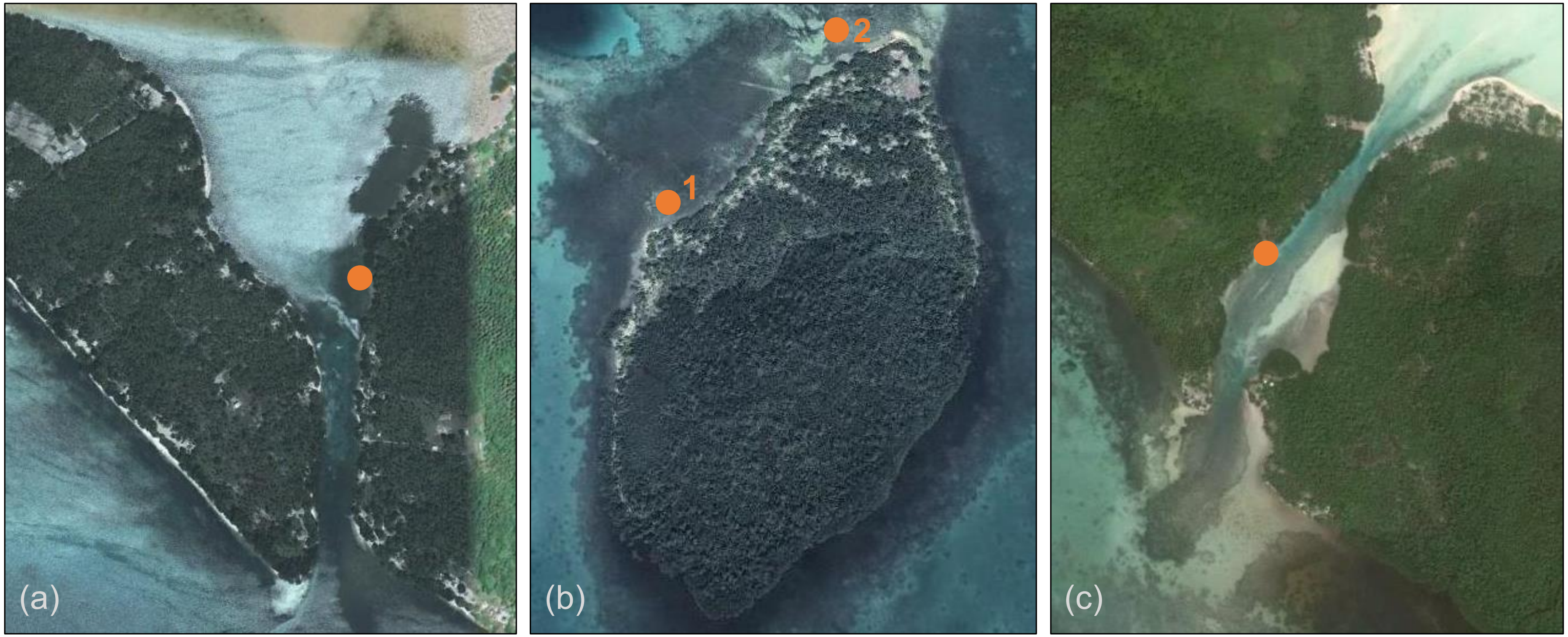


Figure 3.1 Approximate location of experimental sea pens (denoted by orange spheres, not to scale) near partner communities at: (a) Enuk; (b) Limanak (1 and 2); and (c) Ungakum (refer to map Figure 2.1 for island locations).

Site selection was decided in consultation with each community to garner local knowledge and to be mindful of community amenity aspects, customary marine tenure and security issues. Issues around working within communities precluded sea pen replication because of concerns over boat traffic (i.e., inconvenience to community members and risk of damage from outboard engines) and reduced access for fishing. Community 'wardens' were employed at all sites to clean biofouling from the mesh walls and report any problems. Liaison with wardens and VPC members occurred regularly to ensure that there were no problems with respect to the presence of sea pens and research operations.

3.2.3 Source of sandfish juveniles

Sandfish juveniles were produced at NIMRF, using the hatchery protocols of Duy (2010) and reared to at least 3-g body weight in ocean hapa nets (sensu Juinio-Meñez et al. 2012c). Prior to being released into pens for experiments, juveniles were batch-marked using fluorochromes (Purcell and Blockmans 2009). Groups of juveniles of 3–20 g body weight were fluorochrome-tagged with either tetracycline, calcein or calcein-blue, then transferred to separate raceways with substrate for recovery for 10 days prior to release.

3.2.4 Cage release experiments

Protective cage release experiments were conducted within the four 100-m^2 sea pens. Protective cages were designed for predator exclusion, not to prevent escape of sandfish juveniles. They were constructed from rigid plastic mesh sewn onto a metal frame (6-mm pore size, length = 90 cm, width = 90 cm, height = 20 cm with no floor; Fig. 3.2). Two protective cages were positioned in the centre of each sea pen with the lower edge pushed into the substrate to a depth of 1–2 cm (Fig. 3.2). To ensure release habitat was not a confounding factor, similar habitat was used for the free release and protective cage treatments within each sea pen. The release habitat in Limanak-1 and Limanak-2 sea pens was sand with sparse, short seagrass; Enuk was *E. acoroides* (the long-bladed seagrass was bunched inside the cage for the protective treatments); and Ungakum was bare sand.

Experiment releases were staggered because of reliance on hatchery production of juveniles in the desired size range. The Limanak-1 release was in March 2014, Limanak-2 and Enuk in May 2014, and Ungakum in July 2014 (Table 3.1). Fluorochrome-tagged juveniles that had been starved overnight to void their stomach contents were packed into separate, labelled plastic bags with seawater and oxygen, and transported in an insulated container to each site.

After a 20-min acclimation period, 201 sandfish juveniles were released into the central zone of each sea pen as follows: n = 67 tetracycline-marked juveniles were liberated directly onto the substrate with no cage protection (free-release); n = 67 calcein-marked juveniles were transferred through a trapdoor into one cage labelled '1-day' (one-day protection); and n = 67 calcein-blue-marked juveniles were transferred through a trapdoor into the second cage labelled '7-day' (seven-day protection). Thus, there was one replicate of each treatment within each sea 100-m^2 sea pen.

The free-release sandfish juveniles were observed until they started to move or bury. Sandfish interaction with potential predators was noted but not prevented, although predators were removed from the cage interior if seen during deployment. The one-day protective cage was removed from each sea pen after 24 h and the seven-day protective cage was removed from each sea pen after one week.

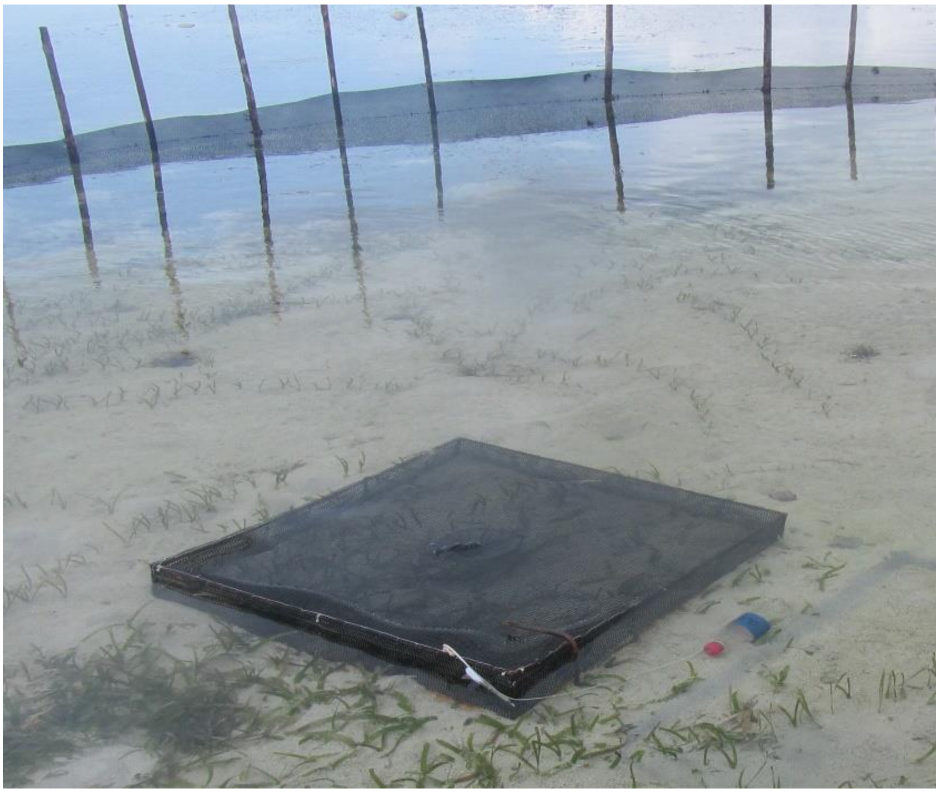


Figure 3.2 Release cage within a sea pen at the Limanak-2 site.

Table 3.1 Sampling schedule for experimental pens.

Sample Time	Limanak-1	Limanak-2	Enuk	Ungakum
0 (release)	Mar 2014	May 2014	May 2014	July 2014
2-Month	May 2014*	July 2014	July 2014	Terminated
4-Month	July 2014	Sept 2014	Sept 2014	
6-Month	Sept 2014	Oct 2015	Oct 2015	
9-Month	Dec 2014	Terminated	Jan 2015	
12-Month	Feb 2015		Apr 2015	
15-Month	May 2015		Aug 2015	
18-Month	Aug 2015		Nov 2015	
21-Month	Nov 2015		Terminated	
24-Month	Feb 2016			

* *Sandfish growth data only, not habitat data*

3.2.5 Survival and growth data collection

Data on long-term sandfish survival and growth were obtained by monitoring sandfish within sea pens until they reached commercial size (or until the pen was terminated for other reasons). Sandfish within each pen were sampled at 2-month intervals for four months for the cage-release experiment, and thence approximately 3-monthly for a maximum of two years for long-term monitoring (Table 3.1). Sampling was always done in the late afternoon and early evening on a rising tide when juvenile sandfish were most likely to be on the surface (Mercier et al. 1999, Purcell 2010). A snorkel diver thoroughly searched the entire pen several times, retrieving sandfish as they emerged from a buried state. Searching was discontinued when no new individuals were found within a 30-min period. Sandfish were handled gently and kept submerged until they reached the sampling station to minimise bloating with seawater or evisceration. Once they were removed from the water, they were left to drain for two min and then weighed to the nearest 0.1 g. After measurement, about 5 mm^2 of skin was shaved from the ventral surface of each individual, preserved in 70% ethanol, and stored in a cool, dark place until processing to check for the presence and type of fluorochrome tagged ossicles (Taylor 2016). All sea cucumbers were returned to their pen after sampling was completed.

Sandfish weight measurements were taken of the same group of sandfish on each sampling occasion but individuals were not differentiated. The daily growth rate (g day^{-1}) was calculated using the mean individual size of the group from the previous sample time as follows:

$$GR = (WW_t - MnWW_0)] / t$$

where WW_t is individual wet weight in grams after t days and $MnWW_0$ is mean initial wet weight in grams.

The specific growth rate (SGR, %) was calculated using the mean individual size of the group from the previous sample time as follows:

$$SGR = 100 * [\ln (WW_t - MnWW_0)] / t$$

Sea pen density was estimated by summing individual weights of all sampled sandfish and dividing this biomass by the pen area to obtain density in grams of sandfish per square metre.

A number of tagged juveniles were maintained at the hatchery to monitor the persistence of the fluorochrome tags for a 6-month period. These individuals were checked at the first three sampling occasions to verify that fluorescent ossicles remained visible.

3.2.6 Biophysical data collection and analysis

Data on sea pen habitat were collected at the time of sea pen installation and thence at each sandfish growth sampling occasion. Biophysical properties related to seagrass and substrate characteristics were recorded from five haphazardly thrown quadrats (0.5 x 0.5 m) in each sea pen, and comprised: seagrass species present; percentage total cover of seagrass to the nearest 5%; average canopy height of the dominant seagrass species (discounting the tallest 20% of leaves); epiphyte load (estimated from proportion of the leaf surface covered with epiphytes, and proportion of leaves with epiphytes, after McKenzie and Campbell 2002); penetrability in cm (measured using a pointed metal rod dropped from a standard height); and presence, depth and subjective strength (light, moderate, strong) of an anoxic layer. Sediment cores were collected from within each quadrat using a cut-off 60 millilitre (mL) plastic syringe (internal diameter 2.9 cm). Sediment from surficial 1-cm cores (n = 2 cores combined) were analysed for chlorophyll-*a* content as a measure of benthic microalgae. Sediment from surficial 2-cm cores (n = 5 cores combined) were analysed for organic matter (OM) content and grain size.

Sediment for chlorophyll-*a* analysis was kept in the dark and on ice in the field, transferred to a freezer, and processed within 30 days (ISO 1992). Approximately 2 g of each sample was weighed into a 15-mL centrifuge tube and 5 mL of 95% ethanol added. The sample was mixed on a vortex stirrer, stood in a 60ºC water bath for 1 h, and left to extract for 12 h at room temperature. After extraction, the sample was inverted to disturb any gradient and centrifuged for 8 min at 4,000 rpm. The supernatant was measured in a spectrophotometer at 665 and 750 nanometres (nm) against a 95% ethanol blank. After measurement, the sample was oven-dried at 60ºC to obtain the dry weight. Chlorophyll-*a* concentration (µg/g) was calculated using the formula of Nusch (1980).

Sediment for OM and granulometric analyses was dried in a 60ºC oven to a constant weight. For OM determination, the loss on ignition (LOI) method was employed at 280ºC for the labile OM component[14], and 500ºC for the refractory OM[15], which also included the loss of carbon due to the biogenic carbonate particles of the sediment (Kristensen 1990, Loh et al. 2008). Approximately 3 g of dried sediment (DW) was transferred to a labelled foil envelope, heated in a muffle furnace to 280ºC for 6 h, cooled and weighed to obtain the ash weight (AW_{280}), then heated to 500ºC for a further 6 h, cooled and reweighed to obtain the ash weight (AW_{500}). Percentage OM fractions were calculated using the following formulae:

% Labile OM = 100 * ($DW-AFDW_{280}$);

% Total OM = 100 * ($DW-AFDW_{500}$); and

% Refractory OM = (% Total OM) - (% Labile OM).

Grain size distribution was determined by dry sieving samples through a series of mesh sizes (2000, 1000, 500, 250, 125 and 63 µm) with a mechanical sieve shaker for 10 min, then weighing the fraction retained by each sieve. For reporting purposes and statistical analysis, grain-size classes were combined into four categories: coarse-grained (> 1000 µm); medium-grained (≥ 250–1000 µm); fine-grained (≥ 63–250 µm) sediments; and silt (< 63 µm).

Water temperature (ºC) near the seafloor at all sites was recorded at 4-h intervals by Hobo™ data loggers. Salinity (ppt) was recorded at 4-h intervals by a Star Oddi™ DST logger at the

---

[14] 'Labile' describes organic matter that breaks down easily.
[15] 'Refractory' describes organic matter (e.g., woody debris) that is highly resistant to degradation.

Ungakum and Enuk sea pens. Other descriptive factors comprised proximity to mangrove forests and the village, exposure to tidal currents and wave action.

3.2.7 Limanak-1 sea pen density reduction

Very high survival and growth of sandfish in the Limanak-1 sea pen resulted in pen biomass surpassing the recommended 'Battaglene density' ceiling of 225 g m^{-2} (Battaglene et al. 1999) six months after stocking. To reduce the risk of stunting, the pen density was modified by: (1) installing a new 50-m^2 sea pen to hold some of the experimental sandfish; and (2) splitting the original 100-m^2 sea pen into two 50-m^2 sections using a dividing fence (6-mm pore size). After the Month-6 sampling, sandfish were divided into four identical batches using sandfish of similar size and weight range (according to number and approximate biomass). These were then restocked into the two pens as follows: half the sandfish were returned to a section of the 100-m^2 pen (i.e., original, high density); one-quarter of the sandfish were transferred to the other 100-m^2 pen section (i.e., reduced, low density); and one-quarter of the sandfish were transferred to the new 50-m^2 pen (i.e., reduced, low density) (Fig. 3.3). Monitoring of sandfish and habitat variables continued as usual in all pen sections.

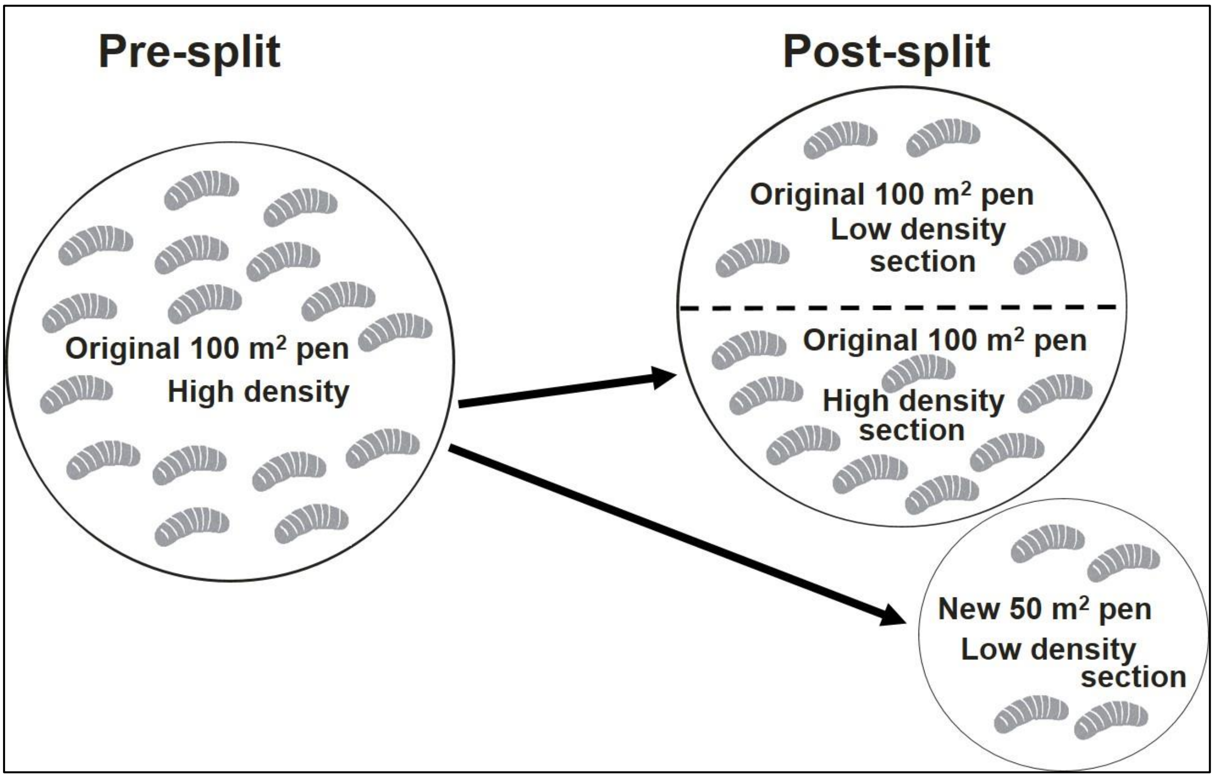


Figure 3.3 Diagram of sandfish density distribution before and after restocking experimental sandfish into the split 100-m^2 and new 50-m^2 sea pens.

3.2.8 Data analysis

Prior to analysis all data were tested for normality and homogeneity of variance with Levene's test at $p \leq 0.05$ (IBM SPSS Statistics 22).

Survival was analysed with one-way analysis of variance (ANOVA) with the cage protection treatment (C = 3) at 2-Month sampling only, as this is the critical early period where mortality occurs. For the cage release experiment, growth of juveniles was analysed with two-way ANOVA with the cage protection treatment (C = 3) and site (S = 3) at 2- and 4-Months. A Tukey's post-hoc test ($p = 0.05$) was used to compare significant differences between survival and growth variables between protection treatments and sea pen sites. For long-term trends, differences in growth of cultured sandfish between the sea pen sites were analysed with ANOVA and with independent samples *t* tests for two sea pen comparisons.

Spatial and temporal patterns in habitat of sea pens were examined using principal components analysis (PCA) to discriminate the sea pen sites (Clarke and Gorley 2006, Anderson et al. 2008). PCAs with eigenvalues > 1.0 were used to describe habitats according to seagrass and sediment characteristics. Significant component loading factors were evaluated using $r < -0.4$ and $r > 0.4$ as cut-off values.

Changes in biophysical parameters through time were analysed using one-way ANOVA. If assumptions of normality and homogeneity of variance were not met, data were transformed. If homogeneity of variance could not be achieved by transformation, raw data were used and $p < 0.01$ was adopted as the significance level.

3.3 Results

3.3.1 Fluorochrome marking of sandfish ossicles

After one week of post-marking recovery at the hatchery, all juveniles were visibly healthy, and showed normal burying and feeding behaviour. All juveniles retained at the hatchery displayed an acceptable proportion of fluorescent ossicles after four months. There was no mortality or differential growth due to the different fluorochrome stains after one month (one-way ANOVA $F = 1.492$, $p = 0.221$). Furthermore, stained ossicles were visible in sandfish skin samples at two years after release into the wild, the longest period reported in the literature to date (see Purcell and Blockmans 2009).

3.3.2 Effects of site and cage protection on survival of released juvenile sandfish

After two months, sandfish were retrieved from sea pens at Limanak-1, Limanak-2 and Enuk, but no sandfish were found at Ungakum. There were significant differences in overall survival between sites (one-way ANOVA, $F = 11.88$, $p = 0.008$): Limanak-1 had the highest survival (93.5%), followed by Limanak-2 (84.6%) and Enuk (52.7%). Overall survival at Limanak-1 was not significantly different to that at Limanak-2 and both were greater than Enuk (Tukey's post-hoc means comparison). Estimated survival at 4-Months was similar to 2-Months (92.5%, 86.6% and 52.7% for Limanak-1, Limanak-2 and Enuk, respectively).

The free-release treatment had the highest survival at all sites (97%, 96% and 66% for Limanak-1, Limanak-2 and Enuk, respectively) (Fig. 3.4), followed by the 7-day protective cage treatment at Limanak-1 and Enuk (95.5 and 52.2%, respectively) and the 1-day protective cage treatment at Limanak-1 (76.1%).

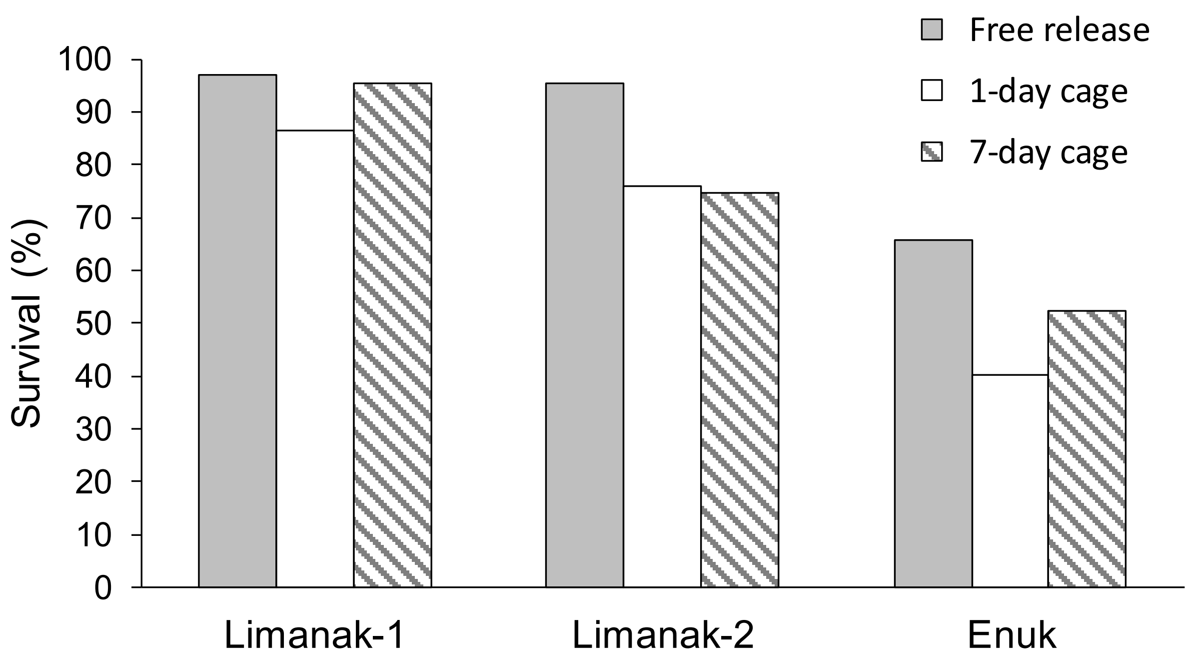


Figure 3.4 Survival (%) of juvenile sandfish from each protection treatment at each site at 2-Months. Free release (solid bars); 1-day cage protection (white bars); and 7-day caged protection (striped bars).

In attempts to discover whether the Ungakum sea pen mortality was due to predation or biophysical factors, two more releases were made in this sea pen. All free-release juveniles died on each occasion, but 93% survival of juveniles was recorded when a batch was released within a fully enclosed mesh basket with roof and floor (C. Hair, unpublished data).

3.3.3 Growth of juvenile cultured sandfish in sea pens

3.3.3.1 Cage release experiment (short-term)

Growth results are reported for Limanak-1, Limanak-2 and Enuk sea pens, where juvenile sandfish survived. There was a significant difference in mean individual weight due to protection treatment at 2-Months but not at 4-Months (Table 3.2, Fig. 3.5). The 2-Month difference arose from variability in sandfish weight at Enuk only.

Mean individual sandfish weight at Limanak-1 and Limanak-2 were not significantly different but both were greater than Enuk at 2-Months (Tukey's means comparisons). By 4-Months, mean weight at Limanak-1 (113.6 ± 2.6 g) was significantly greater than that at Limanak-2 (94.7 ± 2.4 g) and both were greater than that at Enuk (74.8 ± 2.9 g) (Table 3.2, Fig. 3.5).

Table 3.2 Two-way ANOVA results and Tukey's post-hoc means comparisons of mean individual sandfish weight (g) at 2 and 4 Months in the cage-release experiment.

Sampling time	Levene's test	Site	Protection treatment	Interaction	After pooling	Tukeys means comparisons
2-Month	Ns (P=0.215)	F=6.173, p=0.002	F=4.74, p=0.009	F=2.043, p=0.087 ns	Site ** Protection *	Lim1=Lim2>Enuk Free>1-day=7-day
4-Month	Ns (P=0.508)	F=49.646, p=0.000	F=0.160, p=0.852 ns	F=1.281, p=0.276 ns	Site *** Protection ns	Lim1>Lim2>Enuk

SGR (%) showed similar patterns to individual sandfish weight (Table 3.3). Sandfish at Limanak-1 and Limanak-2 showed significantly higher rates of growth than those at Enuk at 2-Months. There were also differences due to protection treatment at 2-Months. At 4-Months, there were no significant differences in growth rates due to protection treatment, and sandfish at Limanak-1 had significantly higher growth rates than those at Limanak-2 or Enuk.

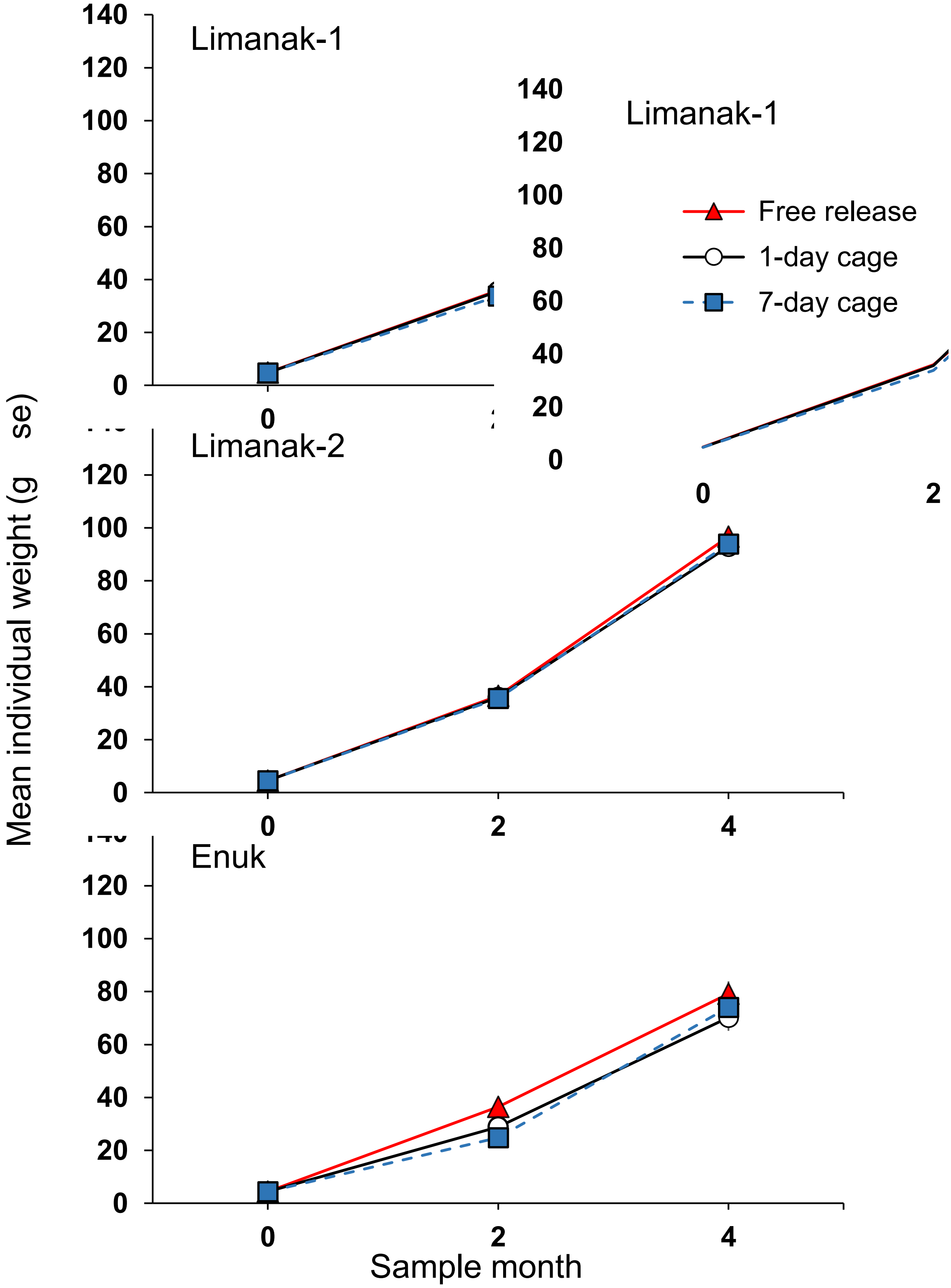


Figure 3.5 **Mean individual weight (g ± se) of sandfish juveniles from each treatment within each sea pen for each sampling month of the cage protection experiment. Free release (red triangle); 1-day cage protection (white circle); 7-day cage protection (blue square).**

Table 3.3 Specific growth rates (%bw ± se) of juveniles from each protection treatment within each sea pen for each sampling month of the cage-release experiment.

Site	Free release	1-day cage	7-day cage
Limanak-1			
2-Month	3.6 ± 0.09	3.5 ± 0.09	3.4 ± 0.09
4-Month	1.9 ± 0.07	2.1 ± 0.08	1.9 ± 0.07
Limanak-2			
2-Month	3.5 ± 0.09	3.6 ± 0.08	3.5 ± 0.12
4-Month	1.7 ± 0.09	1.6 ± 0.09	1.6 ± 0.10
Enuk			
2-Month	3.6 ± 0.13	3.1 ± 0.18	2.9 ± 0.18
4-Month	1.7 ± 0.13	1.5 ± 0.12	1.6 ± 0.15

3.3.3.2 Long-term growth monitoring (six months up to two years)

Children from the village frequently added wild adult sandfish to the Limanak-2 sea pen. Wild sandfish in this pen were differentiated from cultured by ossicle examination; however, as sandfish grew, the inflated pen biomass introduced the risk of stunting the cultured individuals and biasing results. Neither researchers or community members were able to stop the children from interfering with the experimental sandfish, therefore, the Limanak-2 sea pen was terminated after the 6-Month sampling.

Due to Limanak-1 sea pen overcrowding, sandfish were redistributed to two 50-m^2 sections of the original pen and a new 50-m^2 sea pen after the 6-Month sampling (see *section 3.2.7).* The redistribution was as follows:

1. The high-density section of the 100-m^2 sea pen was restocked with the pre-existing sandfish density of 379 g m^{-2} (n = 92; mean weight 203.8 ± 7.7 g; range 95–334 g);

2. The low-density section of the 100-m^2 sea pen was restocked with half of the pre-existing density of 185 g m^{-2} (n = 46; mean weight 200.9 ± 7.7 g; range 87–316 g); and

3. The 50-m^2 sea pen was restocked with half of the pre-existing density of 185 g m^{-2} (n = 46; mean weight 199.4 ± 8.0 g; range 75–355 g).

This dual-density pen remained viable up until the 24-Month sample. Data from the low-density original 100-m^2 pen section were used for Limanak-1 growth rates, but the high-density section consistently supported greater biomass. Where results refer to the low- or high-density sections, the data used is specified.

Enuk retained sandfish until the 18-Month sample, at which time the sandfish disappeared, apparently due to theft.

The mean weight of sandfish in the Limanak-1 sea pen at the 6-Month sample (201.1 ± 3.9 g) was significantly greater than both Limanak-2 (145.8 ± 3.5 g) and Enuk (142.2 ± 5.0 g) (ANOVA, $F = 70.11$, $p < 0.001$) (Fig. 3.6a). Note that this was before the pen was split. At the 18-Month sample, sandfish were significantly larger in the Limanak-1 high-density section (371.5 ± 10.4 g) than Enuk (303.4 ± 7.8 g) ($t(158.25) = -5.04$, $p < 0.001$). At the same time, mean sandfish weight in the low-density section was 499 ± 16.6 g, significantly greater than the mean weight in the high-density section ($t(60.32) = 6.41$, $p < 0.001$) (Fig. 3.6a).

In all pens, growth rates increased until around six months, at which point they plateaued or declined (Fig. 3.6b, c). Sandfish in the Limanak-2 sea pen showed early signs of slowing growth but the sea pen was terminated before mean weight plateaued (Fig. 3.6a, b). The maximum carrying capacity reached in the Limanak-1 high-density section and Enuk sea pen was sandfish biomass of 670 and 300 g m^{-2}, respectively (Fig. 3.6d).

3.3.4 Water quality

Sea temperature values at the four sites during the experiment were: Limanak-1 mean 30.8 ± 0.05ºC (range 25.7–40.3ºC); Limanak-2 mean 32.2 ± 0.09ºC (range 27.8–40.3ºC); Enuk mean 30.3 ± 0.02ºC (26.7–35.3ºC); and Ungakum mean 30.1 ± 0.10ºC (26.2–35.5ºC). All sites experienced occasional heavy rainfall during the experiment, and salinity dropped as low as 19.9 and 23.0 ppt at Enuk and Ungakum, respectively, for a few hours. Wardens reported that brown water discharged from the nearby mangroves at Ungakum during heavy rain. Due to technical issues, salinity data were not obtained at the Limanak sites; however, they were not located near any freshwater sources.

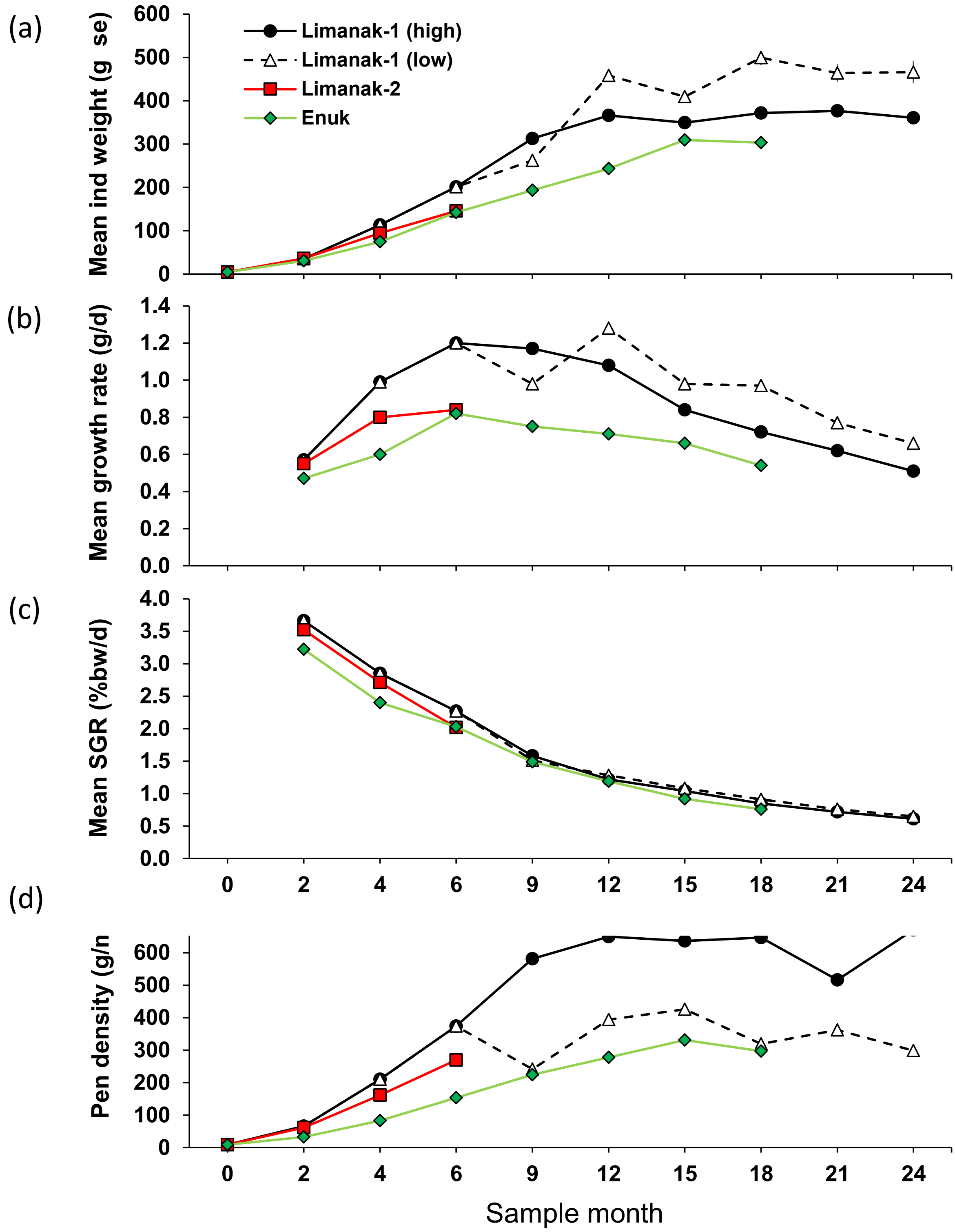


Figure 3.6 Sandfish growth parameters: (a) mean individual weight (g ± se); (b) mean growth rate (g day^{-1}); (c) mean specific growth rate (%bw day^{-1}); and (d) density of sandfish (g m^{-2}). Limanak-1 high-density pen section (black line, circle), Limanak-1 low-density pen section (dash-dotted line, triangle), Limanak-2 (red line, square) and Enuk (green line, diamond) for each sample time.

3.3.5 General description of sea pen habitats

All experimental sea pens were installed in suitable sandfish habitat with resident wild sandfish populations, but they differed in various aspects (Table 3.4). For example, sea pens at Enuk and Ungakum were located in protected areas within tidal channels, near to mangrove forest, while sea pens at Limanak were more exposed, although Limanak-1 was located inshore of an extensive *E. acoroides* meadow that afforded some protection from rough seas. At the time of juvenile release, the sediment profile of the Limanak-2 and Enuk sites was similar, but Limanak-1 and Ungakum comprised relatively higher coarse and fine-grain fractions, respectively. Limanak-2 was the shallowest site and juveniles were observed to remain buried during the day when water temperatures increased to 40°C during extreme daytime low tides, and then emerge during night-time high tides. Predators were noted only at Ungakum, where juvenile *Scolopsis trilineata* nipped at the sandfish during release and the community warden reported crabs inside the pens at night. However, the lack of predator observations at other sites does not prove their absence; the wardens did not check all sites at night.

3.3.6 Principal component analysis of sea pen habitat

PCA separated the sea pens, with minor overlap between Limanak-1 and Limanak-2, also Limanak-2 and Enuk and greater overlap between Ungakum and Enuk (Fig. 3.7). The analysis highlighted the features that contributed to differences between sites (Table 3.5). Four principal components (PCs) had eigenvalues greater than 1, and they accounted for 70% of the variation between sea pen habitats (Table 3.5), while PC 5 (eigenvalue 0.98) explained almost 9%. The proportion of fine and coarse sediment (PC 1), together with chlorophyll-*a* and medium sediment (PC 2), explained nearly half of the variation between sites (Fig. 3.7, Table 3.5). Canopy height, epiphyte load and refractory OM (PC 3); seagrass cover and epiphyte load (PC 4); and penetrability, epiphyte load and labile OM (PC 5), each explained around 10% of variation. Limanak-1 (the 'best' site) separated clearly from the other sea pen sites with higher coarse sediment fraction, labile OM and chlorophyll-*a* (Fig. 3.7), and with lower canopy height, fine sediment fraction and penetrability. Habitat data for the Ungakum sea pen consisted of a single point in time before it was terminated, but showed similarity with Enuk due to high seagrass canopy height at both sites (*E. acoroides*). However, Ungakum had a higher fine sediment and silt fraction, with less coarse sediment and chlorophyll-*a*. Limanak-2 and Enuk had higher proportions of medium sediment fraction, with less chlorophyll-*a* and silt. The wide spread of sample points was due in part to heterogeneous habitat within each pen but also to temporal changes for the three longer-term sites (see *section 3.3.7*).

Table 3.4 Measured biophysical habitat characteristics and descriptive features of the four sea pens at time of stocking with sandfish juveniles. Variables marked with an asterisk were used in the PCA.

Feature	Limanak-1	Limanak-2	Enuk	Ungakum
Measured				
Mean seagrass cover	16.4%	16.4%	7.0%	1.8%
Mean canopy height	6.6 cm	11.2 cm	59.6 cm	33.2 cm
Macroalgae	Nil	Low	Nil	Nil
Mean SG epiload*	45%	20%	30%	38%
Mean chlorophyll-*a**	7.4 µg g^{-1}	3.9 µg g^{-1}	2.2 µg g^{-1}	2.1 µg g^{-1}
Mean labile OM*	1.3%	0.9%	1.0%	1.4%
Mean refractory OM*	1.9%	2.3%	2.2%	1.6%
Mean total OM	3.2%	3.2%	3.2%	3.0%
Grain size* ratio (coarse:med:fine:silt)	C36:M31:F30:S3	C19:M37:F44:S0 *(silt <0.5)*	C17:M38:F43:S2	C6:M31:F59:S4
Anoxic layer (depth/strength)	0.3 cm / med	Absent	1.6 cm / light	Absent
Depth range (m)	~0.3–1.0 m	~0.05–1.0 m	~0.5–1.3 m	~0.5–1.3 m
Penetrability*	5.8 cm	3.4 cm	6.7 cm	5.8 cm
Descriptive				
Patchiness (seagrass)	Patchy	Patchy	Uniform	Patchy
Dominant seagrass sp (+ other seagrass)	*C. rotundata* (*E. acoroides*)	*C. rotundata* (*T. hemprichii*)	*E. acoroides* (*T. hemprichii*)	*E. acoroides*
Other invertebrate fauna	Abundant and varied	Abundant and varied	Not abundant, mostly sea stars	Abundant, mostly sea cucumbers
Wave exposure	Moderate	High	Low	Low
Distance from shore	30 m	100 m	15 m	10 m
Mangroves (distance)	100 m	600 m	3 m	3 m
Houses (line of sight)	In view	In view	Out of view	Out of view
Presence of predators	Not observed	Not observed	Not observed	Fish and crabs
Water flow	Normal tidal	Normal tidal	Moderate one-way tidal	Low one-way tidal

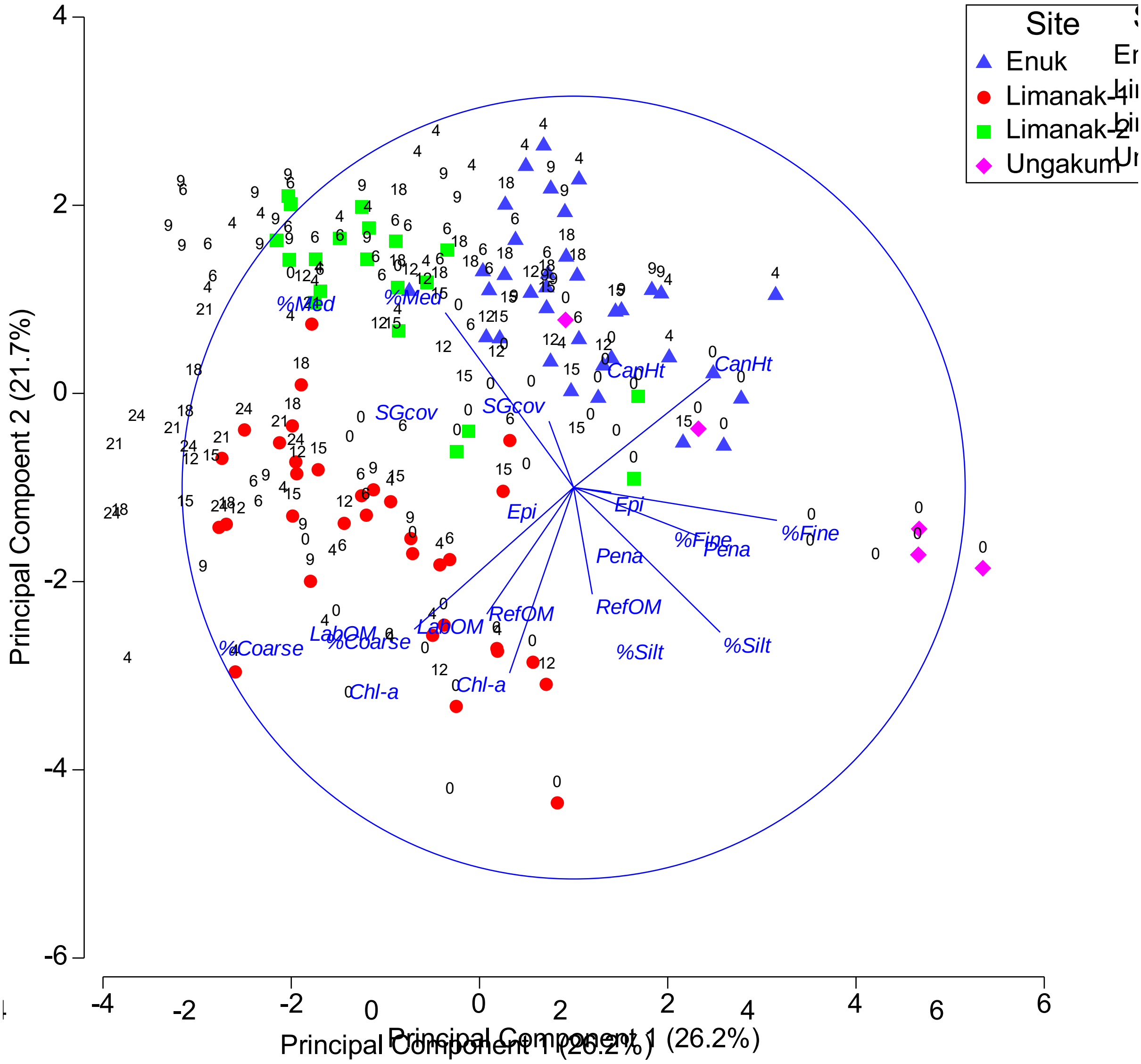


Figure 3.7 **PCA ordination of the four sea pen habitats for the biophysical variables: % coarse grain (%Coarse); % medium grain (%Med); % fine grain (%Fine); % silt (%Silt); % labile OM (LabOM); % refractory OM (RefOM); % total OM (TOM); % seagrass cover (SGcov); chlorophyll-*a* (Chl-*a*); % seagrass epiphyte load (Epi); and sediment penetrability (Pen). Limanak-1 (red circles); Limanak-2 (green squares); Enuk (blue triangles); and Ungakum (pink diamonds). Numbers denote sample months.**

Table 3.5 Important principal components from PCA of biophysical factors for the four sea pen sites at all sample times, with high component loadings ($r < -0.4$ or $r > 0.4$) shown in bold.

	PC 1	PC 2	PC 3	PC 4	PC 5
Eigenvalue	2.88	2.38	1.25	1.2	0.98
% variation explained *(cum. % variation explained)*	26.2 (26.2)	21.7 (47.8)	11.3 (59.2)	10.9 (70.1)	8.9 (79.0)
Component loading					
Seagrass cover	-0.063	0.169	0.002	**0.725**	-0.307
Canopy Height	0.349	0.278	**-0.435**	-0.051	-0.173
Penetrability	0.322	-0.126	-0.347	-0.177	**-0.545**
Epiphyte load	0.096	-0.012	**-0.451**	**0.563**	**0.462**
Labile OM	-0.222	-0.323	-0.318	-0.204	**0.407**
Refractory OM	0.048	-0.273	**-0.421**	-0.047	-0.076
Chlorophyll-*a*	-0.164	**-0.474**	0.154	0.223	-0.355
% Coarse grain fraction	**-0.407**	-0.362	-0.135	0.066	-0.157
% Medium grain fraction	-0.328	**0.447**	-0.258	-0.142	-0.090
% Fine grain fraction	**0.519**	-0.084	0.312	0.071	0.178
% Silt fraction	0.374	-0.370	-0.051	0.009	0.060

3.3.7 Temporal changes in sea pen habitat

Not all biophysical parameters changed significantly through time and, of those that did, some showed no discernible trend (Table 3.6). At all three sites, however, the mean proportion of the medium-sediment fraction increased significantly (by 20%, 22% and 14% for Limanak-1, Limanak-2 and Enuk, respectively) and the fine-grain fraction decreased significantly (by 18%, 23% and 18% for Limanak-1, Limanak-2 and Enuk, respectively) (Fig. 3.8). At Limanak-1, monitored for 24 months, the mean silt fraction also significantly decreased by 2%. The only other significant results were at Limanak-1 for decreasing mean total and refractory OM, and nearly significant increasing labile OM, over 6 months.

Table 3.6 One-way ANOVA for biophysical parameters during sampling of Limanak-1 (24 months), Limanak-2 (9 months) and Enuk (18 months). Significant results with a consistent trend are in bold text and direction indicated. Data transformations are shown in parentheses, (H) denotes heterogeneous variances where transformation could not normalise data (significant at $p \leq 0.01$).

Parameter	Limanak-1	Limanak-2	Enuk
Seagrass cover	F=0.344, p=0.939 (ln+1)	F=0.185, p=0.905	Significant, no trend (H)
Canopy height	F=0.088, p=0.999 (ln+1)	F=1.076, p=0.387	F=1.591, p=0.187
Penetrability	F=1.320, p=0.281	Significant, no trend	F=1.728, p=0.151 (sqrt)
Epiphyte load	F=0.799, p=0.609 (ln+1)	Significant, no trend (sqrt+1)	Significant, no trend (H)
Labile OM	F=1.228, p=0.325 (H)	F=4.770, p=0.015 (ns at p=0.01) (H)	Significant, no trend
Ref. OM	Significant, no trend	**F=16.004, p=0.000 Decreasing (H)**	Significant, no trend (H)
Total OM	F=1.698, p=0.150 (H)	**F=5.398, p=0.009 Decreasing (H)**	Significant, no trend (H)
Chlorophyll-*a*	Significant, no trend	F=12.382, p=0.108	Significant, no trend
Coarse grain	F=0.7.7, p=0.674	F=0.202, p=0.894	F=0.942, p=0.481
Medium grain	**F=4.467, p=0.002 Increasing (H)**	**F=13.519, p=0.000 Increasing (H)**	**F=3.559, p=0.01 Increasing (H)**
Fine grain	**F=3.493, p=0.008 Decreasing**	**F=9.108, p=0.001 Decreasing (Sqrt)**	**F=3.812, p=0.007 Decreasing (H)**
Silt	**F=3.931, p=0.004 Decreasing (H)**	F=3.106, p=0.056 (ns at p=0.01) (H)	F=1.375, p=0.259

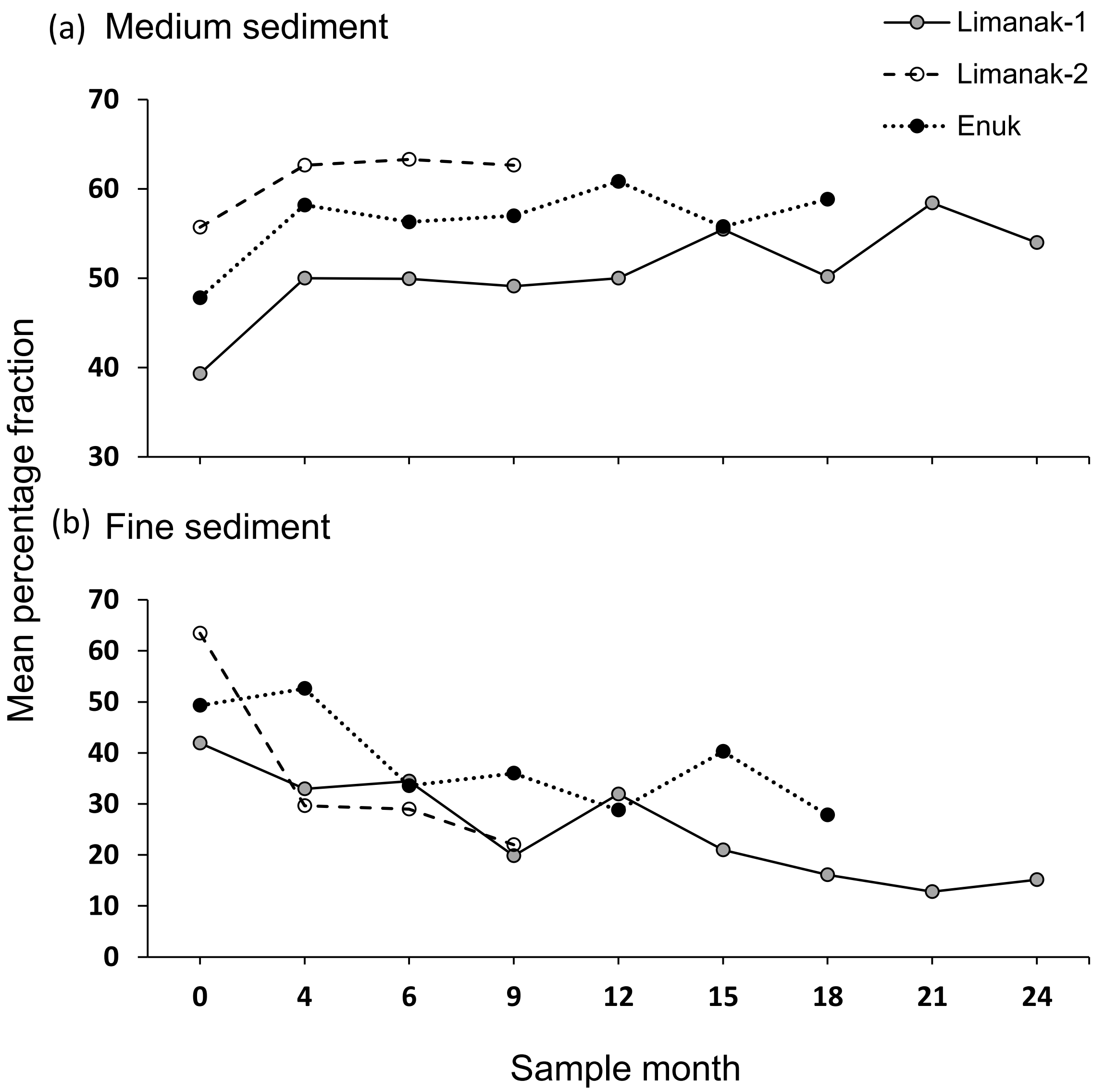


Figure 3.8 **Changes in the mean proportion of (a) medium and (b) fine sediment fraction at Limanak-1 (solid line, grey circle), Limanak-2 (dash-dotted line, white circle), and Enuk (dotted line, black circle) for each sample time.**

3.4 Discussion

Identifying optimal habitats for ocean mariculture, and determination of appropriate stocking densities and husbandry protocols for different habitats are of paramount importance for the development of tropical sea cucumber mariculture (Purcell 2004, Tsiresy et al. 2011, Purcell et al. 2012b, Rougier et al. 2013, Zhang et al. 2015). Knowledge of the level of husbandry required to minimise predation of small juveniles, and selection of sea ranch sites that will optimise survival and growth underpin the success of the mariculture operation. The additional cost and effort associated with intensive husbandry must be clearly warranted, since production of larger juveniles, materials to build cages and time spent clearing predators will reduce profit margins (Raison 2008). Key outcomes from this chapter relate to the utility of protective release systems for juvenile sandfish and the comparative quality of the habitat selected for sandfish mariculture.

3.4.1 Advantages of protective caging for releases

The cage protection experiment showed that short-term protection from predation did not improve survival of juvenile cultured sandfish, regardless of the release habitat. In fact, free release had the highest survival at all sites where sandfish were recovered. After four months, there were significant differences in growth between the sea pen sites, independent of release protection treatment. At the three viable sea pen sites, there appeared to be a direct relationship between survival and growth, i.e., sites with high survival had strong growth and those with low survival had lower growth. This runs counter to most studies of captive sandfish rearing where growth shows a strong inverse relationship to density (Battaglene et al. 1999, Lavitra et al. 2010, Klückow 2017, Kunzmann et al. 2018).

Small juvenile sandfish are associated with seagrass meadows and begin burying behaviour at around 1 cm in length (approximately 1 g weight), later migrating away from dense seagrass to nearby mud-sand substrata when they exceed 4 cm or 3 g (Mercier et al. 2000a). They bury during the day or when conditions are adverse (e.g., low salinity) but emerge and feed at night, presumably to minimise predation (Yamanouchi 1956, Mercier et al. 1999, Purcell 2010b). It was theorised that cage protection would improve survival by enabling juveniles to recover from transport and handling stress (Purcell 2010b), and allowing natural burying and feeding patterns to develop before exposure to predators, as recommended by Dance et al. (2003). Covered nursery pens are used to rear cultured sandfish to 50 g at some sea farming sites in Madagascar due to heavy predation by crabs. There was an expectation that juveniles released with no protection would be more vulnerable to predation; those with the 1-day cage protection would partially recover from release stress, with subsequent higher survival; and those with the 7-day cage protection would recover completely and develop a natural diel burying and feeding cycle, making them less likely to be predated on (Purcell 2010b). Instead, it was found that predator exclusion conferred no advantage at Limanak-1, Limanak-2 or Enuk. Similarly, Lavitra et al. (2015) found that covered nurseries did not significantly increase survival at sites with low predator density in Madagascar. At Ungakum, where predators appeared to be abundant and active, no juveniles were retrieved from any treatment, suggesting that one week of protection was not sufficient to improve survival in areas where predation is likely.

3.4.2 Effect of sea pen habitat on sandfish survival and growth

Suitable juvenile release habitat is a determinant of early sandfish survival and growth (Dance et al. 2003, Purcell and Simutoga 2008, Altamirano et al. 2017, Ceccarelli et al. 2018) but selection of suitable mariculture habitat requires a broader focus because juveniles of 3–15 g are released into the sea with the aim of harvest at commercial size up to two years later. The site must therefore support growth as the sandfish progress through life stages that have shifting requirements (Mercier et al. 2000b, Hines et al. 2008). Therefore, elucidating the relationship of sandfish to habitat is of critical importance to optimising sandfish mariculture outcomes. Long-term monitoring of sandfish and habitat features presented in this chapter was conducted to explain variation in sandfish survival and growth in relation to the habitat they occupy. Sediment features are especially important for sandfish because, not only do they ingest sediment to obtain nutrients, but they bury within it to avoid predation and unfavourable conditions (Mercier et al. 1999, Robinson et al. 2013, Altamirano et al. 2017). Shortcomings of the experimental design, due largely to the pragmatics of working with communities in traditional marine tenure areas in a remote location, include the lack of sea pen replication and no control pens. In addition, two of the original experimental sea pens were terminated early in the study, halving the effective experimental units. The chapter findings are thus limited to description of the features that characterised the observed optimal, moderate and unfavourable sea pen habitats and comparison with similar studies.

It is difficult to explain the highly divergent survival and growth between the four sea pen sites because all sites generally conformed to preferred juvenile sandfish habitat and supported wild sandfish populations. Results at two extremes emerged from the study. First, the Limanak-1 sea pen displayed very high survival, growth and carrying capacity compared to the three other sea pen sites and to that reported for ocean grow-out elsewhere (Purcell et al. 2012b, Juinio-Meñez et al. 2017). Growth rates and survival of sandfish in this sea pen were comparable or exceeded that reported for ex-fish and shrimp ponds (Agudo 2012, Duy 2012). Limanak-1 sandfish reached commercial size within 12 months of release (mean 458.4 g ± 14.1 se in the low-density pen section), despite the fact that their growth may have been stunted from as early as five months after release, due to high pen biomass (also see Klückow 2017). The most surprising aspect, however, was achieving these growth rates at very high density. The survival rate remained at over 90% until sandfish reached maturity and a maximum sea pen biomass of 670 g m^{-2} in the high-density section. This biomass is not the highest recorded for cultured sandfish (see Lavitra 2008, Robinson et al. 2019), but was nonetheless three-times that of a commonly accepted sandfish density ceiling (Battaglene et al. 1999). Limanak-1 sea pen was monitored for two years and constitutes one of the longest available detailed studies of sea pen sandfish growth. The second extreme was the total loss of juvenile sandfish from the Ungakum site; this result was unexpected and unfortunately meant that no growth data were generated from that particular habitat type.

The outstanding performance at Limanak-1 is especially perplexing. Some of its biophysical characteristics seem intuitive and agree with the literature. For example, this site displayed high sediment nutrient content (high seagrass epiload and chlorophyll-*a*). Also, the long-term concentration of sediment labile OM was marginally higher, and it was the only site with a consistent, shallow anoxic sediment layer, which can promote strong growth (see Robinson et al. 2015). However, Limanak-1 was characterised by higher coarse sediment and lower fine sediment fractions, which differs from natural juvenile habitat and choice experiments described in other studies (Mercier et al. 2000b, Altamirano et al. 2017). Further, several habitat features differed from those indicated by Ceccarelli et al. (2018) as optimal for survival (42% seagrass cover, 1.1-m depth), growth (34% seagrass cover) and burying rate (1.9% organic carbon, 0.3-m depth). Slater and Jeffs (2010) also found that wild-caught *Australostichopus mollis* juveniles thrived in non-natural habitat that was very different to natural habitat in sediment characteristics, including lower OM content and coarser grain profile.

There is high natural variability in growth and survival of cultured sandfish (Purcell and Simutoga 2008). Studies on preferred habitat of sandfish often appear contradictory, possibly due to unavoidable compromises when features that promote survival, burying and growth counteract each other as juvenile sandfish grow, or even within a single life stage (Ceccarelli et al. 2018). Cultured juvenile sandfish seem to fare better when released into shallow seagrass beds, which is not surprising as this is their settlement habitat. Results in Chapter 5 show that recently released cultured juvenile sandfish buried more frequently in habitat with seagrass. However, suitable sandfish mariculture habitat must also cater to changing needs and thresholds as they grow: sites that support good survival and strong early growth rates might not sustain them in the long-term. The relationship of sandfish to seagrass illustrates this: post-larval sandfish recruit to seagrass, which provides a bridge between the planktonic and epibenthic juvenile phases where it provides food and shelter. However, dense seagrass inhibits burying behaviour, and gradually loses importance as burying patterns change with increased size until adult sandfish reach the stage of thriving in bare sand habitats (Mercier et al. 2000a, Hamel et al. 2001). Release sites for sea ranching may need to be adjacent to habitats suitable for sub-adult and adult life stages (Mercier et al. 1999, Hines et al. 2008, Ceccarelli et al. 2018), or to include sufficiently heterogeneous habitats to support all sandfish stages. Changing tolerances with sandfish size was further demonstrated by Dumalan et al. (2019), who found that high-nutrient sediments associated with fish farms were unsuitable for small sandfish (~7 g) but advantageous for larger juveniles (> 50 g).

Sediment granulometry is regarded as an important factor affecting deposit feeders and sea cucumber habitat preference. Not all deposit-feeding sea cucumber species are selective for sediment grain size (Yingst 1982, Mezali and Soualili 2013). Wiedemeyer (1992) concluded that sandfish positively select grain sizes less than 500 µm (i.e., mostly fine fractions and silt), although Lavitra (2008) found that they were not selective of particles less than 2 mm. Field studies and choice experiments indicated that juvenile sandfish avoided very fine silty and very coarse sediment areas and preferred medium 'sandy-mud' sediment (90–360 µm in the wild, mean 360 µm in the laboratory), while adults were found on sandy substrata (> 360 µm) in the wild (Mercier et al. 1999, 2000b, Plotieau et al. 2014a, Altamirano et al. 2017). Tsiresy et al. (2011) introduced the concept of sediment 'structure' (interaction between grain size and compactness) affecting OM accessibility after discovering that ploughing sediment led to increased growth of cultured sandfish, but sediment penetrability did not differentiate Limanak-1 from the other sea pen sites in this study. Notwithstanding, sediment structure may provide an alternative explanation for the total loss of juveniles at Ungakum. The predation theory is not implausible because fully caged juveniles survived at this site (C. Hair, unpublished data), escape was low from Limanak-1 and Limanak-2 sea pens but Enuk, close to mangroves, also suffered losses. Yet, an alternative theory is that the combination of relatively high penetrability, fine sediment and silt fractions at Ungakum made burying easy and resurfacing difficult. In tank experiments, it has been shown that silty-mud (35% sediment of <125 µm grain size) is the least preferred burying substrate for juvenile sandfish (Altamirano et al. 2017), also that they bury deeper in fine-grained muddy sand (mean 90 µm) (Mercier et al. 1999). Preferred sediment type may offer a compromise between food availability and ideal burying consistency (Mercier et al. 2000b, Plotieau et al. 2013), and juveniles might get 'bogged' in silty-muddy sediments (e.g., Sloan and von Bodungen 1980). The fine sediment fraction was almost 60% at the Ungakum sea pen but natural juvenile habitat (burying experiment site, Chapter 5) had fine sediment fractions of 26% and 32% in seagrass and bare habitat, respectively. Wild sandfish observed in the vicinity of the Ungakum sea pen site may have migrated there when they were larger and stronger. However, good survival and growth of sandfish just 1 km away in the trial sea ranch in a monitoring sea pen with a similar grain size profile (C. Hair, unpublished data) highlights the pitfalls in singling out a specific biophysical parameter as the deciding one.

There is advantage in identifying key parameters prior to large-scale releases. PCA could be a useful tool for future identification of suitable habitat for sea cucumber mariculture as it provides a repeatable and objective protocol for classifying habitats (e.g., Verfaillie et al. 2009). However, not all potentially important variables were incorporated within the frameworks dealt with in this chapter. Additional biophysical factors could include sediment bacteria content and diversity, redox potential, predator abundance and type, and water quality issues. Human factors may have influenced the outcomes—lower survival of juveniles was recorded at the two sites most distant from wardens and the village. Loss of sandfish from experimental sea pens might increase (e.g., due to theft) or decrease (e.g., due to fishing pressure on predators, such as crabs). Efforts to include as many variables as possible should improve the utility of multivariate analysis. However, unmeasured (e.g., bacteria and redox potential) or unknown/unsuspected biophysical parameters might be the critical ones (Gray 1974, Anderson 2008). Perhaps none of the measured biophysical variables triggered the same responses as in other studies, or as yet unidentified interactions occurred between the measured factors. The results caution against assuming that biophysical parameters controlling sandfish survival and growth can be neatly or easily defined, and recommend more investigation.

3.4.3 Impacts of sandfish on pen habitat

Few studies have investigated long-term changes in habitat utilised by any sea cucumber species (but see Plotieau et al. 2013), although intuitively, the feeding and burying habits of sandfish would be assumed to impact the habitat they occupy. Changes in habitat characteristics due to the presence of sandfish are of relevance in the contexts of depletion (overfishing) and surplus (high-density farming). Feeding and bioturbation of sediment by sea cucumbers can alter sediment grain size structure, sediment and seawater chemistry and seagrass productivity (Hammond 1981, Wolkenhauer et al. 2010, Schneider et al. 2011, Purcell et al. 2016b, Lee et al. 2018b). Plotieau et al. (2013) found that sandfish sea pen sediment that had been farmed intensively for two years showed a 30% decrease in the fine sediment fraction (< 250 µm) compared to unfarmed, unpenned control areas. Similarly, at the three PNG sea pen sites, the medium (≥ 250 µm to < 1 mm) grain sediment fraction increased and fine (< 250 µm) grain fraction decreased, over periods ranging from six to 24 months. The consistency of this result across sites gives some robustness to this inference, however, the lack of experimental controls in the present study means that pen effects cannot be ruled out (Hulberg and Oliver 1980). Furthermore, conflicting results have been reported from elsewhere; a 3-month study in Fiji by Lee (2016) found that 1-mm grain size decreased and 125 µm increased with high sandfish density (note, no changes in control pens with nil or low densities of sandfish); Tsiresy et al. (2011) reported inconsistent grain size changes in three Madagascan sea pens after four months; and Dumalan et al. (2019) did not report any changes in mean grain size in sea pens located in sea grass and fish farm habitats in the Philippines after five months. Evidence of grain size feeding selectivity for sandfish is conflicting (Wiedmeyer 1982, Lavitra 2008) and it is unlikely that sediment size changes appreciably during gut transit (Hammond 1981). Therefore, more research is needed to determine if and how sandfish affect the grain size of sediments they occupy.

The concentration of dietary items such as organic matter, bacteria and chlorophyll-*a* in sediment might also be expected to change with sea cucumber feeding and bioturbation. Plotieau et al. (2013) reported lower chlorophyll-*a* and bacteria but no difference in OM in sediment inside and outside sandfish farming pens, while Wolkenhauer et al. (2010) recorded increased OM and chlorophyll-*a* when sandfish were excluded from seagrass areas. Dumalan et al. (2019) found no change in OM but chlorophyll-*a* decreased in experimental sea pens after five months. In this study, there were no temporal changes in chlorophyll-*a* in any pen, although some OM components decreased at Limanak-2 over six months and bacteria were not measured. No other measured biophysical parameters changed with time in the present study of sandfish in sea pens.

3.5 Conclusions

This chapter presents a useful outcome pertaining to the levels of husbandry involved in early release strategies, with evidence that short-term protection at release is not necessary. It also showed that it is possible to have very high survival and commercial harvest of sandfish in less than a year from release at 3-g size in certain habitat. This finding is positive for communities wanting to participate in sandfish mariculture who have access to similar areas. Communities with less suitable habitat in their fishing grounds will need more time, or perhaps be unable, to produce commercial sandfish crops. Practicality and equality dictate that some sites with sub-optimal habitat will be utilised since benefits will need to be shared amongst a range of communities. The study was unable to prescribe the biophysical features that define optimal habitats for community-based sandfish sea ranching but progressed baseline knowledge of positive and negative parameters. The social aspects of site suitability also affect the success of mariculture; socio-economic considerations (e.g., traditional marine tenure arrangements, traditional leadership and community-based management capacity, fisheries governance, sea cucumber fishing history and practices, community relationships, etc.) may be as important as biophysical aspects. These have been factored into spatial planning methodology (GIS protocol presented in Chapter 4) and are investigated in detail with a large-scale community sandfish sea ranching trial (Chapter 7).

Well-controlled, long-term, replicated studies with greater community involvement are needed to further elucidate the role of specific biophysical variables and their interactions in driving sandfish survival and growth. This will enable managers to predict how a site will perform and fine-tune selection criteria to avoid investing effort at biophysically unsuitable sites, and better manage community expectations regarding the outcomes of aquaculture ventures (Eriksson et al. 2012). Various authors have also advocated pilot studies or test plots to assess site suitability and estimate approximate carrying capacity (Purcell 2004, Robinson and Pascal 2012). These results support the use of preliminary site checks and recommend testing for predation risk with caged (cage or sea pen roof must allow sunlight to enter as sandfish will not grow in dark conditions; C. Hair unpublished data) and uncaged cultured juvenile sandfish for about two months, since more than one week is needed in areas with predators. If predation is deemed a threat to sea ranching success, a worst-case scenario is that the site will be abandoned, or further investigation can be made into the level of protection or husbandry needed, and the appropriate release size (see Lavitra et al. 2015, Eeckhaut et al. 2020). Initial growth data will also indicate if the site supports a growth rate appropriate for sea ranching. Sea ranch managers must remain vigilant though, because sites that appear to be suitable may not be (as demonstrated in this chapter), external events can impact site suitability (Purcell and Simutoga 2008, Hair et al. 2011, Juinio-Meñez et al. 2013), and promising sites may fail to meet expectations when release effort is scaled-up (Robinson and Pascal 2012).

Chapter 4
Preliminary assessment of geographic information system and remote sensing for sandfish mariculture site selection

4.1 Introduction

A critical part of projecting the potential economic impacts of a new mariculture activity, and developing policy for it, is to assess the potentially suitable areas for that activity (Nath et al. 2000, Kapetsky and Aguilar-Manjarrez 2008). Optimal site selection is essential; many mariculture projects create negative environmental and/or social impacts or fail due to poor site selection (Longdill et al. 2008). The capacity of geographic information systems (GIS) to store, analyse and display data related to physical locations on the Earth's surface has generated an expanding role for GIS in natural marine resource management. Remote sensing is an important component of GIS (Merchant and Narumalani 2009), so called because it involves the collection of data remotely via air (e.g., satellite, plane, drone), sea or land-based sensors (Kapetsky and Aguilar-Manjarrez 2008). High-resolution, multi-spectral satellite imagery is an important data source for marine-related research and development, although greatly under-utilised (Green et al. 2000, Radiarta et al. 2008, Meaden 2009, Hamel and Andréfouët 2010, Stuart et al. 2011, Hedley et al. 2016). Use of GIS and remote sensing can assist mariculture ventures through identification of optimal natural conditions for a specific culture species or culture activity (Radiarta and Saitoh 2009, Radiarta et al. 2011, Snyder et al. 2017), assessing expected productivity (Simms 2002, Vincenzi et al. 2006, Silva et al. 2011) and monitoring impacts (Ottinger et al. 2016, Jayanthi et al. 2018, Ren et al. 2018). However, they are constrained by cost, technology limitations (spatial resolution, data availability), expertise, and a lack of appreciation of the importance of spatial planning on the part of managers, researchers and policy makers (Nath et al. 2000, Hamel and Andréfouët 2010, Kapetsky and Aguilar-Manjarrez 2013, Meaden and Aguilar-Manjarrez 2013).

The literature on GIS assessments for pond aquaculture, fish cage culture and suspended mariculture of molluscs is growing (e.g., Grant et al. 2009, Radiarta and Saitoh 2009, Silva et al. 2011) but is uncommonly applied to benthic mariculture commodities, such as sea cucumber. Satellite imagery can be complemented with ancillary data from a range of sources such as conventional or digital maps, numerical models and field surveys. Increasingly, social, economic, logistic and infrastructure considerations are also integrated with environmental criteria using GIS (Salam et al. 2003, Buitrago et al. 2005, Giap et al. 2005, Radiarta et al.

2008, Silva et al. 2011, de Sousa et al. 2012, Kapetsky and Aguilar-Manjarrez 2013, Micael et al. 2015, Stelzenmüller et al. 2017). Although rarely utilised for mariculture planning, traditional, local and anecdotal knowledge can also provide valuable information for GIS analysis (Calamia 1999, Teixeira et al. 2013, Feary et al. 2015), for example historical uses of marine zones (Buitrago et al. 2005).

Factors affecting mariculture site feasibility can be integrated by GIS to produce a thematic map representing levels, or categories of suitability such as, 'high, 'moderate', 'low' and 'unsuitable' (Nath et al. 2000, Micael et al. 2015). In simple cases, multiple data layers describing these factors are overlain to create a suitability map for interpretation. Prior to mapping, however, multi-criteria evaluation (MCE) GIS modelling can be also be done, where factors contributing to mariculture site suitability are ranked by expert(s) according to their relative importance. MCE is a commonly applied GIS method for habitat suitability analysis with application to aquaculture site selection (e.g., Salam et al. 2003, Buitrago et al. 2005, Perez et al. 2005, Silva et al. 2011). The few published GIS studies on sea cucumber mariculture have used an MCE approach to identify, for example, potential sites for sandfish mariculture in Indonesia (Marizal et al. 2012, Wulandari et al. 2016, Basir et al. 2017, Mulyani et al. 2017, Sulistyo et al. 2018) and Tanzania (Ciccia Romito 2012), and for culture-based restoration of the temperate sea cucumber, *Apostichopus japonicus* in China (Zhang et al. 2017). These studies mostly incorporated abiotic criteria (e.g., water temperature, salinity, depth, water chlorophyll-*a*, wave energy, etc.) and broad socio-economic factors such as demography and location of ports. Little attention was paid to habitat features apart from general substrate type, defined by grain size (e.g., Zhang et al. 2017) or seafloor categories (e.g., Marizal et al. 2012), and remote sensing was not used.

Remote sensing can potentially be used to identify habitats that promote high survival and growth of sea cucumber for optimal mariculture outcomes. There is scope for this methodology to be applied to sandfish mariculture site selection in PNG and the Pacific Islands region where there is growing interest in ocean-based culture of sea cucumber (Jimmy et al. 2012, Robinson 2013, Chapter 1). This region is characterised by vast expanses of ocean dotted with thousands of islands, many of them remote, and with associated high travel costs. The use of remote sensing to survey and assess sandfish habitat in remote and inaccessible areas would have substantial logistic and economic benefits, including reduced requirement for on-site activity, and staff/equipment travel, and capacity to access data quickly and easily early in a project.

Effort and funds could then be directed towards sites with more optimal characteristics supporting the best chance of success. To that end, data on distribution of wild sandfish stocks in natural habitats generated during field work on trial sea ranches during this study (e.g., Chapter 7) provided an opportunity to address this research gap. Sandfish habitat classes were derived from remote sensing analysis with the assistance of field data on habitat and sandfish abundance/size at two trial community sea ranch sites in New Ireland Province, PNG.

The objectives of the research described in this chapter were twofold. First to use habitat field data and remote sensing to classify satellite imagery and derive suitable and less suitable habitat classes for sandfish at each trial ranch and assess the potential of this technique to describe habitats in order to better predict suitable sandfish mariculture sites elsewhere; and second to propose a remote sensing/GIS approach to identify suitable sandfish mariculture sites.

4.2 Methods

Remote sensing and field data were obtained for two shallow (0.1–2-m depth) sandfish mariculture sites: a 7-ha trial sea ranch at Limanak and a 5-ha trial sea ranch at Ungakum (Fig. 4.1). Both trial sea ranches contained wild sandfish populations and were subsequently stocked with cultured sandfish juveniles as part of research into community-based sandfish sea ranching (see Chapter 7). In this chapter, detailed information on wild sandfish abundance and size was compared with remote sensing maps to explore how effective these methods are in describing sandfish distribution. The field data sources are detailed in *section 4.2.2* below.

4.2.1 Remote sensing approaches

Two 5 x 5 km (25 km^2) orthorectified WorldView (WV) satellite images with atmospheric correction were purchased for areas that encompassed the Limanak and Ungakum trial sea ranches. These images had resolution of < 2 m, with 8 spectral bands: coastal blue (400–450 nanometre, nm), blue (450–510 nm), green (510–580 nm), yellow (585–625 nm), and red (630–690 nm), red edge (705–745 nm), near infra-red (NIR)-1 (770–895 nm) and NIR-2 (860–1040 nm), the first five of which are water penetrating (Purkis et al. 2019). The requirement for cloud-free satellite images limited the range of acquisition dates. The best quality images closest to field sampling dates and within similar seasons were 21 December 2014 (Limanak) and 21 May 2018 (Ungakum). The images were pre-prepared by removing sun glint (Hedley et al. 2005) and a depth correction method was applied to exclude water column effects (Stumpf et al. 2003). Land and extraneous marine areas were masked, including depths > 3 m as these areas are unsuitable for community sea ranches (Fig. 4.2).

Four approaches were taken to assess the potential of WorldView imagery for identifying sandfish habitat: (1) green band (510–580 nanometre wavelength); (2) normalised difference vegetation index (NDVI); (3) unsupervised classification; and (4) supervised classification. Remote sensing work was undertaken by a GIS specialist technician using the WV 2/3 satellite imagery with Environmental Systems Research Institute (ESRI) GIS ArcMap and Spatial Analyst software.

4.2.1.1 Green band analysis

Spectral analysis using the single green band was chosen to identify varying levels of 'greenness' to denote presence of submerged macrophyte (e.g., seagrass and macroalgae) and test its usefulness in identifying sandfish habitat when compared to NDVI and unsupervised/supervised classifications (Fig. 4.2).

4.2.1.2 Normalised difference vegetation index

Normalised difference vegetation index (NDVI) is a common way to measure terrestrial vegetation (Rouse et al. 1973), and was used to indicate presence and approximate density of macrophytes (Fig. 4.2). This index uses the red and near-infrared (NIR) bands according to the equation:

NDVI = (NIR - Red) / (NIR + Red).

Healthy vegetation (chlorophyll) reflects more NIR and green light but it absorbs more red and blue light (i.e., high NDVI = healthy vegetation, low NDVI = less or no vegetation).

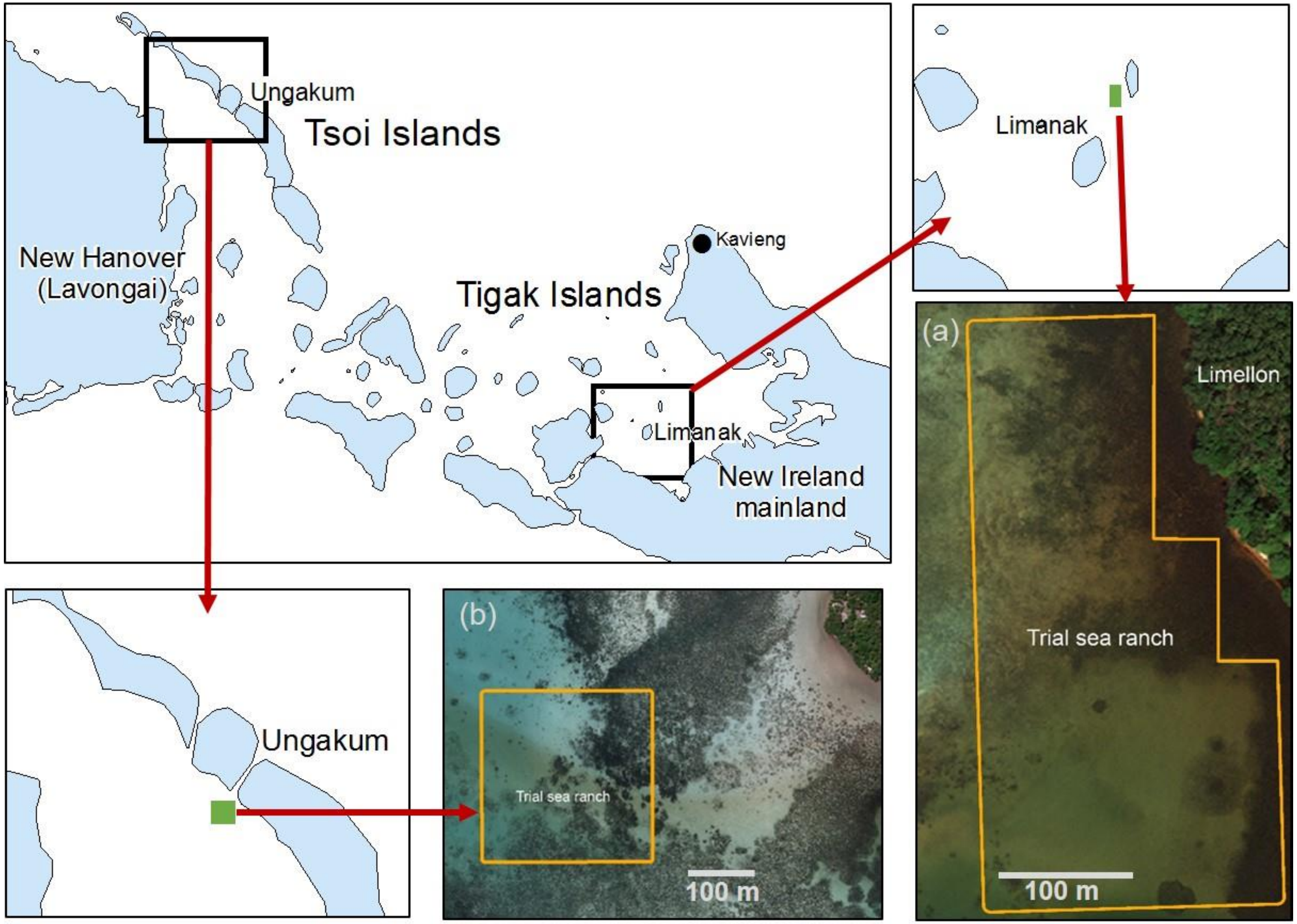


Figure 4.1 **Map showing the study area and approximate location (green block) and boundaries of trial sea ranches (yellow line) at (a) Limanak and (b) Ungakum. Scale bars are 100 m.**

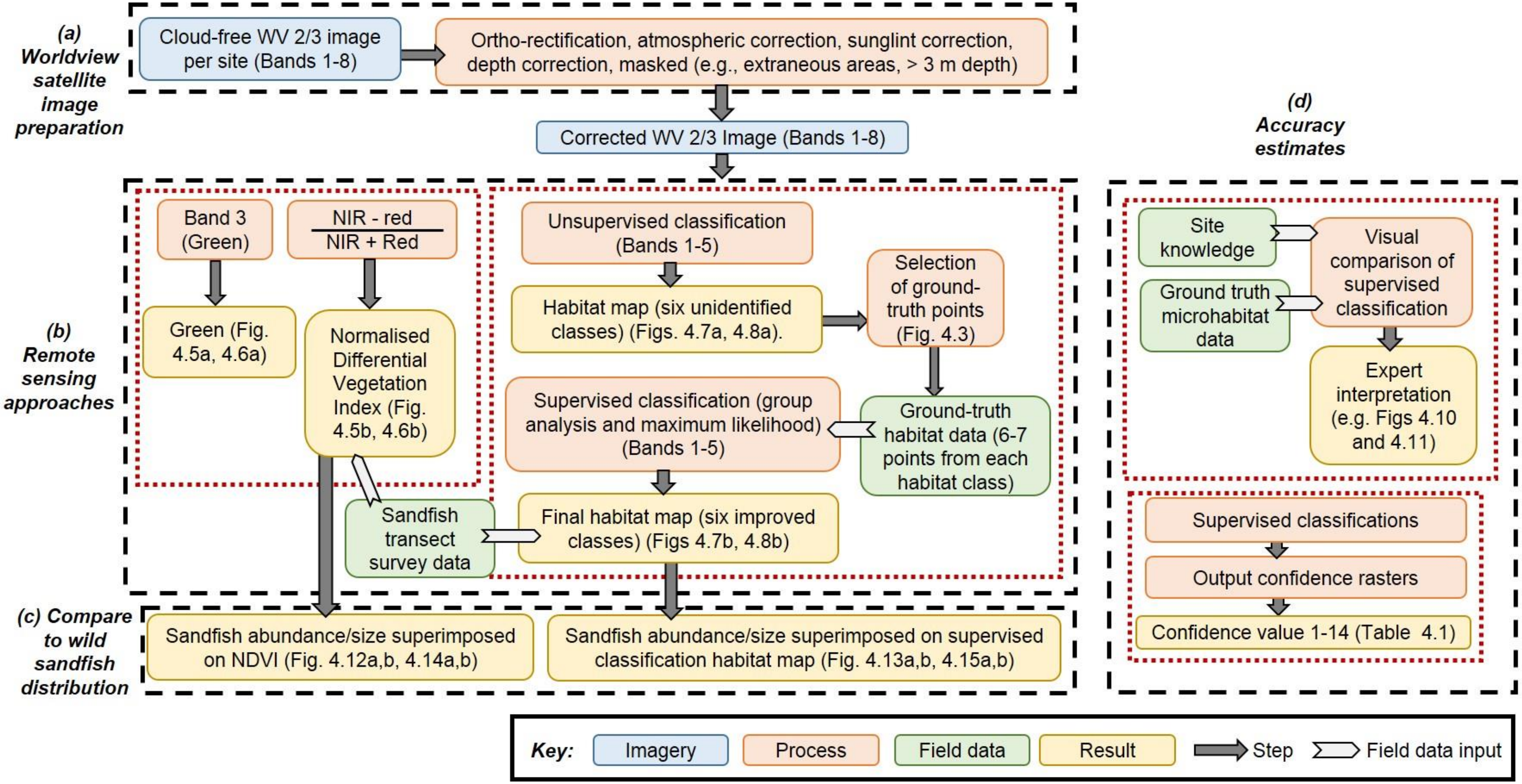


Figure 4.2 Flowchart of the steps taken to produce the remote sensing maps: (a) preparation of WV satellite images for each site; (b) remote sensing approaches used to define marine habitat at each site; (c) visual representation of sandfish distribution and size on selected maps; and (d) estimation of the accuracy of the final supervised classification map. Output maps presented in the Results section are noted for easy reference.

4.2.1.3 Unsupervised classification

Unsupervised classification used the spectral information in the WV image to identify marine habitats according to differences in colour and texture of the image. This technique utilised the first five bands—coastal blue, blue, green, yellow and red visible wavelengths, which are of sufficiently short wavelength to have meaningful penetration in water and enhance differentiation of seabed habitat types (Fig. 4.2). The number of habitat classes was set at five or six: appropriate to represent observed habitat classes without being overly complicated or confusing. For each class, a range of points (± 3 m) were selected for ground-truthing (*section 4.2.2.1*) so that specific habitat could be assigned to each habitat class using supervised classification methods (*section 4.2.1.4*, Fig. 4.2).

4.2.1.4 Supervised classification

Supervised classification also used the first five visible wavelengths but ground-truth habitat data (*section 4.2.2.1*) were used to more accurately assign the habitat classes. For each site, the spatial distribution of six habitat classes (i.e., relatively homogenous spectral variation for each of the five wavelengths) was derived from group analysis and maximum likelihood tools. Due to image resolution limitations (< 2 m), seafloor type variables, such as seagrass, macroalgae, bare sand, and extent (% cover), were used as input data. Despite the obvious importance of sediment variables such as OM and chlorophyll-*a* content, and granulometry to sandfish (see Chapter 3), they were not used in this preliminary assessment as it unlikely that these variables would be detected at the image resolution. Multiple iterations were done using variations in classification, field knowledge and habitat photographs to fine-tune the classification.

4.2.1.5 Accuracy assessment

It is important to consider errors associated with remote sensing in order to obtain a good quality end-product, but also to determine reliability of the result. Estimates of the accuracy of the final supervised classification were obtained in two ways (Fig. 4.2):

1. Visual comparison of the supervised classification results against ground truth habitat data, interpreted by someone with expertise and with detailed knowledge of the area—if the data matched, then the results are acceptable; and

2. Generation of an ‘output confidence raster’ dataset that indicates the certainty of the classification for each trial sea ranch (Fig. 4.2). This dataset provides a confidence

level between 1 and 14 for each individual supervised classification raster cell, where value 1 has a 100% chance of reliably reflecting the input ground-truth habitat data, value 5 has a 95% chance, value 7 has a 50% chance and so on until value 14 has a no more than random chance of matching the data (ESRI 2020).

4.2.2 Field data sources

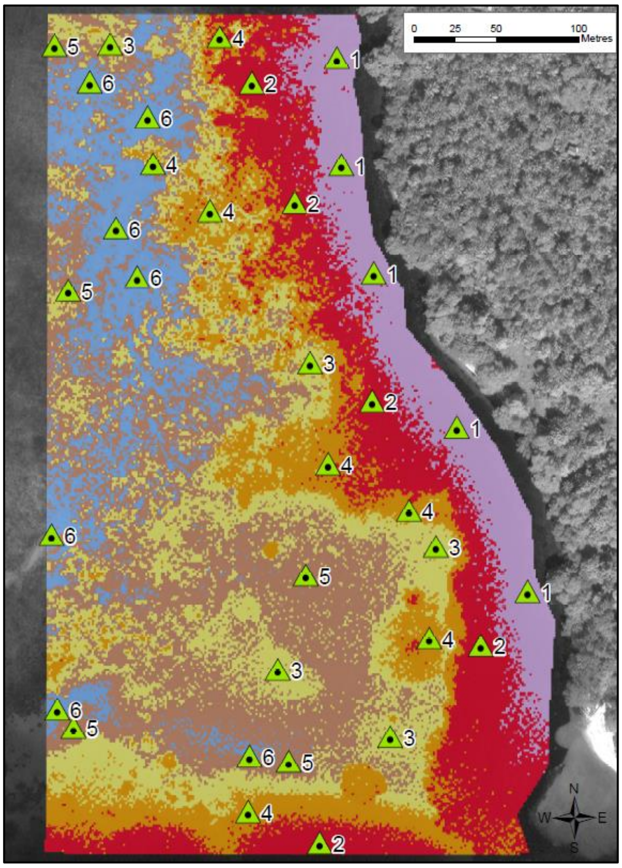
4.2.2.1 Ground-truth habitat data collection

Ground-truth survey locations were selected from within the six broad classes of habitat generated by the unsupervised classification. The habitat data survey was done in March 2019; ground-truth data were collected at 5–7 verification points per habitat class in each trial sea ranch site (Fig. 4.3). Each ground-truth point was the centre of a minimum 9 m^2 of the target habitat class, to ensure that GPS inaccuracy did not extend the ground-truth point into a different habitat class. Only seafloor cover information was collected for ground-truthing (e.g., macrophyte type or sand with an estimate of percentage cover). Photographs were taken of the habitat at each point.

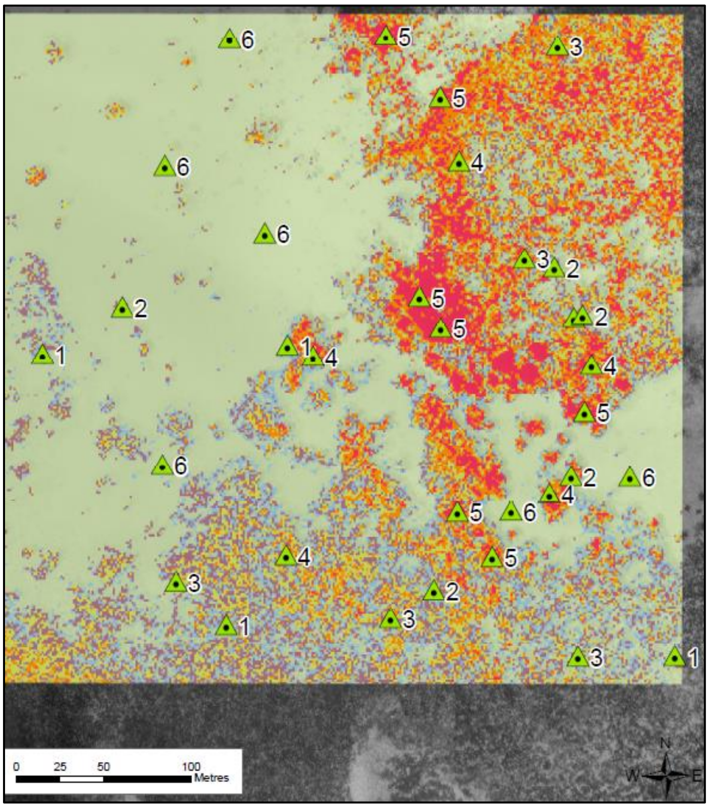
4.2.2.2 Transect data – Sandfish distribution, abundance and size

Surveys of wild sandfish distribution at each trial sea ranch were carried out prior to lifting of the national sea cucumber fishing moratorium in April 2017 (see Chapter 2) and before any cultured sandfish juveniles were released. Within each ranch, a series of transects were arranged according to a stratified design with more survey effort in the central juvenile release area of the trial sea ranch (Fig. 4.4, and see Juinio-Meñez et al. 2013). A snorkel diver counted all holothurians within 1 m either side of 30-m and 100-m transect lines (i.e., 60 m^2 and 200 m^2, respectively). Total surveyed transect area was 6,360 m^2 of the Limanak trial sea ranch (9.1% of the total area), and 5,960 m^2 of the Ungakum trial sea ranch (11.9% of the total area).

Weights of all observed sandfish were measured to the nearest gram (g) in the Limanak trial sea ranch. At the Ungakum trial sea ranch, sandfish length and width were measured to the nearest centimetre (cm) and weight was estimated using the formula of Purcell and Simutoga (2008). These differences in data collection were because the offshore site at Ungakum prevented reliable use of a digital balance. All surveys were carried out in the afternoon on a rising tide to maximise chances of sandfish being on the substrate surface and minimise biases that may result when surveys are done on different days and at different locations (Skewes et al. 2000).

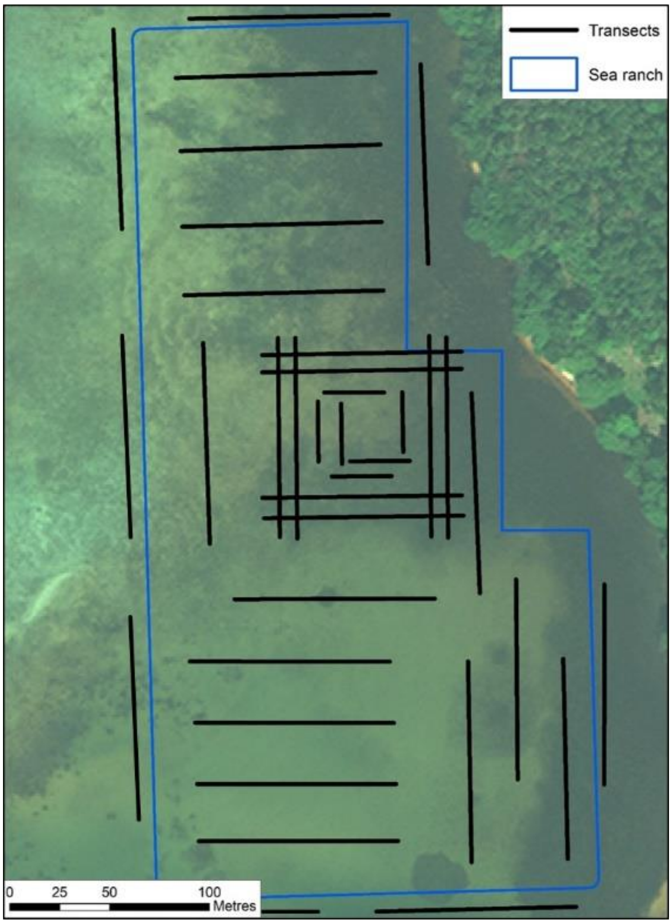


(a)

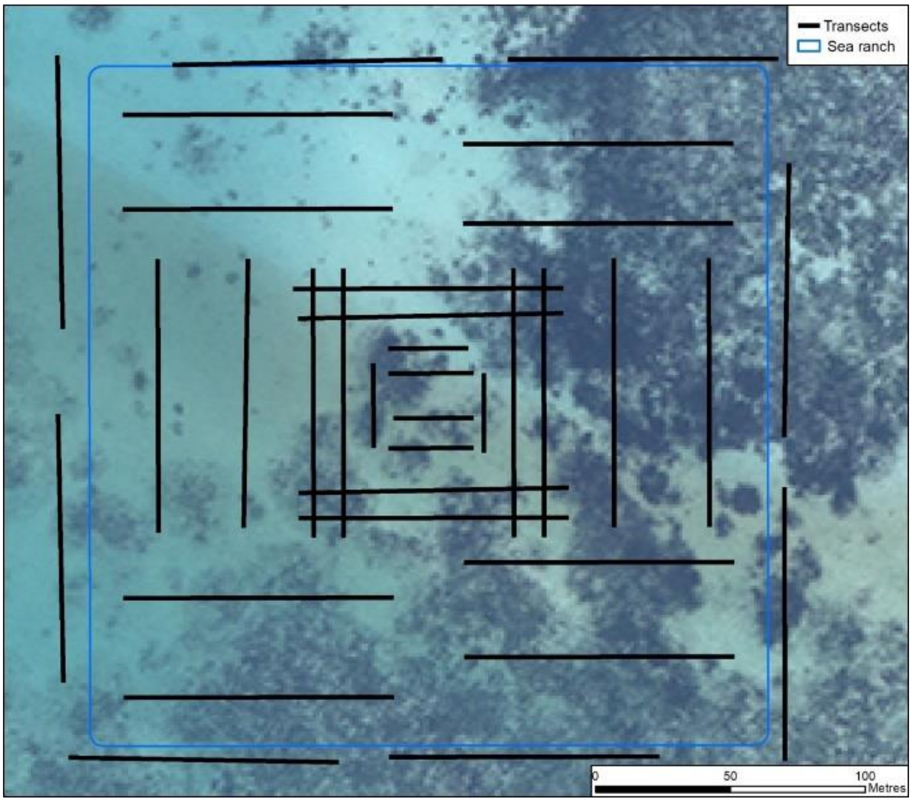


(b)

Figure 4.3 Ground-truth points (triangle) selected for (a) Limanak, and (b) Ungakum trial sea ranches, from habitat classes (denoted by number) identified through the unsupervised classification.



(a)



(b)

Figure 4.4 Location of sea cucumber survey transects (black lines) in (a) Limanak, and (b) Ungakum trial sea ranches. Blue line denotes boundary.

The sandfish transect surveys were to be repeated one year after completion of stocking of juvenile cultured sandfish to generate data on survival, growth, migration patterns and habitat preferences of cultured sandfish within the sea ranches. However, due to poaching of sandfish within both sea ranches during the sea cucumber fishing seasons in 2017 and 2018, no data were obtained on cultured sandfish (see Chapter 7). All results reported in this chapter refer to wild sandfish, which, at the time they were surveyed, had been unfished for a minimum of seven years since the moratorium was imposed in 2009 (Chapter 1).

4.3 Results

4.3.1 Green band and NDVI

Green wavelength and NDVI showed similar capability to differentiate habitat types within the trial sea ranches through visual comparison of different colours or colour shades (Figs 4.5, 4.6). However, neither of these spectral analyses distinguished seagrass from macroalgae beds where both habitats were present in the Ungakum trial sea ranch.

4.3.2 Unsupervised and supervised classifications

Habitat classes within the trial sea ranches were differentiated by unsupervised and supervised classifications. Unsupervised classifications were less effective than supervised classifications because, after visual inspection, only some of the resulting habitat polygons matched researcher's knowledge and manual interpretation of the WorldView imagery (Figs 4.7, 4.8). On the other hand, the supervised classification showed the best agreement between the resulting classes, researcher knowledge and the ground-truth data. Notwithstanding, and in line with recognised marine remote sensing limitations (Purkis et al. 2019), there were cases where field data did not match the supervised classification. It is quite likely that one or more of the following factors may have been responsible for the discrepancies: (1) areas where there was greater heterogeneity of habitat at a relatively fine scale; (2) GPS inaccuracy; and (3) changes in habitat between the time of data collection and image acquisition.

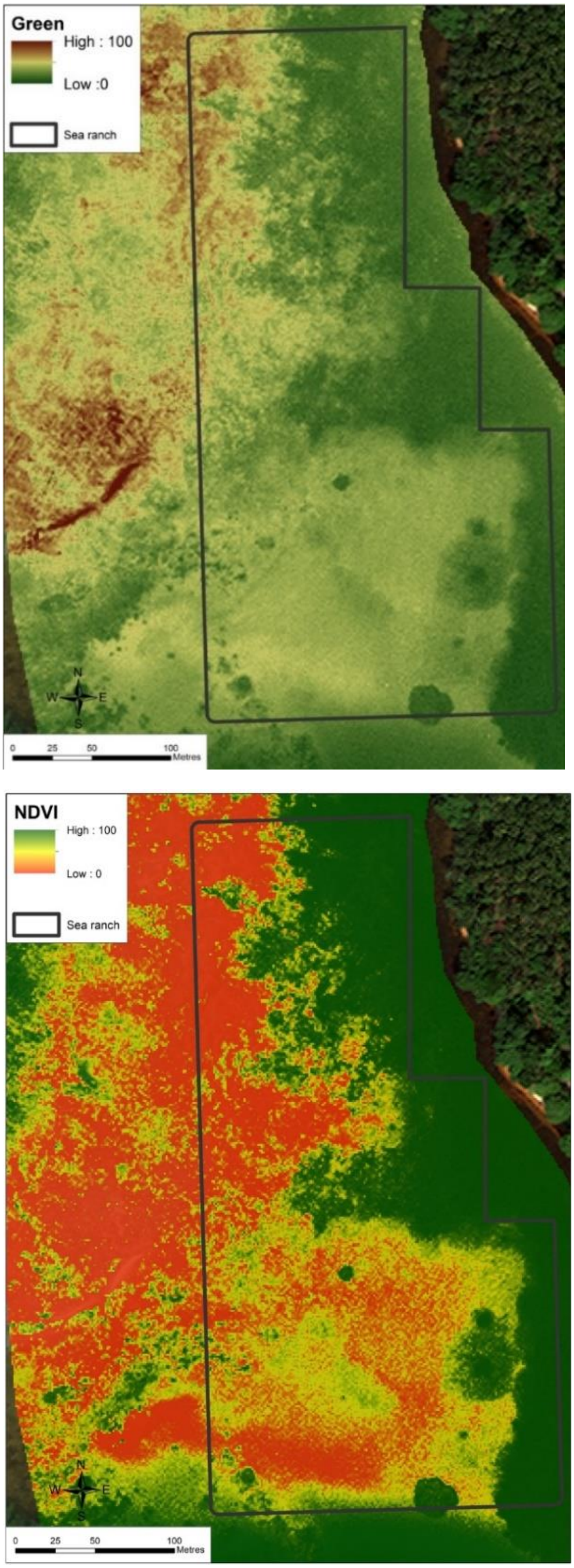
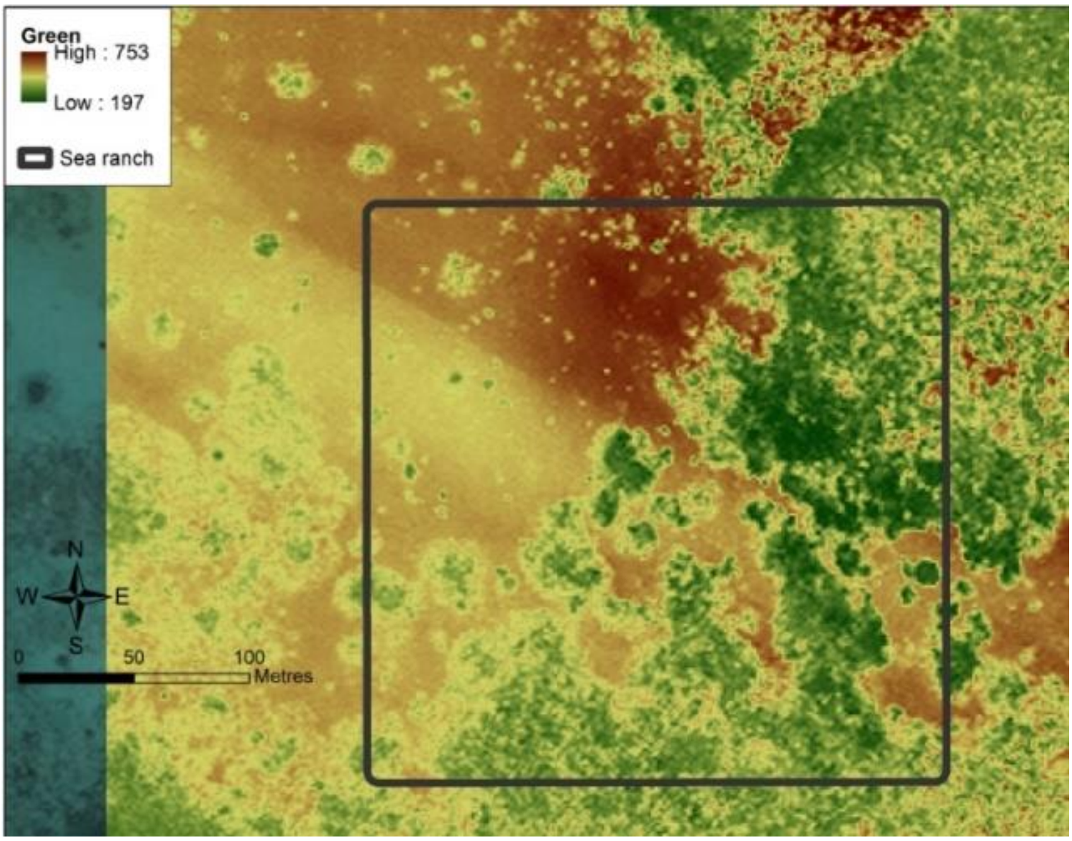
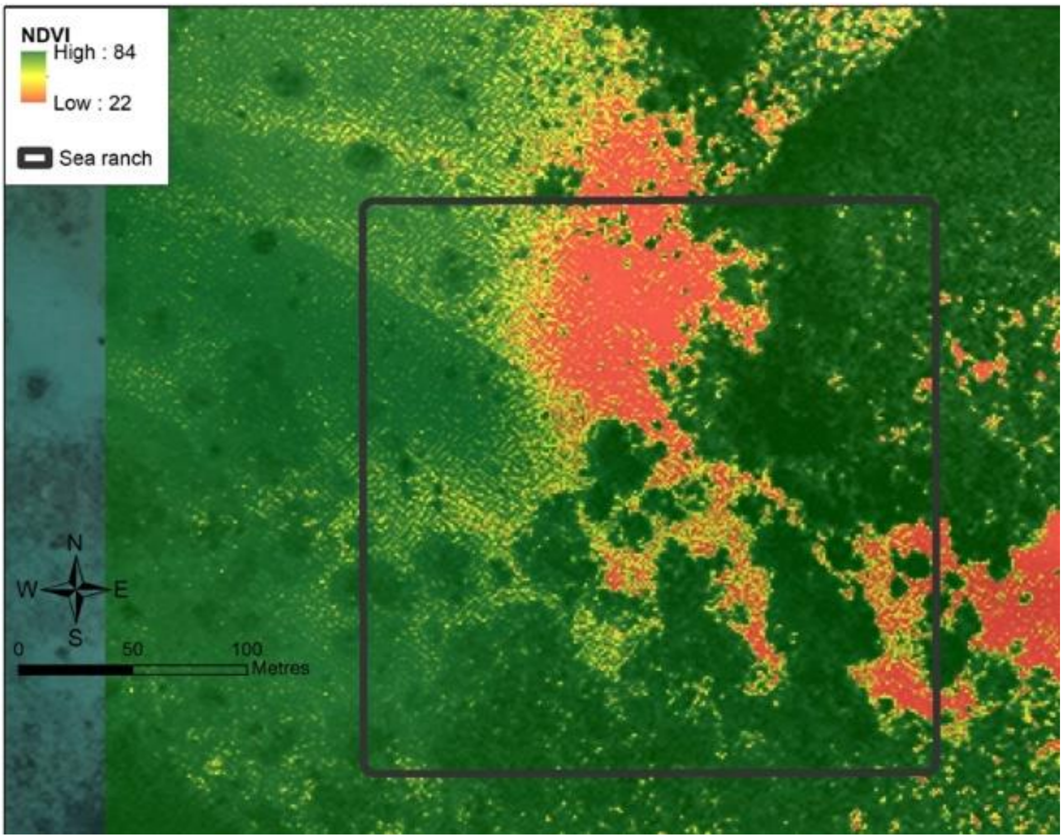
(a)
(b)


Figure 4.5 Maps of Limanak trial sea ranch: (a) green band; and (b) NDVI.

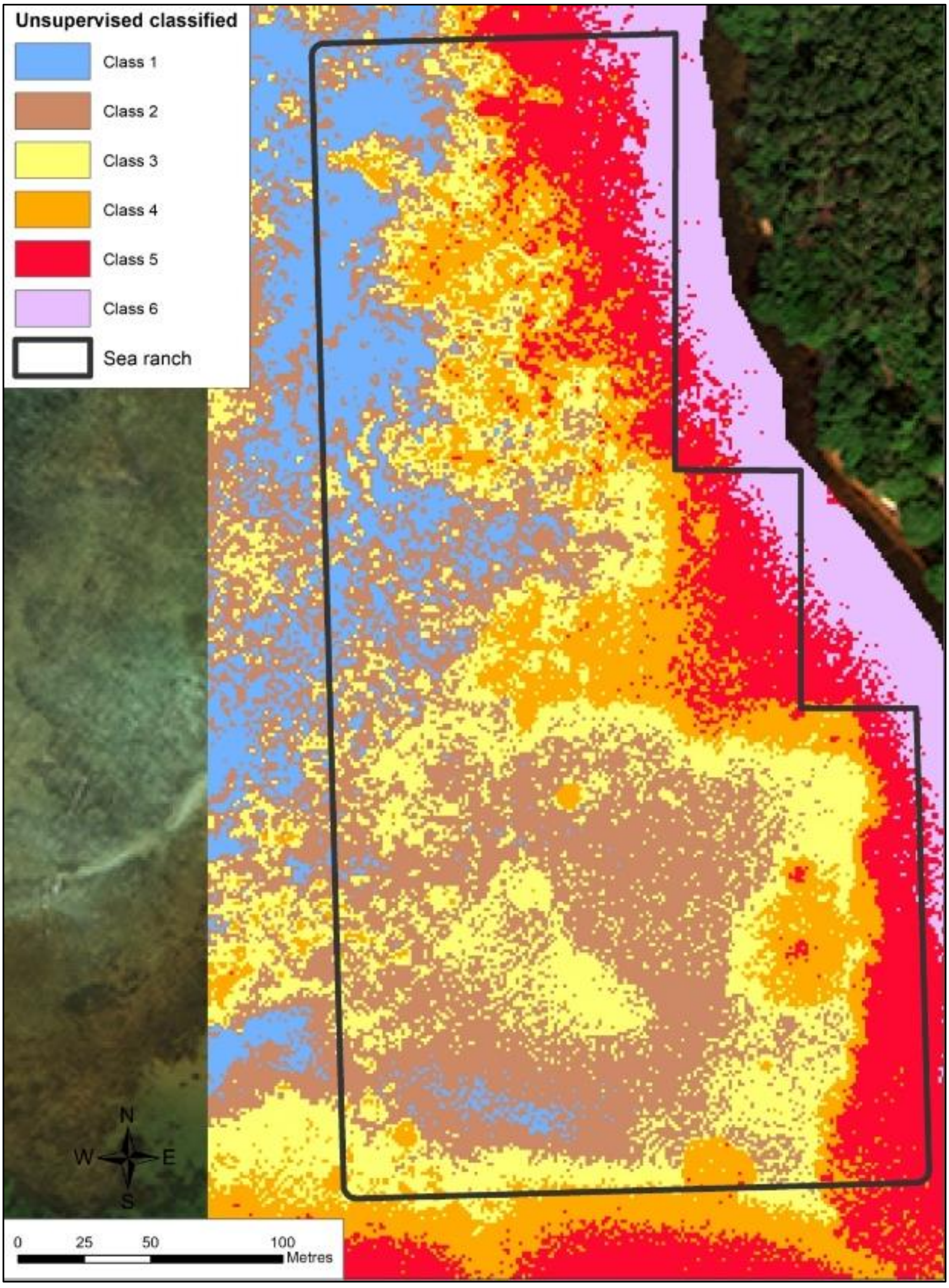


(a)



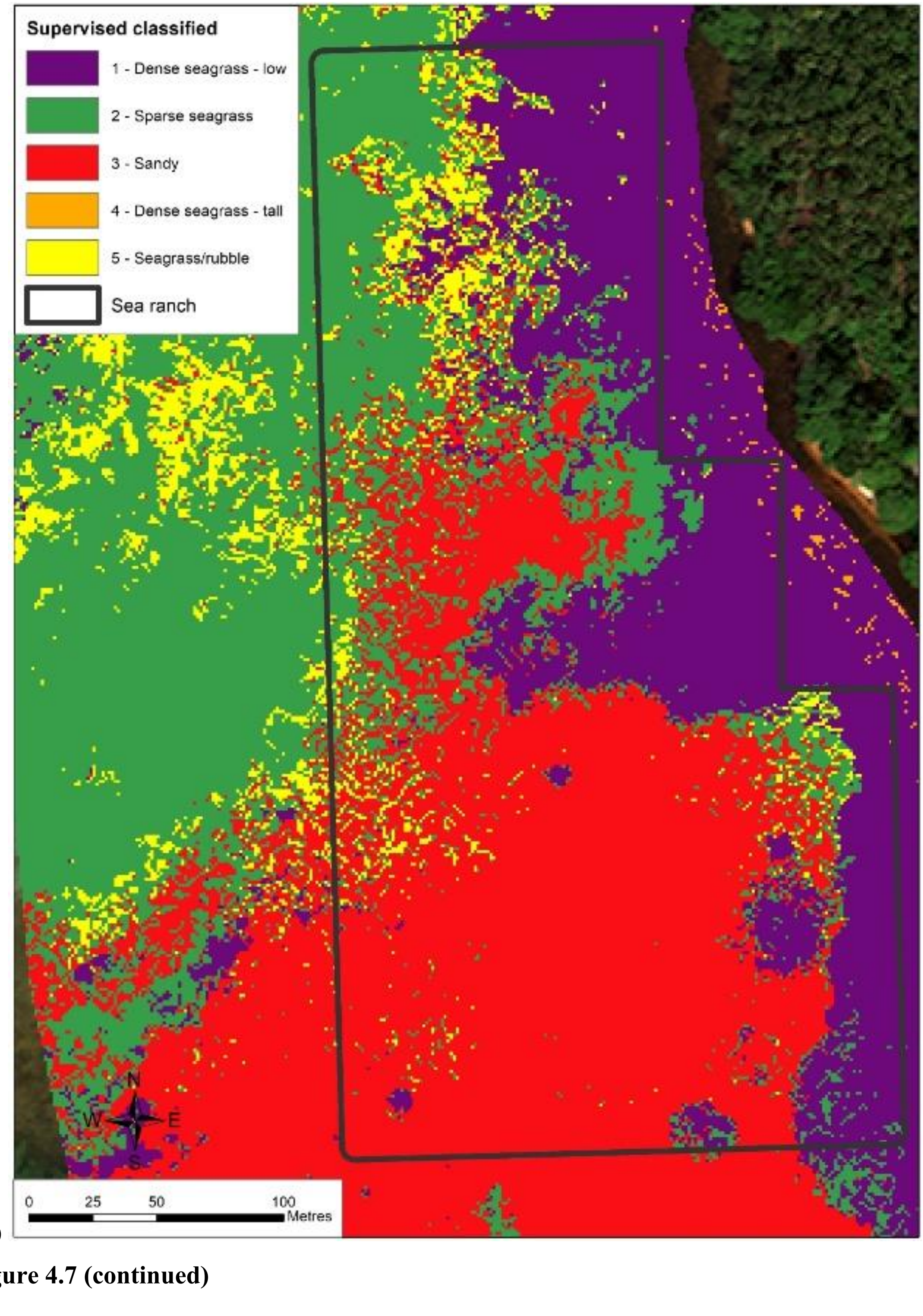
(b)

Figure 4.6 Maps of Ungakum trial sea ranch: (a) green band; and (b) NDVI.



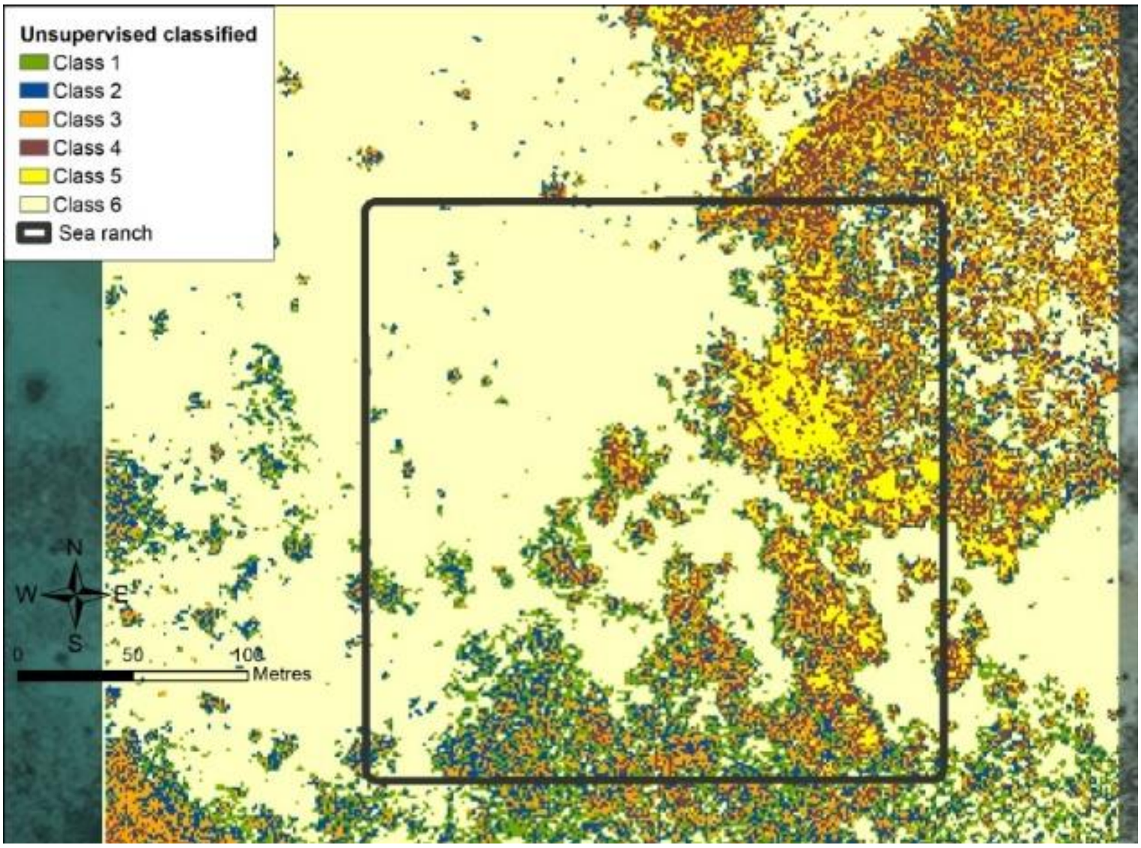
(a)

Figure 4.7 Classification maps of the Limanak trial sea ranch: (a) Unsupervised; and (b) Supervised.

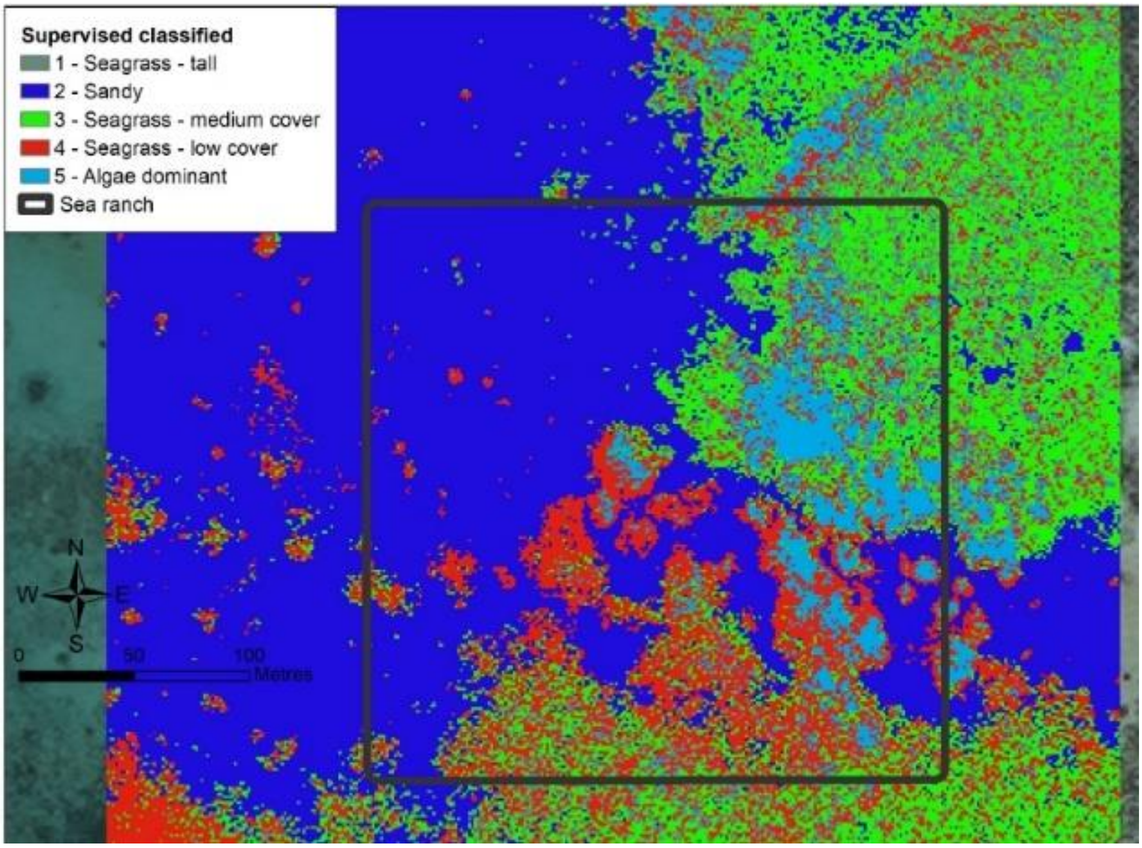


(b)

Figure 4.7 (continued)



(a)



(b)

Figure 4.8 Classification maps of the Ungakum trial sea ranch: (a) Unsupervised; and (b) Supervised.

4.3.3 Output confidence raster values for supervised classifications

The output confidence raster values for the supervised classification of each trial sea ranch indicate the amount of confidence for classified cells (ESRI 2020) (Table 4.1). Confidence levels were approximately normally distributed, but 60–70% of pixels in each image had < 50% likelihood of matching their assigned habitat class., suggesting that more ground truth points may be necessary to boost the raster scores in the more reliable 1–7 value range.

Table 4.1 Output confidence raster summary (no of pixels per confidence level) and percentage chance of being correctly classified, for the supervised classification of Limanak and Ungakum trial sea ranches.

Reliability value	Chance (%)	Limanak	Ungakum
1	100	414	210
2	99	372	229
3	98	1078	768
4	95	1736	1519
5	90	3367	3684
6	75	11216	15507
7	50	23135	30657
8	25	32859	28955
9	10	27798	16910
10	5	12114	6774
11	2.5	6942	4101
12	>1 – 2.5	5519	3855
13	0.5 – 0.1	2185	1927
14	~ 0	4646	10418
Total		133381	125514

4.3.4 Sea cucumber transect data

In May 2016, a total of 943 wild sandfish were recorded on transects in the Limanak trial sea ranch. The transect density of 0.15 individuals m^{-2} extrapolated to an estimated 10,379 sandfish in the 7-ha sea ranch area. Mean estimated individual sandfish weight was 247 ± 8 g (range 17–1,288 g), and 62% of surveyed sandfish weighed less than 200 g (i.e., juvenile and sub-adult individuals) (Fig. 4.9). Greater abundance of juvenile sandfish was recorded in the shallow, dense seagrass zones (density of 0.49 m^{-2}, mean weight 93.2 g ± 2.3 se) with fewer, commercial-size sandfish in deeper, sandy habitat (density of 0.09/m^2, mean weight 702 g ± 24.9 se).

In June 2016, a total of 256 wild sandfish were recorded on transects in the Ungakum trial sea ranch. The transect density of 0.04 individuals m^{-2} extrapolated to an estimated 2,147 sandfish in the 5-ha sea ranch area. Mean estimated individual weight was 426 ± 10 g (range 135–1,102 g), three individuals weighed less than 200 g (Fig. 4.9). Mostly mature sandfish were recorded throughout the sea ranch area and there were no obvious distribution patterns related to specific habitats.

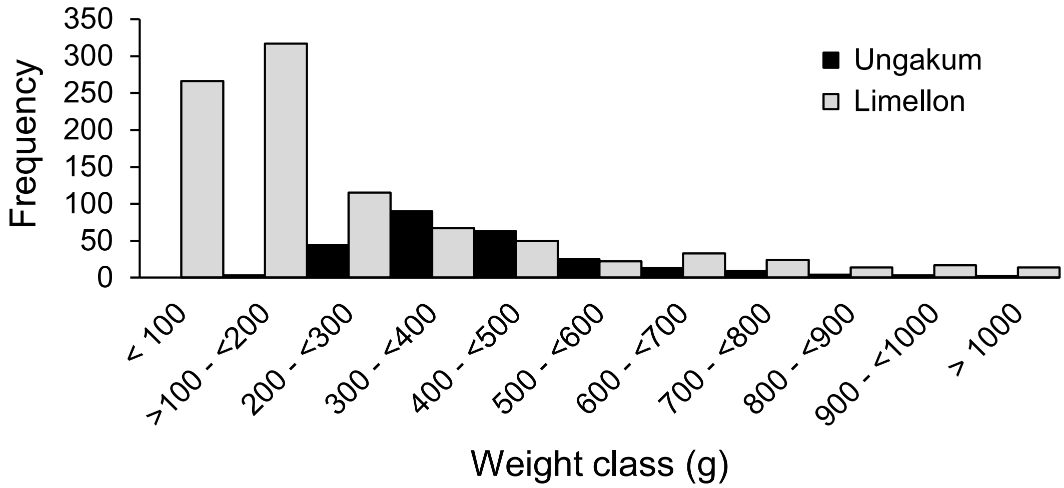


Figure 4.9 **Sandfish weight frequency histogram for the Limanak (*n* = 943) and Ungakum (*n* = 256) trial sea ranches.**

4.3.5 Comparison of field survey data with remote sensing maps

4.3.5.1 Biophysical habitat data

By comparing knowledge acquired during on-site field work and the supervised classification, the Limanak sea ranch site can be shown to contain five distinct habitat zones (Fig. 4.10). These were:

1. Shallow, dense seagrass meadow of low-canopy *Thalassia hemprichii* and *Halodule* sp. along the north-east sea ranch edge;

2. High-canopy *Enhalus acoroides* (sometimes with a *T. hemprichii* understory) along the south-east sea ranch edge;

3. Sparse to medium, low-canopy seagrass meadow with bare sand patches to the north;
4. Deeper sandy area to the south; and
5. Coral, rubble and sparse seagrass along the western edge of the sea ranch (unsuitable sandfish habitat).

During field work activities, many small sandfish were observed in the shallow, dense seagrass habitat and commercial-size sandfish inhabited the deeper, sandy areas.

In contrast, the Ungakum sea ranch site comprised a more heterogeneous mosaic including bare habitat with sandy mounds (Fig. 4.11), interspersed with sparse-medium seagrass patches, mostly *T. hemprichii* and some *E. acoroides*. There was an area of dense macroalgae (mostly green algae) with some seagrass in the northeast of the trial sea ranch. The site was mostly shallow, although depth increased slightly towards the west side of the trial sea ranch.

4.3.5.2 Sandfish transect data

When sandfish abundance and size data were superimposed on the Limanak NDVI map (Figs 4.12a, b) and supervised classification map (Figs 4.13a, b), there are clearly more, and smaller-sized, sandfish in dense sea grass meadows portrayed as dark green (NDVI) and purple (supervised classification) habitat class. Conversely, there were fewer, but larger-sized, sandfish in low seagrass/bare sand portrayed as yellow/red (NDVI) and red (supervised classification) habitat class.

There was no clear sandfish size-associated distribution within the Ungakum trial sea ranch, either observed during field work or demonstrated with NDVI (Figs 4.14a, b) or supervised classification (Figs 4.15a, b).

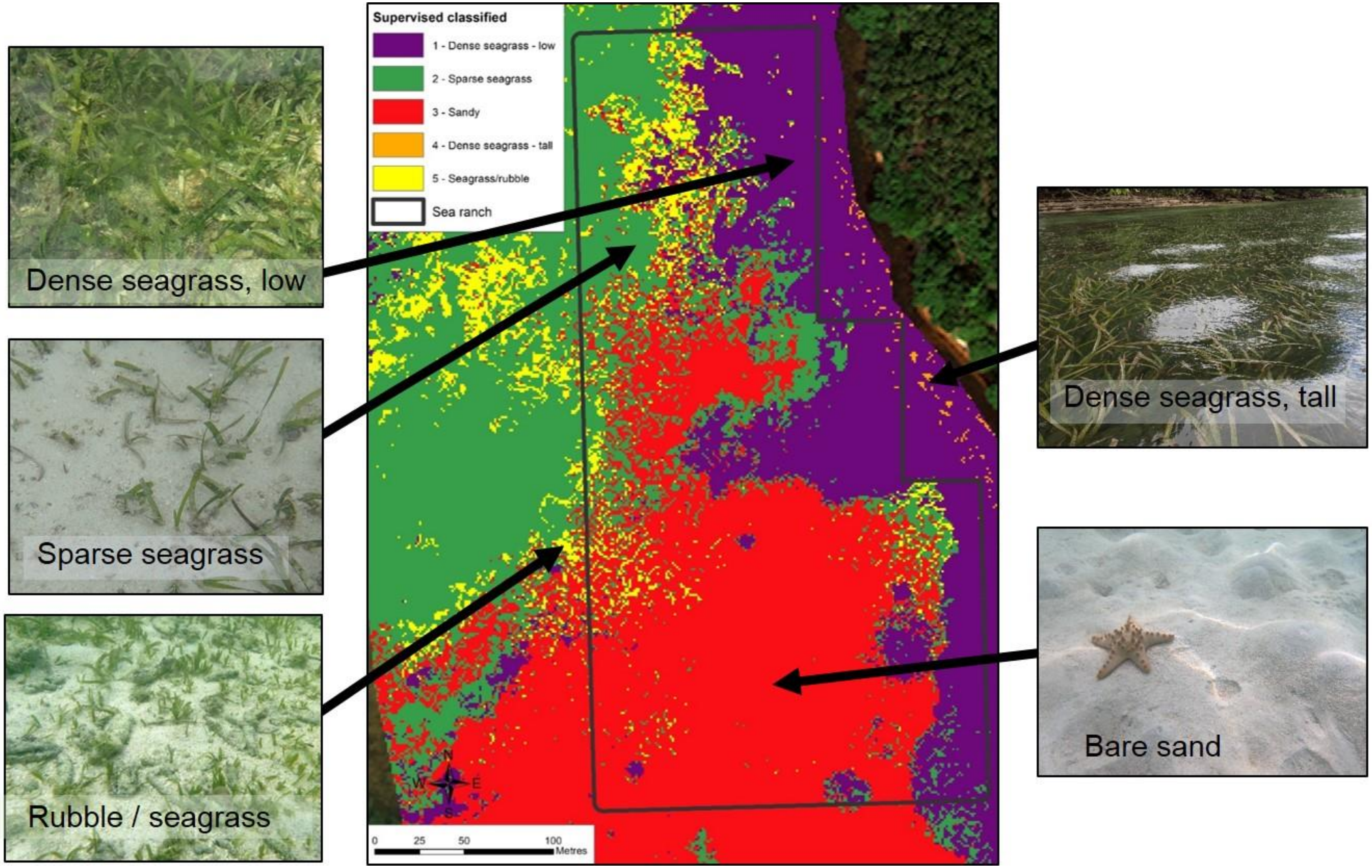


Figure 4.10 Supervised habitat classes for the Limanak trial sea ranch compared with field data photographs.

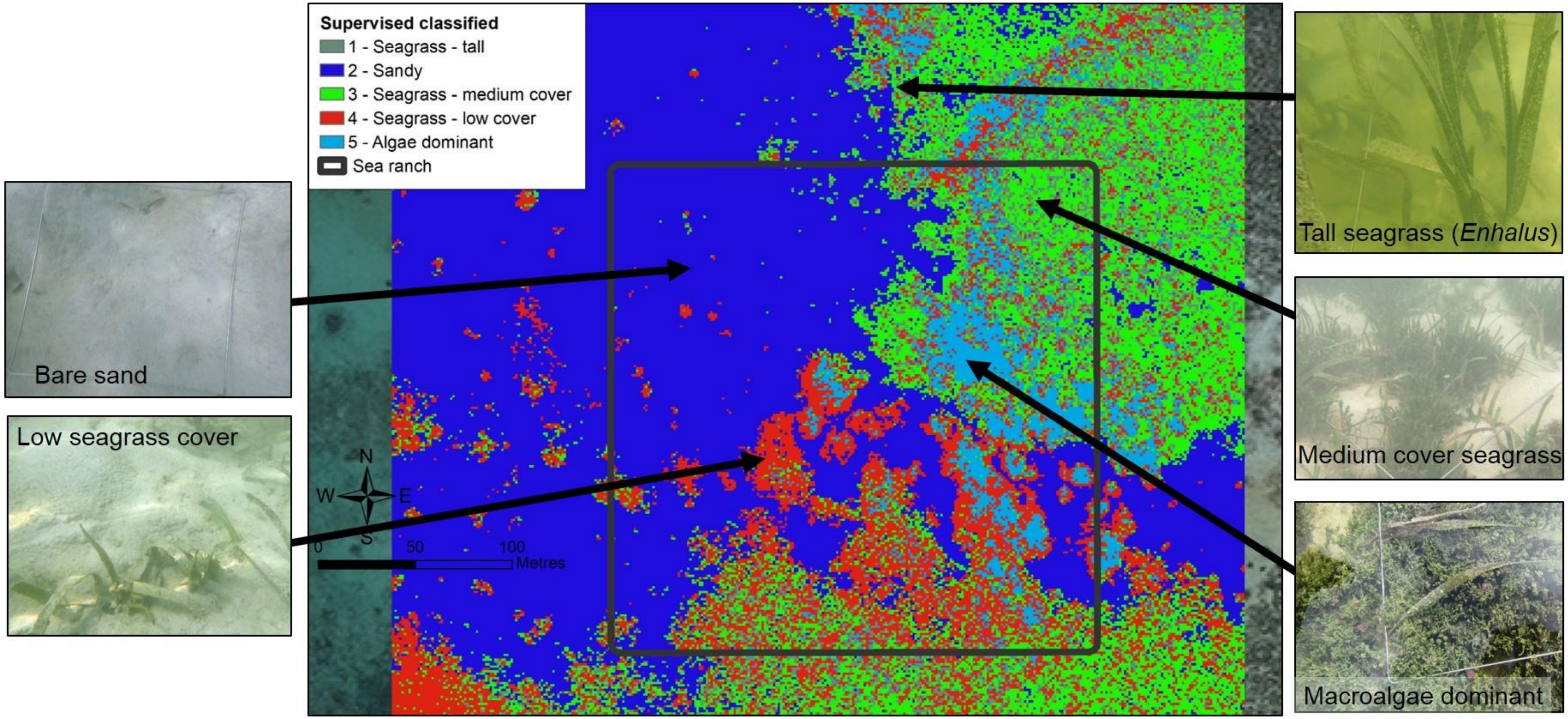


Figure 4.11 Supervised habitat classes for the Ungakum trial sea ranch compared with field data photographs.

(a)

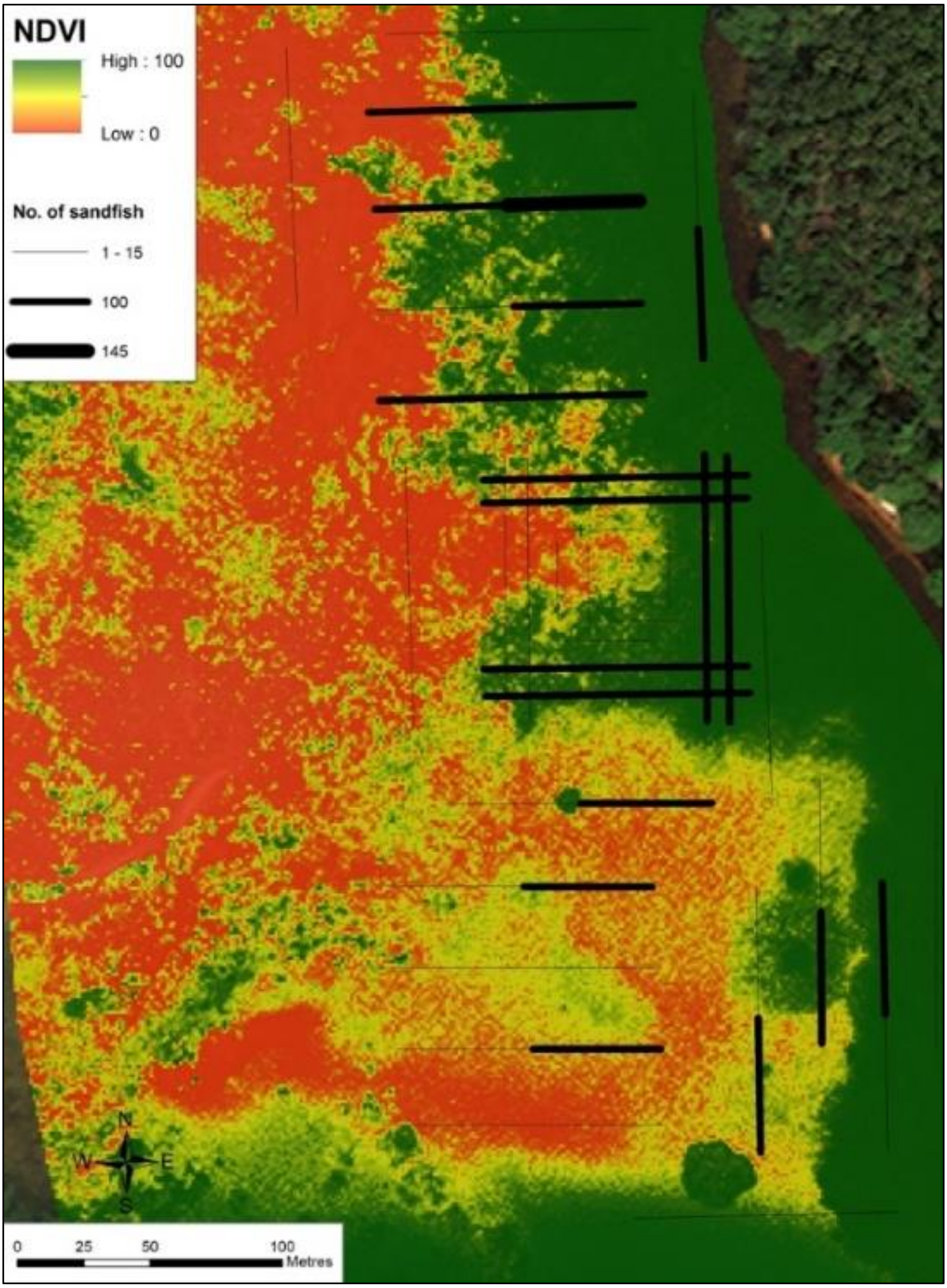


Figure 4.12 Limanak trial sea ranch NDVI map with: (a) sandfish transect abundance; and b) mean sandfish weight (g) per transect.

(b)

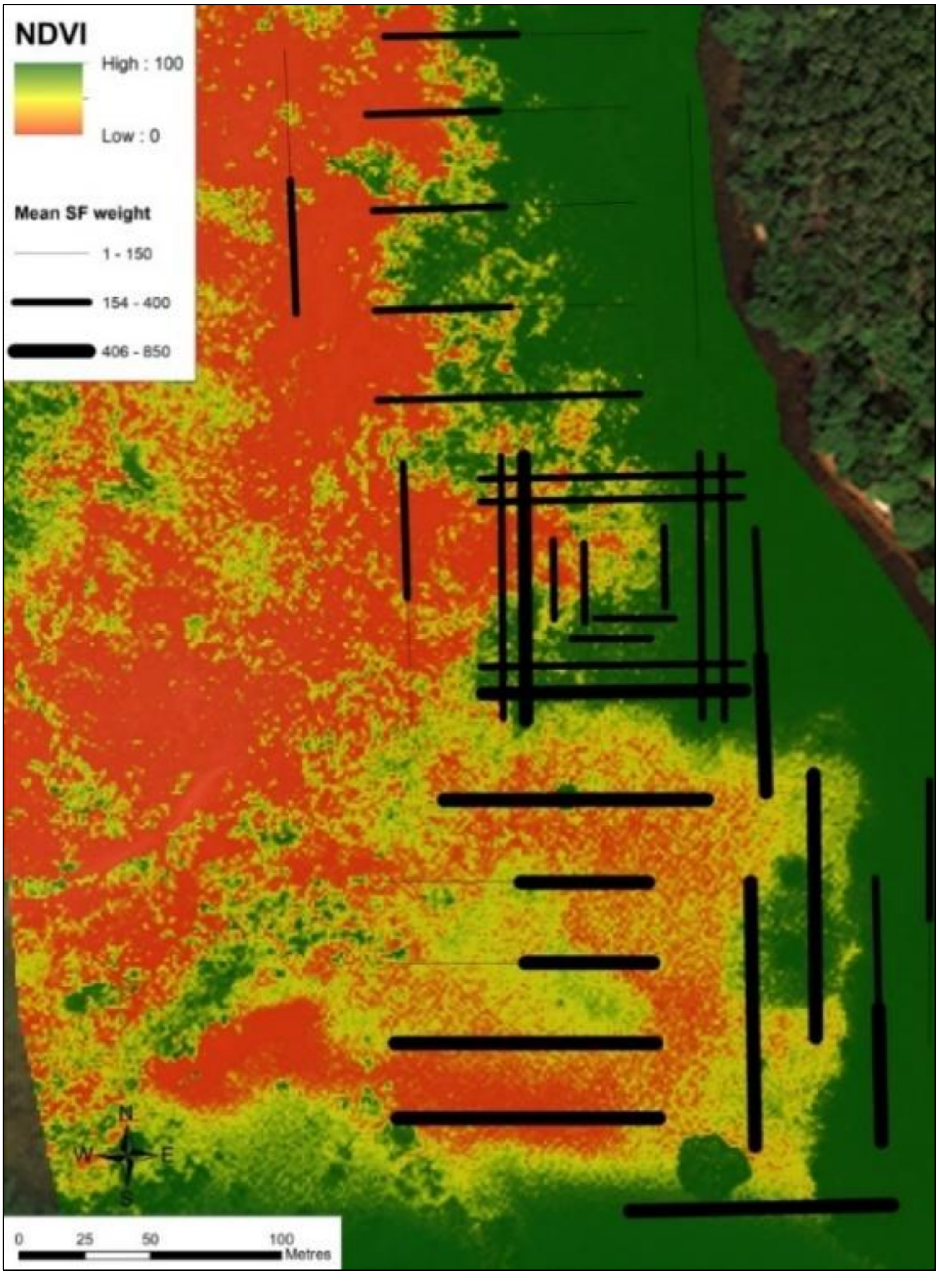
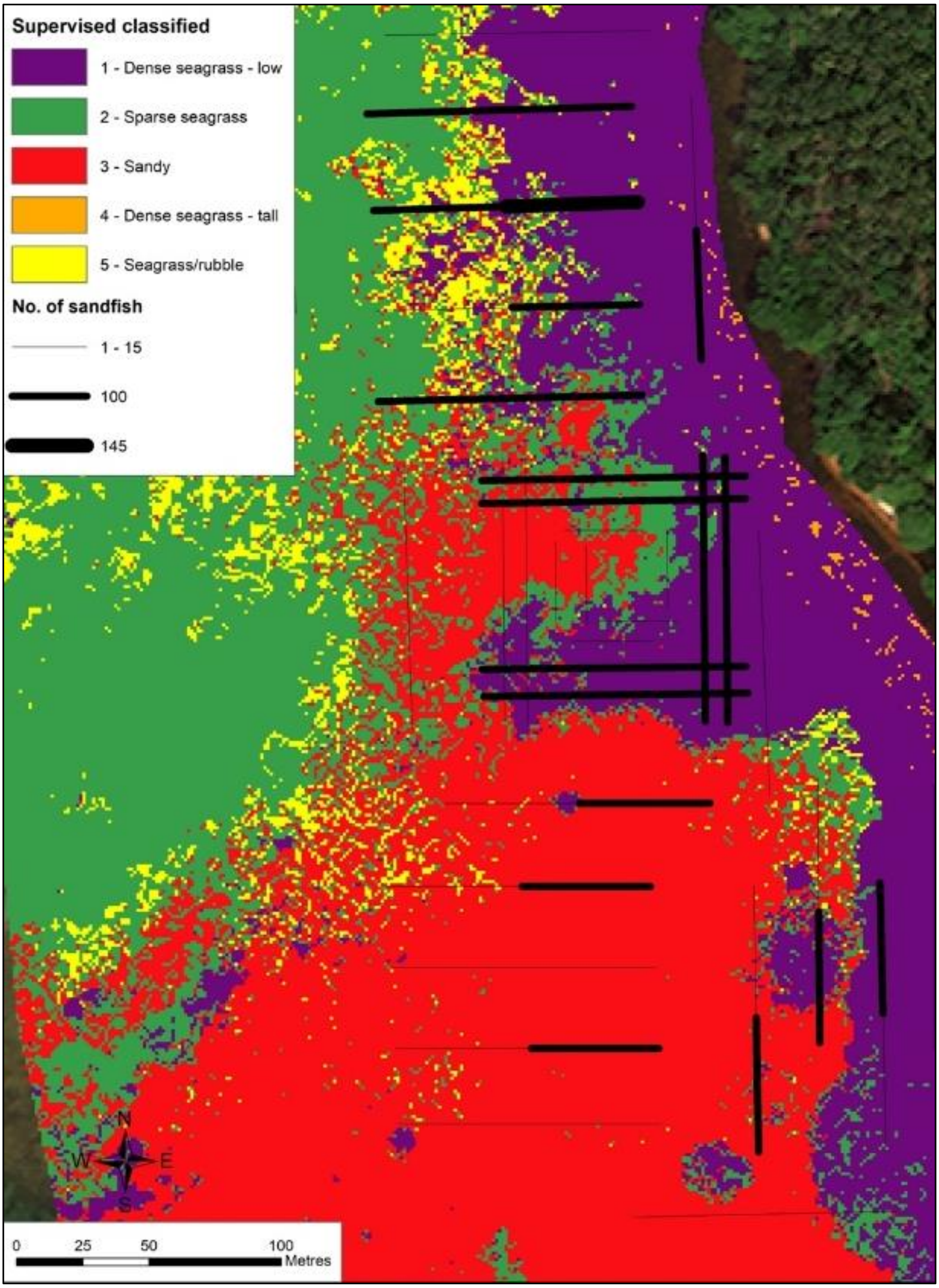
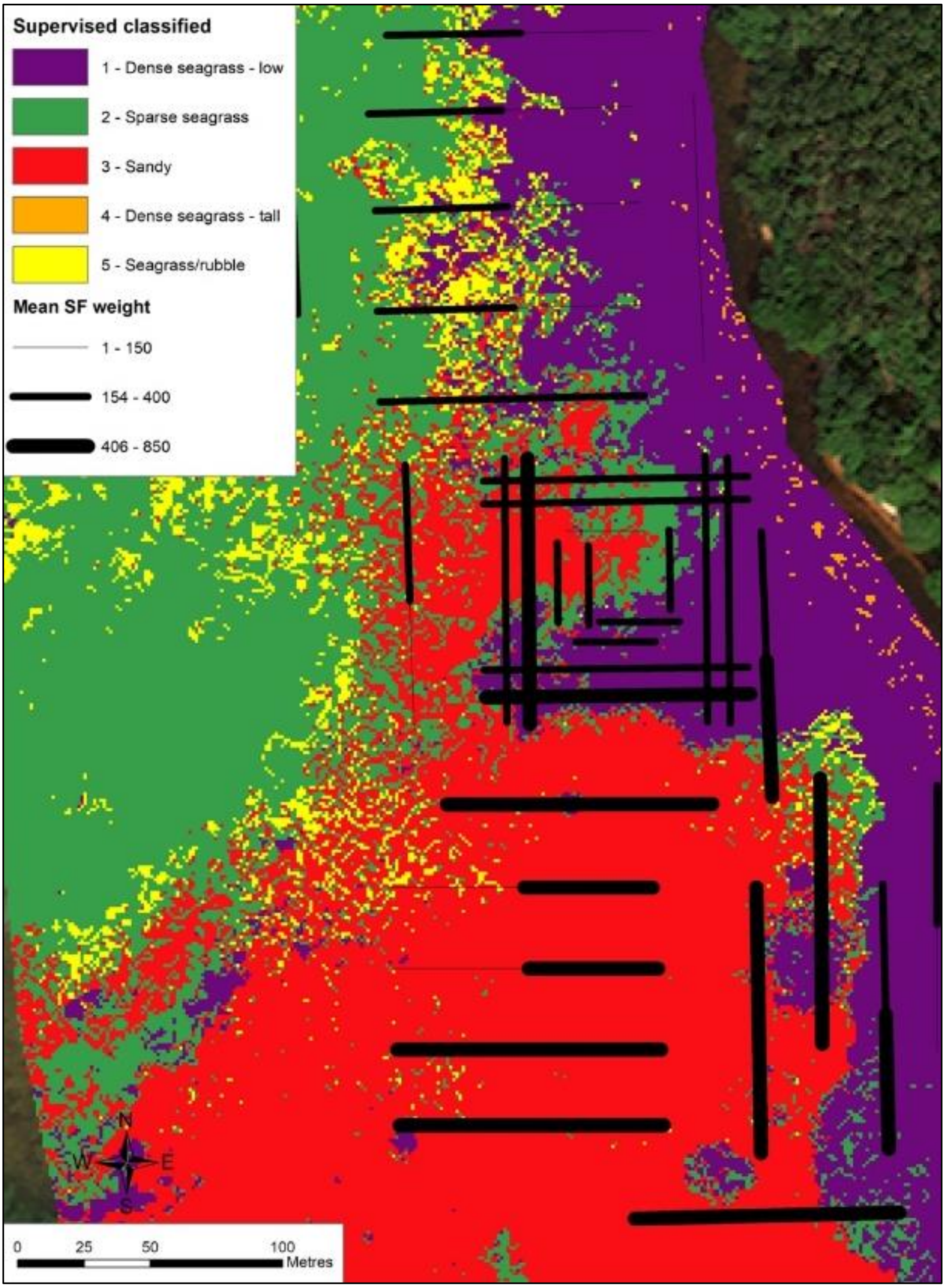


Figure 4.12 (continued)



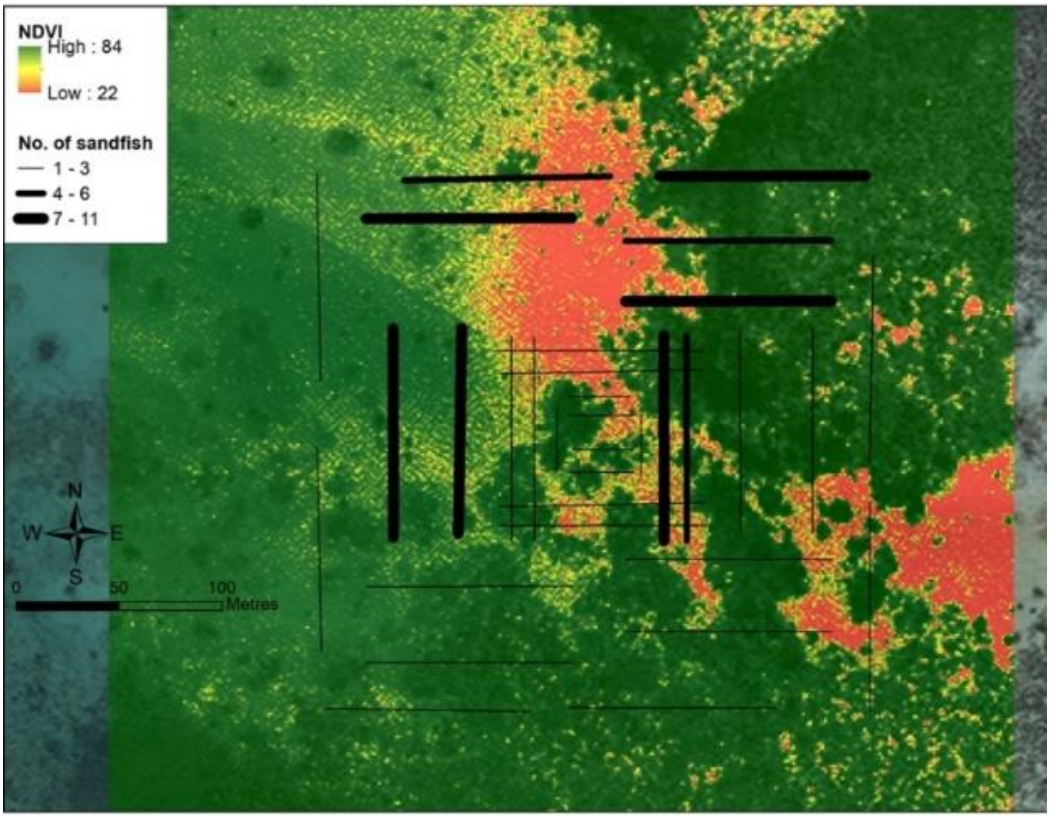
(a)

Figure 4.13 Limanak trial sea ranch supervised classification with: (a) sandfish transect abundance; and b) mean sandfish weight (g) per transect.

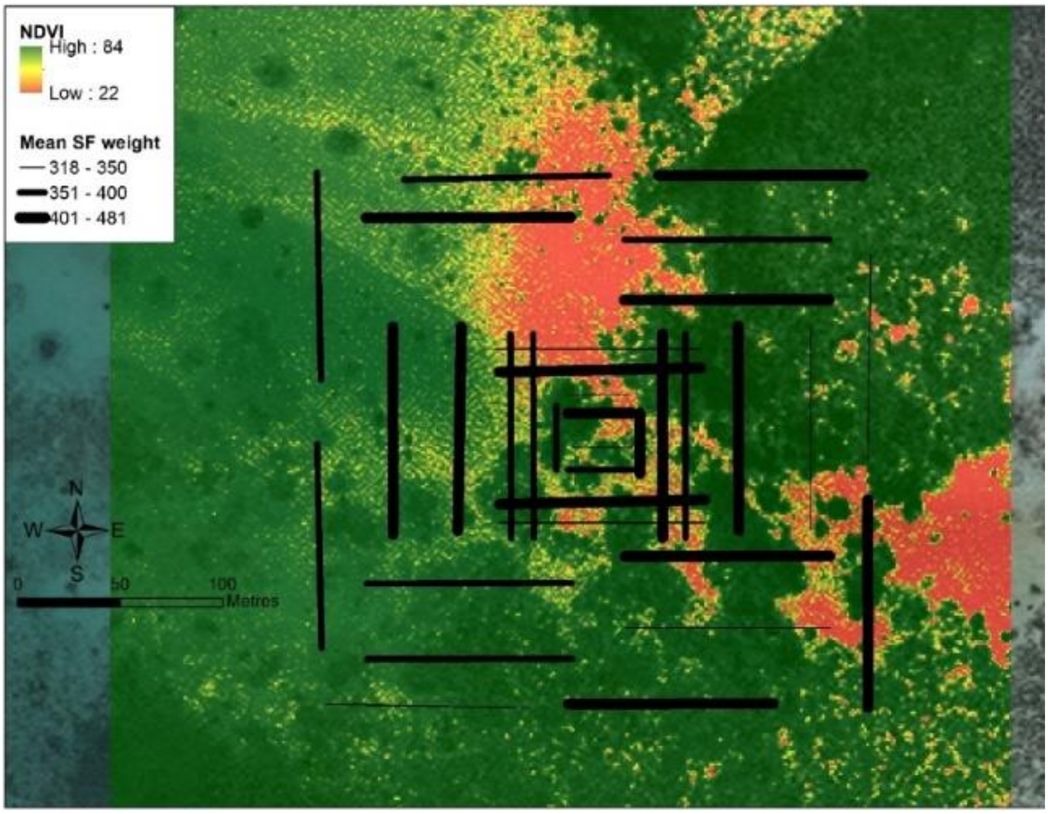


(b)

Figure 4.13 (continued)

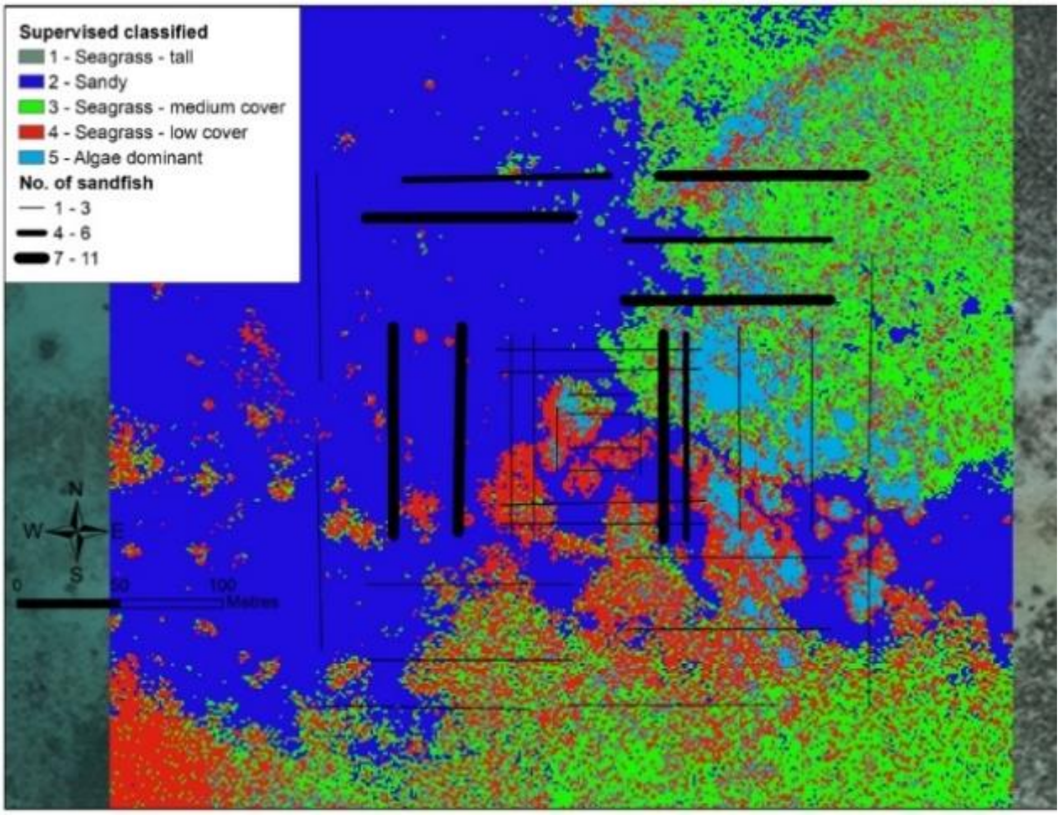


(a)

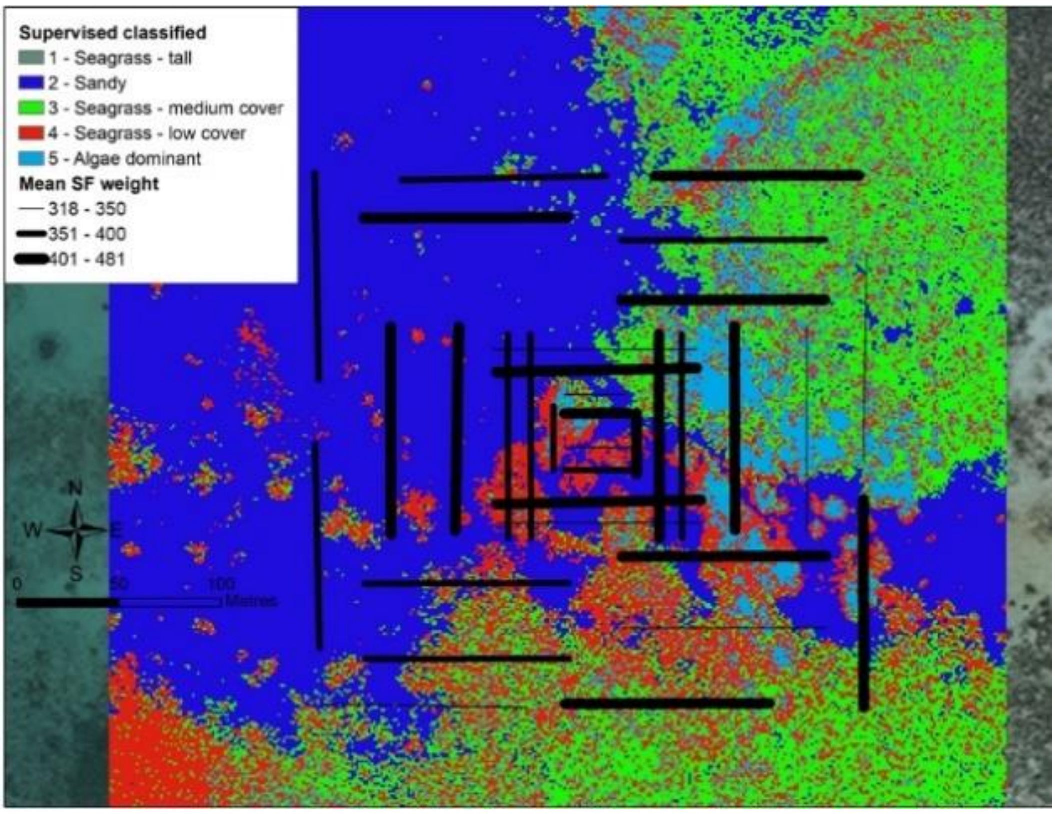


(b)

Figure 4.14 Ungakum trial sea ranch NDVI map with: (a) sandfish transect abundance; and b) mean sandfish weight (g) per transect.



(a)



(b)

Figure 4.15 Ungakum trial sea ranch supervised classification with: (a) sandfish transect abundance; and b) mean sandfish weight (g) per transect.

4.4 Discussion

It should be noted that while this chapter delves into remote sensing in some detail, is not intended to be a specialist contribution to the remote sensing field at this time. Rather, it presents a preliminary exploration of the potential of remote sensing to contribute to development of the sea cucumber mariculture industry within the greater context of this thesis.

4.4.1 Effectiveness of remote sensing techniques for assessing sandfish habitat

Supervised classification, with ground-truthing field data, was the optimal remote sensing approach to represent habitat classes for both trial sea ranches. At Limanak, there were two supervised classes that corresponded to nursery (dense, shallow seagrass) and adult (deeper, bare sand) sandfish habitats that were similar to those described in Solomon Islands and PNG (Mercier et al. 2000b, Feary et al. 2015, respectively). This was not the case at Ungakum, where predominantly adult sandfish were found throughout the trial sea ranch, regardless of habitat class. However, supervised classification with ground-truth data was effective in delineating dense macroalgae from seagrass as a distinct habitat class where these macrophytes co-existed at the Ungakum site. This is useful because seagrass is acknowledged as an important habitat for juvenile sandfish (Hamel et al. 2001, Ceccarelli et al. 2018). Less is known about the utility of benthic macroalgae for sandfish, although sandfish were recorded in this habitat at the Ungakum site and it may have potential as suitable habitat. There is continuing progress on differentiating macroalgae and seagrass using remote sensing (Hossain et al. 2015, Pe'eri et al. 2016, Alkhatlan et al. 2018) and this will support more accurate assessment of these habitats using GIS in the future.

4.4.2 Limitations of remote sensing for assessing potential sandfish habitat

Despite some acceptable preliminary remote sensing results, using these techniques for marine habitats is not precise and has limitations. Errors can be introduced at multiple stages during field data collection, image processing and the classification process itself (Olofsson et al. 2014, Purkis et al. 2019) and so error in marine remote sensing is unavoidable. As well as complex classification processes, these limitations are attributed to spectral and textural similarity of different habitat classes, effects of depth and presence of turbidity in the water column (Hossain et al. 2015, Purkis et al. 2019). Misclassification occurred using supervised classification in this study; for example, deep sandy habitat presented as the same class (colour) as shallow, dense seagrass in the Limanak sea ranch. Water turbidity considerations are pertinent because sandfish occur in inshore habitat near mangroves, often in muddy seawater (Hamel et al. 2001, Purcell et al. 2012a). This reinforces the need for accurate bathymetry data and expert local knowledge in remote sensing applications.

Cost is a limitation since accurate remote sensing requires satellite imagery (cost increases with improved quality), ground-truth data, in-depth site knowledge and considerable remote sensing/GIS expertise. Less expertise-intensive green band and NDVI analysis were found to be visually useful but results are considered relatively coarse, e.g., macrophyte presence-absence detection. Further, the differentiation of macroalgae from seagrass in the Ungakum sea ranch was only possible using supervised classification with field data. NDVI is not considered ideal for assessment of all seagrass parameters (Hossain et al. 2015), although technological and methodological progress continues to improve NDVI for aquatic applications (Fyfe 2003, Barillé et al. 2010, Yang et al. 2010, Hwang et al. 2019). Unsupervised classification, while less costly and not requiring field data, did not reliably identify suitable sandfish habitat. Another potential problem is matching ground truth data collection with satellite image acquisition date because of infrequent satellite passes over the area of interest close to the time of field data collection, and cloud cover obscuring the image. This presents problems if habitat features (e.g., seagrass or macroalgae cover) change between the survey date and image acquisition date. For example, this study used WV imagery from December 2014 (Limanak) and 21 May 2018 (Ungakum), which were the best available imagery available despite different years and imprecise seasonal match. New satellite sensors (e.g., PlanetScope) offer frequent site revisits that will increase the likelihood of cloud-free images near field data collection dates.

Due to constraints such as image limitation, cost, image availability, the need for ground truth data, and the unique nature of supervised classification algorithms per site, these results suggest that remote sensing alone cannot be used to predict suitable sandfish mariculture sites at this time. However, it can contribute usefully to a broader GIS approach. The remainder of this Discussion is devoted to outlining a flexible and cost-effective GIS protocol that could be customised for PNG and Pacific Island fisheries and aquaculture departments to reduce dependence on traditional field scouting in identifying potentially suitable locations for ocean-based mariculture of sandfish. This three-stage GIS approach is designed primarily to assist in assessing and prioritising community requests for sandfish mariculture, as proposed in this study. Alternatively, the first stage alone could be used to conduct large-scale provincial or national planning activities. The process proposed here requires appropriate input data, GIS software, a competent GIS practitioner and expert advice on ranking/weighting of site feasibility factors since it also incorporates multi-criteria evaluation.

4.4.3 Proposed GIS protocol for mapping suitable sandfish mariculture sites

4.4.3.1 Stage 1

Stage 1 of the proposed process involves assembling useful and available primary data sources, including: variables that directly or indirectly influence the culture of sandfish, such as environmental (e.g., bathymetric, temperature, salinity, wave height, currents, river mouth location, turbidity, submerged macrophyte type/presence, seafloor type, slope), and socio-economic factors (e.g., population density, resort/port location, market chain, hatchery location); and fisheries data (e.g., sea cucumber surveys, BDM exports) (Fig. 4.16). These factors are ranked and scaled using information from available literature on habitat preferences and tolerances for sandfish (Mercier et al. 1999, 2000a, Hamel et al. 2001, Lavitra 2008, Plotieau et al. 2014a, Altamirano et al. 2017, Ceccarelli et al. 2018) and consultation with experts in the field, then transformed to comparable units for use in MCE. The issue of changing habitat requirements with sandfish size (Mercier et al. 2000b, Ceccarelli et al. 2018, Chapter 3) should be incorporated into a GIS site suitability model, just as Zhang et al. (2017) considered seasonal differences in release habitat in relation to life history stage of *A. japonicus*. Constraints that exclude sandfish mariculture or require a buffer zone must also be included (Nath et al. 2000). For sandfish, these might include depth (too shallow or deep), seafloor slope (too steep), location (excessive distance from cultured juvenile source), freshwater discharge, built-up areas (e.g., ports), marine protected areas (MPAs), areas nominated by communities as unsuitable, uninhabited areas (lack of security for cultured stocks) and high wave energy areas. Some MCE models use tourism as an exclusion for sandfish farming because of the assumption that fences will impact on visitor amenity or ascetic aspects (Ciccia Romito 2012, Basir et al. 2017). This may not be a restriction with sea ranches if sea cucumber harvest is permitted in these areas. Similarly, an MPA might not be incompatible with sea ranching if local management rules allow periodic sea cucumber harvest. These factors would need to be considered on a case by case basis in consultation with all stakeholders (as part of the Stage 2 process).

Basic remote sensing functions can also be included in Stage 1. The choice of imagery will depend on budget constraints, as well as the desired spatial scale and spectral profile. Red-green-blue aerial photography could be used for green band analysis. There are a range of options for satellite images ranging from free (Google Earth, Landsat 8), relatively inexpensive (Sentinel, PlanetScope) or costly high-resolution, multi-spectral (e.g., WorldView, QuickBird, Ikonos), bearing in mind that image cost is likely to be offset by savings in travel to remote sites. Nonetheless, as demonstrated in this study, NDVI and green band analysis can assist in identifying macrophyte habitat classes without the need for field data. Remote sensing and ancillary data will be analysed to produce a Stage 1 'indicative' suitability map, which eliminates unsuitable sites and indicates promising suitable areas (Fig. 4.16).

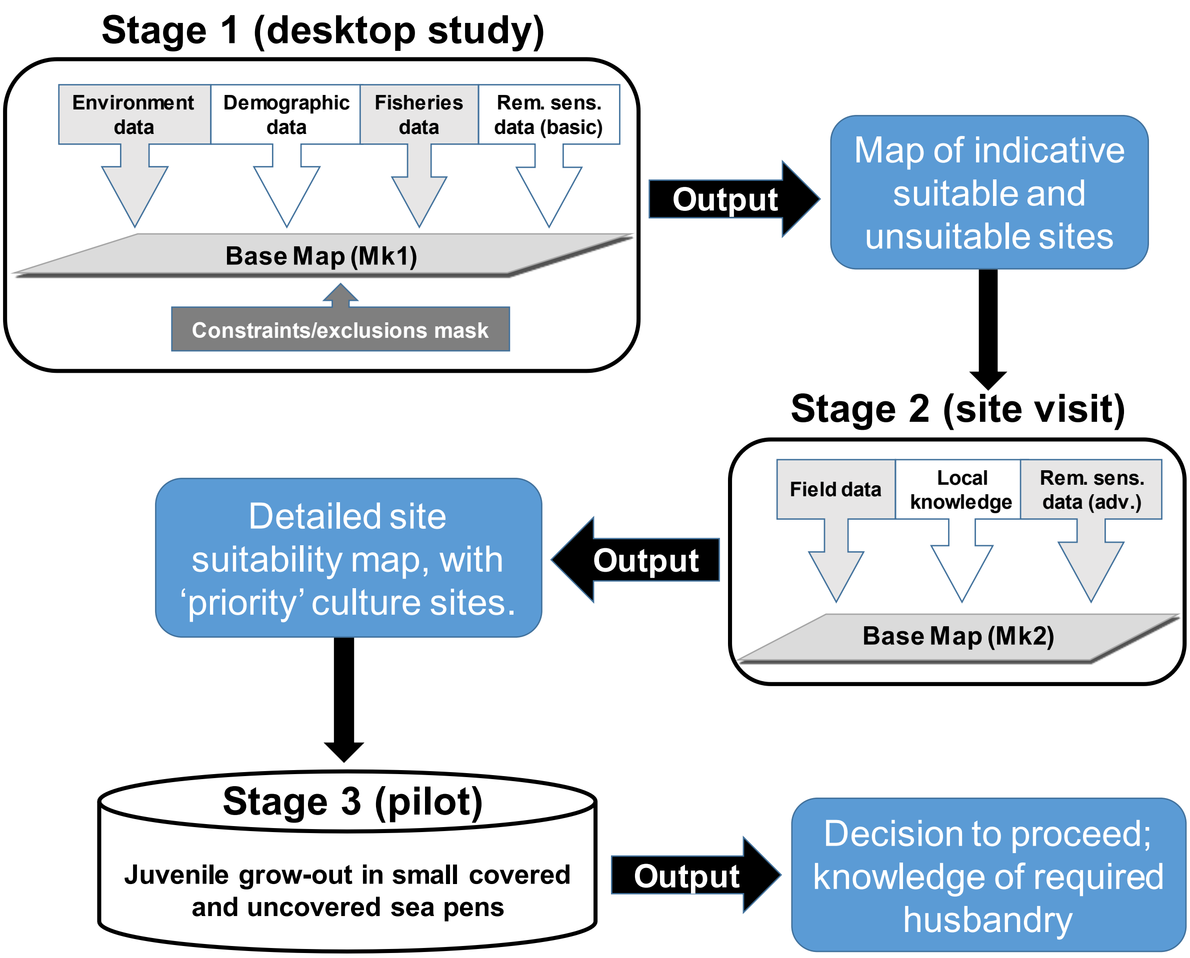


Figure 4.16 **Schematic representation of proposed three stage GIS multi-criteria approach: Stage 1 = coarse scale using available data and basic remote sensing; Stage 2 = site visit (ground-truthing, field data collection, local knowledge), perform supervised classification of optimal sites; and Stage 3 = pilot grow-out of juvenile sandfish in small pens to confirm acceptable sandfish performance.**

4.4.3.2 Stage 2

Once broadly suitable areas are known and if funding permits, then Stage 2 involves a visit to the proposed mariculture site(s) (e.g., to assess a community request for a sandfish sea ranch) (Fig. 4.16). If satellite imagery and GIS expertise are available, ground-truthing of selected GPS points for informing a supervised classification can be conducted (based on key areas identified by unsupervised classification). At this stage, more detailed information on biophysical factors (e.g., sediment analyses, Chapter 3) and observations of underwater habitat, should be obtained. Likewise, data on relative abundance, distribution and size of wild sandfish (if they are present) or anecdotal evidence and fishing history (if they are not), are valuable.

A mariculture livelihood has a better chance of success if the target community is involved in in the planning process as early as possible (Calamia 1999, Krause et al. 2015), with socio-economic factors also influencing success (see Chapter 7). Liaison with the potential sandfish-ranching community and other local stakeholders to discuss the Stage 1 GIS desktop study and obtain their input on mariculture site suitability and prioritisation should be carried out in Stage 2. Local ecological knowledge such as location of seabed features, current and historical sandfish harvest areas and methods, and customary marine tenure (CMT) arrangements (e.g., fishing grounds access, shared access zones, disputed areas, and tambu areas), can be integrated into the GIS model (Calamia 1999, Anuchiracheeva et al. 2003, Aswani and Lauer 2006, Teixeira et al. 2013). The potential for conflict in drawing boundaries for fishing grounds, whether they are regarded as disputed or not (e.g., Foale and Macintyre 2000, Kinch 2020) must be taken into account. An important caveat to their inclusion in GIS mapping applications, therefore, is that sea territory boundaries are treated as 'provisional' for the purposes of planning and do not confer ownership to, or favour, a particular group. Stage 2 will determine whether all of the environmental, logistical and socio-economic criteria have been satisfied and will assist in assessing sites as 'moderately suitable', 'suitable' or 'optimal'.

4.4.3.3 Stage 3

Finally, all criteria may indicate site suitability but sandfish mariculture can still fail due to high predation rates, social factors or some unknown or unanticipated factor/s (Purcell and Simutoga 2008, Robinson and Pascal 2012, see Chapters 3 and 7). Stage 3, therefore, involves stocking cultured sandfish juveniles into one or more small sea pens in the optimal category areas to monitor their survival and growth for up to two months (Fig. 4.16). This is the final step to assess site suitability and provides guidance on the level of animal husbandry required before committing to a large-scale community sea ranching operation.

4.5 Conclusions

GIS capacity varies widely among countries but there has been a steady rise in adoption of spatial planning for mariculture site selection since the mid-1980s (see Micael et al. 2015). As improvements in the field occur and as more is learnt about the optimal habitat for sandfish, spatial modelling will improve and use of these techniques is likely to become routine. An important first step for sandfish mariculture is to collate available information to develop a preliminary MCE model. GIS data can then be maintained and updated as knowledge gaps are filled, new data sources become available and as local contexts change. In addition to the conventional oceanographic and seafloor biophysical factors, the methodology proposed here advocates inclusion of appropriate socio-economic factors, including local knowledge obtained from community sources and on-site appraisal.

Chapter 5
A comparison of survival, growth and burying behaviour of cultured and wild juvenile sandfish: implications for ocean mariculture[16]

5.1 Introduction

Cultured marine invertebrates are released into the ocean for various reasons, including conservation (e.g., stock restoration) and commercial mariculture (e.g., stock enhancement, farming and sea ranching) (Bell et al. 2008, Froehlich et al. 2017, Taylor et al. 2017). To maximise production from released, cultured juveniles, it is important that they have appropriate physical, physiological and behavioural characteristics (Le Vay et al. 2007, Young et al. 2008). Differences in the attributes of hatchery-reared juveniles compared to wild juveniles have been demonstrated for some cultured invertebrates, and may indicate low quality or reduced fitness of cultured juveniles. For example, cultured blue crab (*Callinectes sapidus*) were lighter in colour and had shorter lateral spines than wild conspecifics (Davis et al. 2005), and cultured scallops (*Placopecten magellanicus* and *Argopecten purpuratus*) demonstrated reduced clapping escape response compared to wild individuals (Lafrance et al. 2003, Brokordt et al. 2006), leading to higher mortality following releases into the wild. Fortunately, many potentially compromising behavioural characteristics may be resolved through appropriate conditioning, such as exposure to predators and to different substrates prior to release (Davis et al. 2005, Parkes et al. 2011, Palomar-Abesamis et al. 2017). The release process itself may also place cultured juveniles at risk if, for example, they are stressed by handling, packing, transportation and the shock of release into different environmental conditions (van der Meeren 1991, Dobson 2001, Oliver et al. 2005, Purcell et al. 2006a, Zamora and Jeffs 2015). These impacts can be exacerbated by releasing cultured juveniles without considering diurnal rhythms, the suitability of the release environment, appropriate acclimation, or by not following best practice release protocols (Purcell 2004, Mills et al. 2005).

Sea cucumbers are mostly slow-moving and soft-bodied, and these features influence their susceptibility to predation after release into the wild in ocean mariculture (Chapter 3). They

---

[16] Data from this chapter were published as: Hair, C., Militz, T., Daniels, N. and Southgate, P.C. (2020). A comparison of growth and burying behavior of wild and cultured juvenile *Holothuria scabra*: implications for ocean mariculture. *Aquaculture* 526, 735355. https://doi.org/10.1016/j.aquaculture.2020.735355

have developed various measures to avoid or minimise predation, including the presence of saponins in their skin and viscera, which is unpalatable or toxic to predators (Caulier et al. 2011), shedding part of their body or evisceration (Francour 1997, Hamel and Mercier 2000), the presence of ossicles in the body wall, and body stiffening or swelling (Kropp 1982, Francour 1997). For juvenile sea cucumbers, however, nocturnal activity, cryptic concealment and shelter seeking are arguably the most important of these strategies for juvenile sea cucumbers (Hammond 1982, Purcell et al. 2006a, Palomar-Abesamis et al. 2017).

Cultured sandfish juveniles are usually released into the wild when they reach 3–20-g body weight (Purcell and Simutoga 2008, Robinson and Pascal 2012, Juinio-Meñez et al. 2013, Chapter 3). They often experience high mortality following release due to predation, stress or disease (Dance et al. 2003, Purcell and Simutoga 2008, Lavitra et al. 2009), or emigrate out of farming areas either by choice or accident (Uekusa et al. 2012, Hamel et al. 2019). Movement of released sandfish is limited for the first few years after release, indicating low risk of migration out of sea ranches (Purcell and Kirby 2006, Lee et al. 2018a). However, newly settled and juvenile sea cucumbers are vulnerable to a variety of diurnal and nocturnal predators, such as crabs, fish, and molluscs (see Chapter 3). The primary predator avoidance strategy of juvenile sandfish is nocturnal activity and daytime burying (Mercier et al. 1999, Purcell 2010b). Increased post-release survival has been reported for ≥ 3-g sandfish juveniles that buried more frequently in daylight hours (Ceccarelli et al. 2018). The timing, duration and frequency of burying in sandfish has been shown to vary due to: water quality and environmental factors (Mercier et al. 1999, 2000b, Lavitra et al. 2009, Purcell 2010b, Altamirano et al. 2017); location and season (Purcell 2004, Wolkenhauer 2008, Purcell 2010b); water depth and tidal movement (Mercier et al. 2000b, Skewes et al. 2000, Ceccarelli et al. 2018); handling and transportation stress (Purcell et al. 2006a, Purcell 2010b); and size (Mercier et al. 1999, Purcell 2010b). Further, exposing hatchery-reared sandfish juveniles to sandy substrate prior to release, to gain experience in burying, has been shown to increase growth rate and initial burying speed after release (Juinio-Meñez et al. 2012c).

There is little information about the influence of hatchery rearing on post-release survival or subsequent growth of sandfish juveniles (Dance et al. 2003, Robinson and Pascal 2012). Comparative data on wild conspecifics is scarce because of the difficulty in obtaining wild sandfish juveniles of a suitable size and age (Hamel et al. 2001, Shiell 2004). Similarly, there is little, if any, literature regarding behavioural differences between cultured and wild sandfish juveniles, although differences to the burying regime of cultured juveniles have been reported following simulated transportation (Purcell et al. 2006a) and handling stress (Purcell 2010b). Studies of predator-avoidance behaviour of hatchery-reared sea cucumber juveniles, such as burying by sandfish (Mercier et al. 1999, Purcell 2004, Juinio-Meñez et al. 2012c), and shelter seeking by *Stichopus horrens* (Palomar-Abesamis et al. 2017), suggest that a greater understanding of this behaviour may improve the success of release programs through increasing survival and growth of released juveniles. It is critical, therefore, to identify whether hatchery production and/or release stressors influence the performance and behaviour of cultured sandfish juveniles after release, as a basis for improved ocean mariculture outcomes.

5.2 Materials and methods

Two experiments are reported in this paper. Experiment 1 compared growth and survival of cultured and wild sandfish juveniles. Experiment 2 compared the burying behaviour of cultured and wild sandfish juveniles following release into two different natural habitats.

5.2.1 Preparation of experimental sandfish juveniles

Cultured sandfish juveniles were produced at the Nago Island Mariculture and Research Facility (NIMRF), a multi-species marine hatchery near Kavieng, New Ireland Province, PNG (Fig. 5.1). Following larval rearing (Militz et al. 2018), early juveniles were maintained in tanks without substrate until they reached around 0.5–1 g body weight, when they were transferred to nursery tanks with approximately 5 cm of sand substrate in the base. The sand was sourced from a nearby seagrass meadow and passed through a 1-mm sieve to remove the coarsest sand fraction. Juveniles were reared under these conditions until the majority had reached a minimum release size of 3 g (range 3–15 g). All cultured juveniles were batch-marked with tetracycline fluorochrome (Purcell et al. 2006b) and left to recover for eight days in a seawater pond with a flow-through water supply and sand substrate. The fluorochrome marking was necessary for distinguishing cultured from wild juveniles in Experiment 1 and was also routine practice for all cultured sandfish prior to release into the wild.

Wild sandfish juveniles of similar size to cultured juveniles were obtained from a natural, shallow seagrass meadow at Ungakum (Fig. 5.1), about 35 km from NIMRF. Wild juveniles used in Experiment 1 were marked with calcein fluorochrome and left to recover in the seawater pond in separate enclosures to those used to hold cultured sandfish juveniles. Wild juveniles used in Experiment 2 were not marked.

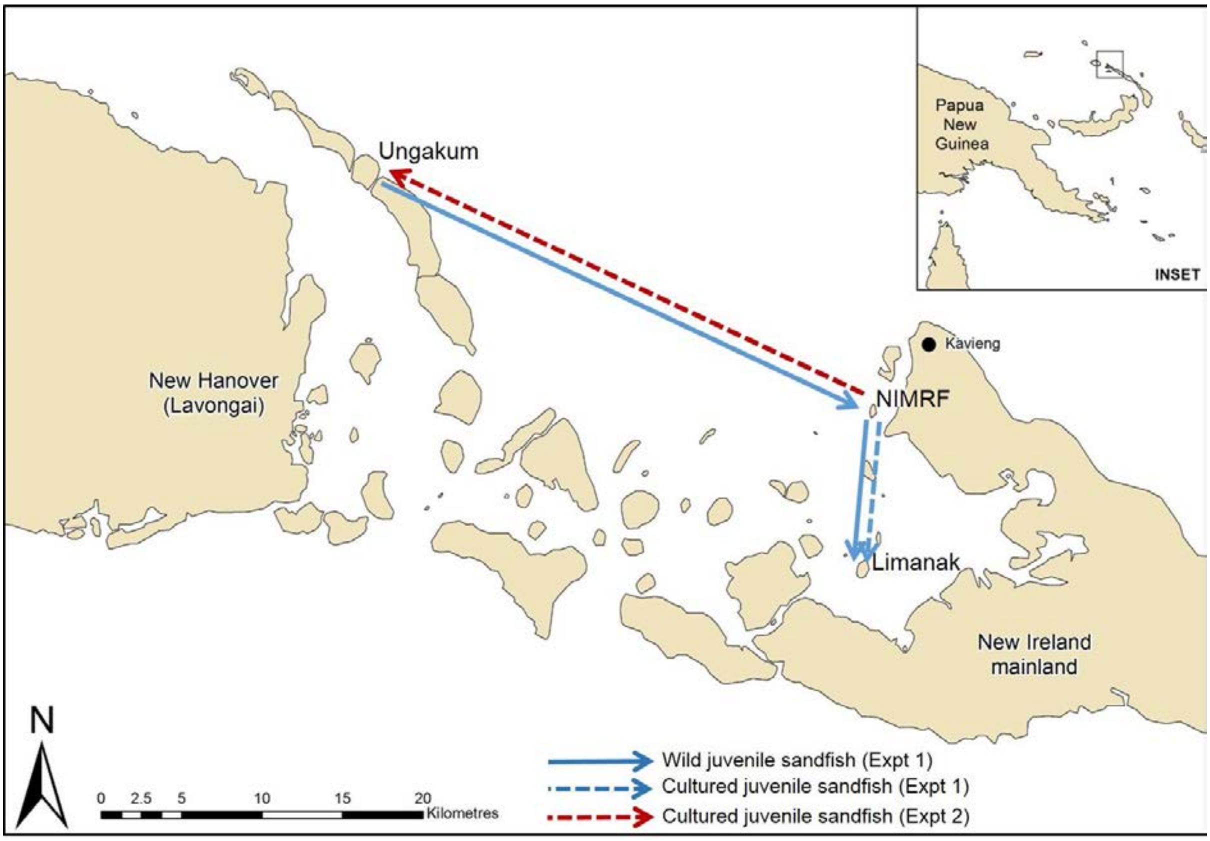


Figure 5.1 Map showing location of NIMRF (source of cultured sandfish juveniles), Limanak (Experiment 1 site) and Ungakum (source of wild sandfish juveniles and Experiment 2 site). Coloured arrows denote transportation routes for cultured (dashed line) and wild (solid line) juvenile sandfish for Experiment 1 (blue) and Experiment 2 (red), from their respective sources.

5.2.2 Experimental sites

The growth and survival experiment (Experiment 1) was conducted in a shallow seagrass meadow at Limanak (Fig. 5.1), about 10 km from NIMRF. Wild juveniles were collected from Ungakum and transported for ~1.5 h in an insulated container with seawater to NIMRF. For this experiment, both juvenile groups were transported to Limanak in containers with seawater, a 15-min boat trip (Fig. 5.1). The burying experiment (Experiment 2) was conducted in a shallow seagrass meadow at Ungakum (Fig. 5.1), the source of the wild sandfish juveniles. For this experiment, cultured juveniles were packed into labelled plastic bags with seawater and oxygen (Purcell et al. 2006a), placed in an insulated container and transported for ~1.5 h by boat to Ungakum and then held for ~5.5 h before commencement of the experiment (Fig. 5.1).

Like-size wild sandfish juveniles did not require any transportation because they were collected in situ from their natal habitat.

5.2.3 Data measurements

Descriptive habitat variables were recorded from within experimental pens at Limanak and Ungakum. Data were collected on seagrass species, seagrass cover (%), seagrass canopy height (cm), and substrate penetrability (cm, measured by dropping a pointed metal rod from a fixed distance) (refer to Chapter 3, *section 3.2.6* for detailed biophysical sampling methodology). Within each pen, core samples of the upper 2 cm of substrate (n = 5 cores combined) were collected and dried at 60ºC. The dried substrate (~3-g sample) was analysed for organic matter (OM) by loss on ignition (LOI) in a muffle furnace at 500ºC for 6 h. A larger sample (minimum 50 g) was analysed for grain size by dry sieving through a series of mesh sizes, where the percentage of the sample retained on 1000, 250, 63 µm sieves and the receiving tray was categorised as coarse, medium, fine and silt, respectively. Water temperature (ºC) near the seafloor was recorded at 2-h intervals by a Hobo™ data logger (both experiments). Photosynthetically active radiation (PAR, µE m^{-2} s^{-1}) was recorded at 2-h intervals by a light logger (Experiment 2 only).

The standard protocol for weighing sandfish involved removing animals from the water, draining for 2 min and weighing on an analytical balance to the nearest 0.1 g. Sandfish juvenile weight data are presented as mean ± standard error (SE). Where practicable (i.e., when working at NIMRF), sandfish juveniles were held overnight in containers without substrate to allow them to void their gut contents, thereby obtaining a 'voided' weight. Non-voided weight can be unreliable because of varying amounts of sand and water retained within the gut and respiratory tree (Sewell 1991, Battaglene et al. 1999). Sandfish juveniles were also usually voided before transportation to reduce contamination of the transportation water (Purcell et al. 2006a).

5.2.4 Experiment 1 – Survival and growth of cultured and wild sandfish juveniles

5.2.4.1 Experimental set up

Eight 'acclimation' pens of 1 m^2 in area, constructed from plastic oyster mesh (3-mm pore size), were installed within a 100-m^2 'ranching' pen at Limanak that had previously been used for cultured sandfish grow-out experiments (Chapter 3). Acclimation pens were buried to a depth of 15 cm and stood 30 cm above the substrate. The inner, upper edge was fitted with a mesh skirt to minimise the loss of juveniles by climbing (sensu Ceccarelli et al. 2018). Seagrass within the large ranching pen was patchy, therefore all acclimation pens were installed in areas where seagrass was absent, to standardise habitat features among individual pens.

At the hatchery, 40 cultured sandfish juveniles were allocated randomly to four batches of ten individuals of similar mean voided weight and weight range. The same procedure was carried out for wild juveniles. At the site, four replicate acclimation pens were each stocked with a batch of cultured sandfish juveniles (n = 10 per pen) and four pens were each stocked with a batch of wild sandfish juveniles (n = 10 per pen). Cultured and wild juveniles were kept in the acclimation pens for a period of 34 days, after which all sandfish were released into the larger ranching pen to mix freely for a further 50 days.

5.2.4.2 Sampling protocol

The number and individual weights of sandfish juveniles in each acclimation pen were recorded at stocking, weekly up to 34-days post-release (DPR), and then on two occasions in the ranching pen, at 61 DPR and at the end of the experiment (85 DPR). Sampling was done in the late afternoon on a rising tide by retrieving emerged juveniles and searching for buried individuals by hand to a depth of 4–5 cm. Juveniles were removed from the water and weighed, then returned to their respective pen. The final sampling at 85 DPR was done at night between 18:00 and 21:30 on a rising high tide. The ranching pen was searched thoroughly several times by two snorkel divers and searching was discontinued when no new individuals were found within a 30-min period. After the final sampling, all sandfish juveniles were returned to NIMRF and their voided weights recorded the next morning. A 5-mm^2 skin sample was shaved from the ventral surface of each juvenile during sampling at 61 DPR and 85 DPR so that the presence of tetracycline or calcein-marked ossicles could be used to verify cultured or wild origin, respectively, for allocation of weight measurements.

5.2.4.3 Data analysis

Growth rates of cultured and wild sandfish juveniles during the acclimation period were determined through development of a linear regression model that accounted for repeated measures from replicate acclimation pens. A linear mixed-effects model using the *R* function *lme* (package *nlme*) with juvenile source (cultured or wild) and time (DPR) as the main effects, and a random effect of pen was employed. The appropriateness of the model was validated through inspection of the standardised residuals plotted against fitted values and through comparison against simplified models. At the end of the acclimation period (34 DPR) the mean weights of cultured and wild juveniles were compared using a two-sample *t* test (function *t.test*, package *stats*).

Following liberation of sandfish juveniles into the larger ranching pen, the mean weight of cultured and wild juveniles was compared at 61 DPR and again at 85 DPR, using two-sample *t* tests (function *t.test*, package *stats*). For 85 DPR, a square-root transformation of the raw weight data was necessary to correct skew and satisfy assumptions of normality. Finite survival of cultured and wild juveniles at 85 DPR was compared using a χ^2 test with Yates continuity correction (function *prop.test*, package *stats*).

5.2.5 Experiment 2 – Burying behaviour of cultured and wild sandfish juveniles

5.2.5.1 Experimental set up

At the hatchery, voided cultured juveniles were individually weighed and sorted into batches of similar approximate weight, packed into labelled plastic bags, transported by boat to Ungakum, then held in the shade until the start of the experiment. The transportation time was calculated as boat travel plus holding time. Like-size wild sandfish juveniles were collected as they emerged from their buried state in natural substrate around sunset. In order to minimise handling stress, wild juveniles were selected by eye, based on size, and then held in tubs of seawater for a short period until the start of the experiment (i.e., no transportation).

Six experimental culture pens were installed for each of the cultured and wild-collected juvenile groups, and they were divided equally among two habitat types where seagrass was either present or absent (n = 3 for each level of juvenile group and habitat), in areas that would not dry out at low tide. The experimental pens were 1 m^2 in area and constructed from plastic oyster mesh (6-mm pore size); their bases were buried in the substrate to a depth of 10 cm and the walls stood 35 cm above the substrate (Fig. 5.2). Approximately 5.5 h after arrival at the site and 1 h after collection of wild sandfish juveniles, cultured and wild juveniles were randomly allocated to experimental pens (n = 10 juveniles per pen).

Figure 5.2 Experimental site at Ungakum showing six 'seagrass present' pens (left) and six 'seagrass absent' pens (right).

5.2.5.2 Sampling protocol

The first observations of burial state of all sandfish juveniles in each pen was recorded at 22:00 (1 h after liberation) and then at 2-h intervals for 48 h (a total of 25 observations). Burial state was defined as either 'buried' (i.e., no part of the body, or just the anus tip, visible above the substrate, Mercier et al. 1999), or 'not buried' (i.e., fully on the surface or part of the body showing, since visual predators are the main threat to juveniles, Francour 1997, Dance et al. 2003).

After final burial observations were recorded, all sandfish juveniles were retrieved and weighed at the field site. There were differences in mean group non-voided weights as a result (Table 5.1). ANOVA of weights showed that there was no significant difference between cultured and wild juvenile groups overall (F = 2.516, p = 0.115) but that mean juvenile weight was significantly greater in 'seagrass absent' habitat than 'seagrass present' habitat (F = 8.147, p = 0.005).

Table 5.1 Mean (± se) individual weight (g) and weight range of non-voided sandfish juveniles used in the treatments for Experiment 2.

Source	Habitat	Mean	Range
Cultured	Seagrass present	8.5 ± 0.4	4.5 – 14.1
Wild	Seagrass present	9.1 ± 0.6	3.0 – 15.7
Cultured	Seagrass absent	9.7 ± 0.6	5.3 – 15.5
Wild	Seagrass absent	11.0 ± 0.6	3.2 – 16.7

5.2.5.3 Data analysis

A model-building approach was used to investigate temporal change in the burying behaviour of sandfish juveniles following release into natural habitat. Three explanatory variables were used in the model: hours post-release (HPR), the source of juveniles (cultured or wild), and presence (or absence) of seagrass at the release site. A generalised additive model (GAM) was used (Hastie and Tibshirani 1987), rather than a more conventional linear modelling approach, because the expected relationships were likely to follow a nonlinear diel rhythm (Mercier et al. 1999).

To construct the GAM, a forward and backward stepwise model-fitting procedure was used, based on the Akaike's Information Criterion (AIC) statistics (Chambers and Hastie 1992). The model-fitting procedure was carried out using the *R* functions *gam* (package *mgcv*) and *AIC* (package *stats*), using the inbuilt cross-validation tool in *mgcv* to determine the optimal shape of the smooth functions. As the measured response was binomial ('buried' or 'not buried'), a binomial error structure was used. Initially, the time post-release predictor was modelled as four separate nonlinear (smooth) terms accounting for all levels of the categorical variables (i.e., juvenile source and presence of seagrass). After simplification, the final working model was validated by graphically assessing the normality and homogeneity of residuals.

Finite survival of cultured and wild sandfish juveniles at the end of the experiment was compared using a χ^2 test with Yates continuity correction.

5.3 Results

5.3.1 Experiment 1 – Survival and growth of cultured and wild sandfish juveniles

5.3.1.1 Biophysical habitat description

The habitat within the acclimation pens consisted of muddy-sand substrate with no seagrass, a mean OM of 3.6%, penetrability of 2.8 cm, and the grain fraction distribution was coarse (26%), medium (54), fine (18%) and silt (2%). The larger ranching pen had approximately 15% seagrass cover comprising *Enhalus acoroides*, *Cymodocea rotundata*, *Thalassia hemirampii* and *Halodule uninervis*. Water temperature near the seafloor during the experiment ranged from 28.2–39.7ºC, averaging 32.3ºC (± 0.07), with the highest water temperatures occurring in mid-afternoon and the lowest in the hours after midnight.

5.3.1.2 Survival and growth of sandfish

At the start of the experiment, the mean voided weight of cultured sandfish was 4.8 ± 2.5 g (range 2.1–8.5 g) and of wild individuals was 4.9 ± 2.5 g (range 2.2–7.9 g). The fitted linear growth model (R^2 = 0.43) showed that cultured and wild sandfish juveniles were of similar weight upon release (0 DPR) into acclimation pens (t = 0.25, p = 0.81).

Growth rates differed significantly during the 34-day acclimation period depending on juvenile source (t = 2.10, p = 0.03) with cultured juvenile growth rate higher than that of wild juveniles (Fig. 5.3). While the replicate acclimation pens had a significant explanatory effect in this model (p < 0.01), differences between acclimation pens were negligible as the amount of variance in the response associated with the random effects term was < 0.1% that associated with model error. At 34 DPR, cultured sandfish juveniles were significantly larger than wild juveniles (16.9 ± 0.8 g versus 13.2 ± 1.2 g, respectively) (t = 2.59, p = 0.01) (Fig. 5.3). At 61 DPR, the mean weight of cultured juveniles was not significantly different from that of wild juveniles (35.8 ± 2.5 g versus 29.2 ± 2.3 g, respectively) (t = 1.83, p = 0.07). Similarly, at 85 DPR, the mean voided weights of cultured and wild juveniles (46.9 ± 3.1 g versus 42.0 ± 3.3 g, respectively) were not significantly different (t = 1.16, p = 0.25).

Average growth rates of juveniles over the 85-day experiment were 0.50 ± 0.04 g day^{-1} for cultured and 0.44 ± 0.04 g day^{-1} for wild sandfish juveniles. Survival of cultured (90%) and wild (85%) juveniles was also not significantly different at the end of the experiment (85 DPR) ($\chi 2$ = 0.11, p = 0.74).

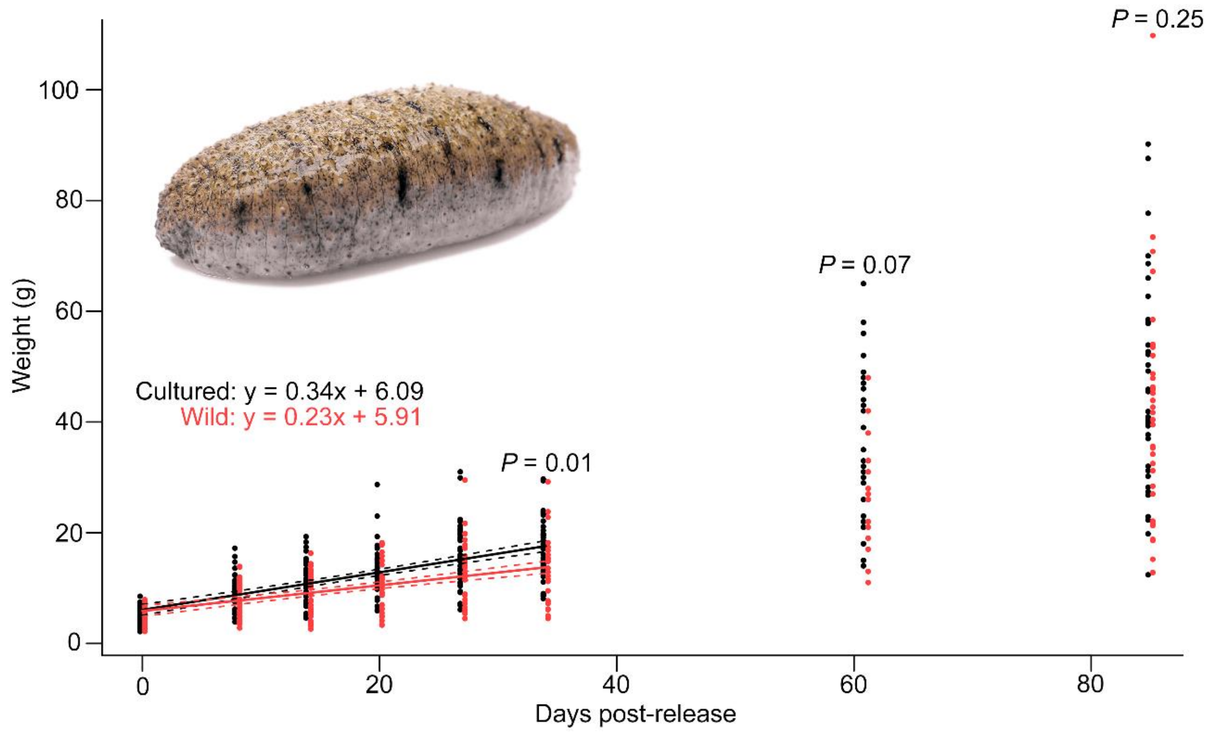


Figure 5.3 Temporal change in weight for cultured (black) and wild (red) sandfish juveniles (pictured) following release into natural habitat. For the acclimation period (0–34 DPR), the solid lines represent the linear regression equations for cultured and wild juveniles while the dashed lines approximate the 95% confidence interval. The *p*-values from *t* tests comparing the mean weights of cultured and wild juveniles during the ranching period (35–85 DPR) are also presented.

5.3.2 Experiment 2 – Burying behaviour of cultured and wild sandfish juveniles

5.3.2.1 Biophysical habitat description

Key biophysical parameters for the two experimental habitats are presented in Table 5.2. Seawater temperature ranged from 27.3–40.2ºC and PAR ranged from 0–2,109 µE m^{-2} s^{-1}. Due to daytime low tides at the time of the experiment, the depth, PAR and temperature were strongly co-linear, i.e., temperatures and light levels were at a maximum during the day when shallow depths were recorded (Appendix 4).

Table 5.2 **Mean (± se) values of biophysical parameters for habitats (seagrass *Thalassia hemirampii* and *Cymodocea rotundata,* present and absent) used in Experiment 2.**

Habitat	Seagrass present	Seagrass absent
Seagrass cover (%)	14.2 ± 1.5	0
Canopy height (cm)	5.3 ± 0.6	0
OM (%)	3.0 ± 0.1	3.0 ± 0.1
Penetrability (cm)	3.0 ± 0.2	3.4 ± 0.2
Grain size ratio	C22:M49:F26:S3	C16:M47:F32:S5
Water depth (cm)	11–81	19–88

5.3.2.2 Sandfish survival and burying behaviour

Almost all (n = 120) sandfish juveniles survived to the end of the experiment (χ^2 = 3.02, p = 0.39), except one wild juvenile that was unaccounted for in the 'seagrass present' treatment.

Fitted values from the GAM illustrate the nonlinear relationship between juvenile burial state and time post-release (adjusted for all other predictors in the model) (Fig. 5.4). Most of the time, cultured and wild sandfish juveniles showed a significantly different nonlinear relationship, which was further modified by the presence or absence of seagrass in the release habitat as a significant linear term (Table 5.3, Fig. 5.4). The AIC stepwise approach resulted in dropping the presence of seagrass as an independent nonlinear (smooth) term from this model, but retained the predictor as a significant linear term, which interacted with juvenile source (Table 5.3). The proportion of variance explained by the model was 69.6%.

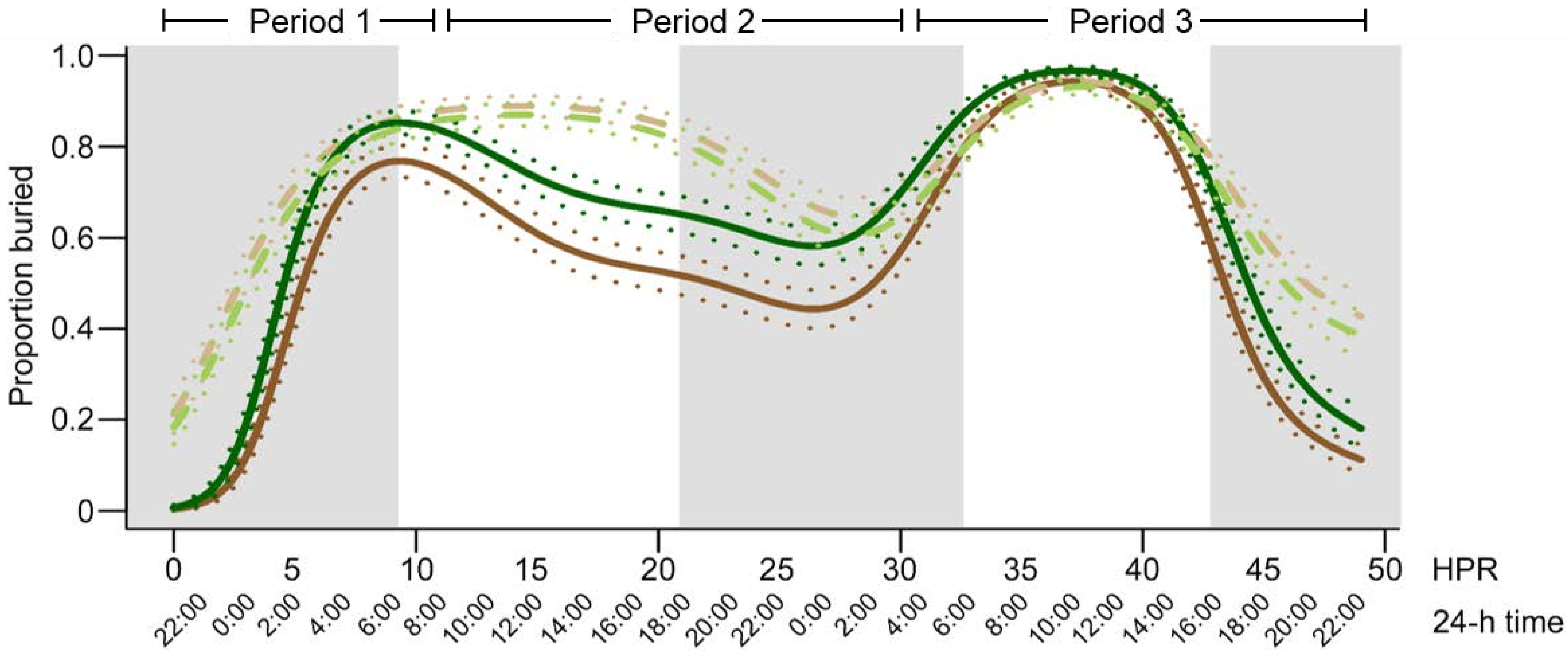


Figure 5.4 **Fitted values from the GAM illustrating temporal change in burial state following release of cultured (solid lines) and wild (dashed lines) sandfish juveniles into habitats where seagrass was either present (green lines) or absent (brown lines). Standard errors (dotted lines) are also shown. X-axis scales are presented as hours post release (HPR) and time (24-h format). The three periods corresponding to the ecological interpretation are illustrated. Shading indicates night-time.**

Table 5.3 Statistical significance of the linear and nonlinear (smooth) terms in the GAM explaining the relationship between juvenile burial state and time-post release, with juvenile source (cultured or wild) and the presence (or absence) of seagrass as predictors influencing the response.

Model terms	df/edf	χ^2	*P*-value
Linear terms			
Juvenile source	1	76.6	< 0.001
Presence of seagrass	1	19.9	< 0.001
Juvenile source × presence of seagrass	1	17.4	< 0.001
Nonlinear (smooth) terms			
Juvenile source: cultured	8.56	271.8	< 0.001
Juvenile source: wild	8.18	241.7	< 0.001

An ecological interpretation of the GAM reveals three distinct periods characterising the differential burial state of cultured and wild sandfish juveniles following release into natural habitat (Fig. 5.4):

1. Period 1: from 0 to 11 HPR (22:00–07:00): immediately after release both cultured and wild juveniles began burying, with wild juveniles burying more rapidly than cultured juveniles.
2. Period 2: from 11 to 30 HPR (07:00–03:00): cultured and wild juveniles showed different trends. Wild juveniles mostly stayed buried, with minimal difference in burial state between habitat treatments. Cultured juveniles were less likely to be buried than wild, and significantly fewer of this group buried in habitat without seagrass.
3. Period 3: from 30 to 48 HPR (03:00–22:00): all emerged juveniles began burying, reaching nearly 100% burial between 36 and 40 HPR (09:00–13:00). The two groups synchronised for about 16 h during this period, both groups burying and then emerging at similar times. From 45 to 48 HPR (18:00–22:00) the groups diverged again as fewer cultured juveniles remained buried than wild juveniles. However, there was limited divergence in burial state due to habitat for either group.

5.4 Discussion

5.4.1 Survival and growth

Reported low survival of cultured sea cucumber juveniles following release is usually attributed to predation (Hatanaka et al. 1994, Dance et al. 2003, Purcell and Simutoga 2008, Yu et al. 2015), although migration, being washed away, smothered by mud, being overlooked during surveys, isopod infestation and frailty at time of release have also been blamed for low retrieval in prior studies (Hamano et al. 1996, Tanaka 2000, Masaki et al. 2007, Lavitra et al. 2009, Robinson and Pascal 2012, Uekusa et al. 2012, Hamel et al. 2019). Survival of both cultured and wild sandfish juveniles was high (> 85%) in Experiment 1, exceeding the rates commonly reported in the literature (Purcell and Simutoga 2008, Lavitra et al. 2015, Juinio-Meñez et al. 2017, Ceccarelli et al. 2018), although lower than the 93% reported in prior research at this location (Chapter 3).

Growth rates of sandfish in Experiment 1 were comparable with those reported for cultured sandfish in sea pens in prior studies (Juinio-Meñez et al. 2017, Chapter 3), noting that no published data on wild sandfish juvenile growth are available. It is not clear why cultured sandfish growth surpassed that of wild juveniles in the first 5 weeks of the experiment, but the difference was not significant after 60 days. Early post-release growth of wild juveniles may have been compromised due to the additional transport stress they experienced prior to the experiment (Fig. 5.1, Table 5.4). Cultured sandfish reached commercial-size within a year at the same site (Chapter 3), suggesting that there were no major or long-lasting impediments to growth (and by inference, feeding and nutrient assimilation) resulting from hatchery rearing or handling and/or transportation stress in this study.

5.4.2 Burying behaviour

5.4.2.1 Survival

Both cultured and wild sandfish juveniles also showed very high survival in the burying experiment, despite the comparatively greater stress that cultured juveniles were subjected to prior to release (Table 5.4). This is a very encouraging result and the first time that survival of stressed cultured sandfish has been directly compared to that of wild counterparts. The reported low mortality may be attributed to a lack of predators at the study site (Lavitra et al. 2015, Chapter 3), but the fact that cultured juveniles had 100% survival demonstrates that hatchery-rearing and transport stress, in themselves, do not lead to post-release mortality in suitable habitat. However, timely adoption of a natural diel burying cycle is essential for predator avoidance by newly released sandfish juveniles. While the finding that cultured juveniles were slower to bury after release and then spent more time on the surface than wild conspecifics was not unexpected, released juveniles may be more vulnerable in areas where predators are active (Eeckhaut et al. 2020).

Table 5.4 Potential stressors on cultured and wild sandfish juveniles in the growth and burying behaviour experiments. Transportation stress is expressed as estimated total time in transit and distance travelled. NA denotes not applicable.

	Growth Experiment 1		Burying Experiment 2	
Stress	Cultured	Wild	Cultured	Wild
Fluorochrome marking	Yes	Yes	Yes	NA
Voiding period	Yes	Yes	Yes	NA
Handling	Yes	Yes	Yes	Yes
Transport	30 min; 10 km	2 h; 35 km (from source) 30 min; 10 km	7 h; 35 km	NA

5.4.2.2 Potential hatchery effects

It may be that the hatchery burying regime differs from what would occur under natural oceanic conditions due to reduced exposure to natural environmental cues (e.g., full sunlight, tidal flows, predation pressure). However, cultured juveniles in the present study readily adopted a diel burying pattern under hatchery conditions following transfer of 1-g juveniles to sand substrate (C. Hair pers. obs.). Tank studies on juvenile burying behaviour from various locations have identified some variations in diel burying patterns (Battaglene et al. 1999, Mercier et al. 1999, Purcell et al. 2006a, Altamirano et al. 2017), but reported appropriate burying responses to known environmental stimuli, such as water temperature, light and water level. Therefore, hatchery rearing per se does not impair this ability (see Bell et al. 2005). Tank studies have also shown that cultured sandfish juveniles experience disrupted burying behaviour following handling and simulated transport stress (e.g., Purcell et al. 2006a). Only one study has investigated cultured juvenile burying behaviour a month after release in natural habitat (Purcell 2010b), but none have made direct comparisons with like-size wild juveniles, or observed behaviour immediately following release into the wild when normal patterns were likely to be affected and predation risk highest. Data on the degree and timing of divergence of the burying patterns of cultured and wild sandfish juveniles generated by this study augment information from tank studies with cultured juveniles and observations of wild sandfish, to provide a basis for developing improved juvenile release protocols.

5.4.2.3 Effects of transportation stress

Adverse effects on juvenile sea cucumbers have been demonstrated during simulated transportation studies investigating the effects of packing density, transportation duration, temperature, and transportation with or without seawater. These include: physical impacts such as death, evisceration and lesions; physiological changes such as lowered immunity and altered metabolism; and disruption to normal behaviour such as attachment, feeding and burying (Purcell et al. 2006a, Wang et al. 2007, Purcell 2010b, Guo et al. 2014, Zamora and Jeffs 2015, Tan et al. 2016, Hou et al. 2019, Tuwo et al. 2019). Identifying the causes of these responses is problematic since most published studies have used cultured juveniles and any study on ocean mariculture entails handling, packing and travel to the release site (Table 5.4), inevitably confounding the hatchery-rearing and transport-stress factors. Of the studies cited above, only that of Zamora and Jeffs (2015) used wild-collected *A. mollis* juveniles, hence their findings were unrelated to hatchery effects. Most studies have concluded that, except in extreme circumstances (e.g., prolonged transportation when not immersed in seawater), the effects of transportation are reversible, but consequences such as mortality following release are difficult to monitor. For example, based on investigations into low recovery of cultured *A. japonicus* juveniles released onto artificial reefs in Japan, Tanaka (2000) concluded that handling and transportation were not responsible for losses, while Uekusa et al. (2012) suggested that juveniles were weakened by handling and transportation, particularly during detachment from hatchery tank walls.

Generally, the more severely stressed cultured juveniles (handled and transport-stressed, Table 5.4) buried in the hours after release, but then entered a period of reduced burying compared to wild juveniles that lasted until 30 HPR. These results contrast those from similar studies where burying was suppressed immediately after release and then followed by increased burying for several days (Purcell et al. 2006a, Purcell 2010b). It is possible that a natural burial regime was not observed for either group in the present study because handling of the wild juveniles may have affected them (see Purcell 2010b). Nonetheless, the fact that wild sandfish juveniles (handled but not transported) buried more rapidly after release and then spent more time buried than cultured juveniles, suggests that transportation stress was a major contributor to the observed differences. Greater synchronisation of cultured and wild juvenile burying patterns occurred after 30 HPR when cultured juveniles buried at a similar rate to wild juveniles for 16 h. At this point, both groups adopted a more typical regime, i.e., burying peak from 06:00–14:00 and emerging peak 20:00–04:00 (Mercier et al. 1999, Altamirano et al. 2017). The reasons for the differences in the burying patterns of cultured and wild juveniles observed from 45–48 HPR at the end of the 2-day experiment are unclear, but they were comparatively minor compared to those observed before 30 HPR. The more similar trends observed after 30 HPR also suggested that full synchronisation was imminent, in less than the four days suggested by Purcell (2010b) for resumption of normal burying behaviour after handling.

5.4.2.4 Effects of habitat type

Burial rates of wild juveniles were similar in habitat with and without seagrass in this study, but cultured juveniles were always more likely to be buried in habitat where seagrass was present. This difference was more pronounced for a restricted period of 20 h in the middle of the experiment and the reasons for this are unclear. The 'seagrass present' habitat used in this study was characterised by relatively sparse seagrass cover, greater coarse grain fraction, less fine/silt sediment, shallower depth, and slightly harder substrate (i.e., lower penetrability), than the 'seagrass absent' habitat. Seagrass is the natural juvenile habitat of sandfish and is believed to provide food and shelter; larvae recruit onto seagrass leaves and spend their early stages closely associated with seagrass meadows (Mercier et al. 2000b, a). Among other factors, the presence, species composition and density of seagrass influences sandfish size distribution (Mercier et al. 2000b, Skewes et al. 2000, Feary et al. 2015) and outcomes of cultured sandfish juvenile releases (Dance et al. 2003, Purcell and Simutoga 2008, Ceccarelli et al. 2018). However, Ceccarelli et al. (2018) found that, although moderate seagrass cover improved survival and growth of released 3-g cultured sandfish juveniles, this was not a significant factor in their burial rate. Sandfish juveniles have been shown to spend more time buried in substrates with high organic carbon content (Ceccarelli et al., 2018), and enriched with Sargassum mulch (Sinsona & Juinio-Meñez, 2018). These studies suggested that enhanced food availability may reduce foraging time and allow higher burying frequency. In the present experiment there was no difference in OM between habitats and both groups of juveniles accessed the same food sources. Therefore, it is unlikely to explain the observed differences in behaviour. Altamirano et al. (2017) reported that sandfish juveniles preferred to bury in sandy-mud substrate

(C14:M63:F23) compared to silty-sand (C3:M62:F35) or coarse sand (C42:M56:F2), but this does not account for differences in the burying patterns observed in the present study because the grain size profile of both experimental habitats was similar to the sandy-mud category of Altamirano et al. (2017). The shallower depth of the 'seagrass present' habitat agrees with prior studies showing that this feature promotes burying behaviour in sandfish juveniles (Mercier et al. 1999, Ceccarelli et al. 2018).

5.4.3 Improving release strategies

Results of the two experiments reported here increase our knowledge of differences in survival, growth and behaviour of cultured and wild sandfish juveniles, and shed light on the relative contributions of hatchery rearing and stressors imposed during transportation and release of juveniles. Increased awareness of whether differences exist, their extent, whether they cause negative impacts, and how long they persist, can be used to fine-tune release strategies and improve ocean mariculture outcomes. Survival and growth were found to be similar between cultured and wild sandfish juveniles, and more than adequate to support ocean mariculture activities. However, important differences were observed in burying behaviour that may negatively affect survival of cultured juveniles at release sites with high predation risk.

5.4.3.1 Transportation

Differences in burial behaviour between cultured and wild sandfish juveniles were attributed to transportation, an activity that cannot be avoided during ocean mariculture activities. Further research into handling and stress during transportation and their potential mitigation should be considered a priority for future research in this field. Stress-free transportation methods are probably not achievable for sea cucumber juveniles, but the results of this study and those reported in prior transportation and release studies with cultured sea cucumbers (Purcell et al. 2006a, Duy 2012, Robinson and Pascal 2012, Zamora and Jeffs 2015, Hou et al. 2019, Tuwo et al. 2019), advocate the following considerations to minimise stress on sea cucumber juveniles:

1. Starve juveniles for at least 12 h to void gut contents before transportation;
2. Remove juveniles from tanks using gentle handling methods;
3. Select only healthy, undamaged individuals;
4. Transport juveniles immersed in seawater, ideally in a small amount of seawater in a plastic bag filled with oxygen (e.g., < 300 individuals in 1 L seawater plus 5 L of

oxygen for durations less than 12 h), but open transportation in containers with seawater is also acceptable if the distance is very short (combined with water exchanges if necessary). Transportation without seawater (e.g., on damp sponges or towels) is not recommended, unless there is no other option and only for short distance and duration.

5. Transport plastic bags containing juveniles in an insulated container, and keep cool (~24°C); and
6. Minimise shaking, bouncing and jolting.

5.4.3.2 Site selection

Seagrass meadows provide food and shelter for sandfish juveniles and reduce predation (Mercier et al. 2000b, Dance et al. 2003). Suitable release site habitat can facilitate rapid adoption of normal burying and feeding patterns, reduce exposure to predators, and provide good nutrition leading to faster growth (Altamirano et al. 2017, Ceccarelli et al. 2018, this chapter). Transport-stressed cultured juveniles buried more in the presence of seagrass in the present study, supporting the use of habitat with moderate to sparse seagrass for cultured sandfish juvenile release. The study, however, failed to determine the primary biophysical driver behind this finding, acknowledging that there may be some combination of features associated with seagrass meadows that are conducive to mariculture of sandfish.

5.4.3.3 Timing of release

Burying of sandfish juveniles has been positively correlated with light and water depth, and negatively correlated with water temperature (Mercier et al. 1999, Purcell 2010b). These factors were not able to be analysed in the present study due to their strong co-linearity, but the effects of light and water depth were more clearly observed after 30 HPR when the majority of both cultured and wild juveniles buried during the low-tide daytime hours and began emerging at night. In the present study, sandfish juveniles were released at night in order to obtain wild juveniles with least disturbance, but, for logistical reasons, the usual release time in PNG mariculture research is during the daytime. Following daytime releases, cultured sandfish juveniles usually lie immobile on the seafloor for some minutes before starting to bury, and most are buried within one hour (C, Hair pers. ob). During this time, an added risk is that the release activity can attract predators (see Oliver et al. 2006). At one PNG mariculture research site, fish (*Scolopsis* spp.) may investigate the sand disturbance during releases and often nip at sandfish juveniles before they can bury (see Dance et al. 2003). At this site, the risk is mitigated by releasing juveniles into protective cages for two hours but this practice is considered impractical for commercial-scale releases.

5.4.3.4 Protection of newly-released sea cucumber juveniles

Structures that retain or protect sea cucumber juveniles following release are costly and only effective for reducing mortality of sandfish where predators are active (Dance et al. 2003, Lavitra et al. 2015, Chapter 3). Results of the present study suggest that at sites where curious, aggressive, visual predators occur, release at night may be advantageous. Conversely, the high survival recorded in the present study suggests that daytime releases (with more rapid initial burial) may be preferable at sites where predators are not active. Only one other study has compared behaviour of cultured and wild sea cucumber juveniles; Palomar-Abesamis et al. (2017) reported extended feeding time and reduced shelter seeking of cultured *S. horrens* juveniles exposed to light, concluding that these behaviours would increase mortality of juveniles released into the wild. To reduce this risk, they proposed releasing *S. horrens* juveniles at dusk to coincide with their activity peak, and releasing them into enclosures with shelter. In contrast, for sandfish, we suggest that release timing be decided on a case-by-case basis once predation risk has been assessed, because heavy predation on released sandfish juveniles has been reported for night time (Tsiresy et al. 2011, Robinson and Pascal 2012) and daytime (Dance et al. 2003) releases. The use of protective cages is probably not economically viable until practical and inexpensive designs are available for large numbers of sandfish for extended periods.

5.5 Study limitations and conclusions

A limitation of this study was our adoption of a minimal-handling approach for wild sandfish juveniles used in Experiment 2. This was done in an effort to minimise factors that may affect their burying behaviour. On this basis, wild sandfish juveniles were not weighed at the start of the experiment, instead they were visually matched with cultured sandfish juveniles that had been weighed at NIMRF, after voiding, prior to transportation to the experimental site. This unfortunately resulted in an anomaly in the size distribution of juveniles. Size matching was acceptable overall, with no significant difference between cultured and wild sandfish mean weights, and all juveniles represented the typical weight range of cultured sandfish released during this study (e.g., Chapter 3). However, mean weight of juveniles in the ‘seagrass present’ treatment was up to 2 g smaller than that of juveniles in the ‘seagrass absent’ treatment and this difference was significant. However, it is unlikely that this small difference in weight between treatments influenced the different responses of cultured juveniles to wild juveniles in the 'seagrass present' habitat. This is because, although ontogenetic changes in burying behaviour of sandfish juveniles have been reported (Mercier et al. 1999, Purcell 2010b), the 2-g difference between the group weights used in this study is small, and the range of weights between groups used in Experiment 2 is well within the size class of sandfish juveniles that have been shown to have similar burying behaviour in other studies (e.g., 5–21 g; Purcell 2010b).

It is important to determine whether physical, physiological and/or behavioural characteristics acquired during hatchery culture or due to transportation stress have negative consequences for sandfish ocean mariculture. Survival and growth of cultured sandfish juveniles were similar to those of wild-collected juveniles, but the tendency of cultured juveniles to delay burying and to spend more time on the substrate surface than wild juveniles, following release, could increase mortality. Transportation stress was the most likely cause for difference in burying behaviour of cultured juveniles, but handling of the wild juveniles in establishing this study precludes a definitive answer to the stress versus source question. Regardless, cultured sea cucumber juvenile must always be transported from the hatchery to an ocean mariculture location, so reduction of stress where possible, adherence to best practice transportation techniques, and release into optimal habitat is strongly recommended. Results indicate that the time of day to release and use of mitigation strategies should be based on release site characteristics and predation risk (type and abundance of predators). Observation of cultured juveniles for some time after release is an essential component of developing site-specific release strategies because of the complexity, spatial variability and low predictability of these patterns in sandfish (Purcell 2010b). Survival from field experiments where juveniles are subjected to different levels of stress and released into high and low predation risk areas will be valuable in further development of improved release strategies. The findings presented here are supportive of the suitability of cultured sandfish for ocean mariculture in PNG, and they provide increased awareness of key behavioural differences between cultured and wild juveniles that can assist in improving the success of release programs.

Chapter 6
Is there a difference between bêche-de-mer processed from ocean-cultured and wild-harvested sandfish?[17]

6.1 Introduction

To produce BDM, the fresh sea cucumber is gutted, boiled at least once, and dried in the sun or over a fire (Preston 1993, Purcell 2014a, Chapter 1). The method has changed little in the Pacific since it was introduced in the 1800s (Anon 1994, Ram et al. 2014), although salting is an increasingly popular step in BDM processing (Lavitra et al. 2008, Purcell 2014a). The method used and care taken during processing are important because both can affect the quality of resulting BDM and the recovery rate, i.e., the amount of BDM recovered from the initial fresh weight of live sea cucumbers (Skewes et al. 2004, Ram et al. 2016b, Pardua et al. 2018). Traditionally, sandfish require the additional processing step of removing the calcareous ossicles in their outer skin layer in order to produce high-grade sandfish BDM. The skin is usually softened after the first boiling, either by overnight soaking in seawater, burying in sand, or treating with papaya leaf extract, and then the chalky layer is removed by brushing or scraping (Preston 1993, Purcell 2014a, Fig. 1.3). Despite recent trends towards marketing of more contemporary products (e.g., gutted and frozen, or gutted, cooked and vacuum packed), most sea cucumbers from the Pacific Islands region are still processed as BDM for export (Kinch et al. 2008a, Purcell et al. 2014a, Barclay et al. 2016).

Claims that pond-cultured sandfish lose more than twice the amount of water during processing than wild conspecifics (Agudo 2012), and speculation that their body wall may be thinner (Purcell and Duy 2012), have not yet been tested, and no information on potential differences between ocean- (pen-) cultured sandfish and wild-harvested sandfish is currently available. If such differences exist, they could compromise the economic viability of sandfish mariculture. The above assertions refer to pond-cultured sandfish and do not elaborate on whether such differences might result from the use of hatchery progeny or grow-out conditions or some other factor. However, perceived inferiority of cultured sandfish could negatively impact future prospects and profitability of sandfish mariculture. Additionally, if cultured sandfish require

---

[17] Data from this chapter were published as: Hair, C., Ram, R and Southgate, P.C. (2018). Is there a difference between bêche-de-mer processed from ocean-cultured and wild-harvested sandfish (*Holothuria scabra*)? *Aquaculture* 483, 63-68. https://doi.org/10.1016/j.aquaculture.2017.09.044

longer culture periods to achieve comparable recovery rates to wild-harvested individuals, then profitability will be reduced. The cropping cycle (i.e., grow-out duration to commercial size) is especially crucial in sandfish mariculture because larger sandfish BDM has greater value. The price of sandfish BDM increases exponentially above 10 cm in length (Purcell et al. 2018b), from around USD 100/kg for 5–6-cm long individuals to four times that value for individuals greater than 11 cm (Purcell 2014b). Body wall thickness is also a key determinant of commercial value of BDM (Skewes et al. 2004) because thicker body wall flesh usually results in better texture and improved eating quality (Lo 2004). The body wall of sea cucumbers contains a high proportion of collagen (Xia and Wang 2015), which has a major influence on BDM firmness and texture quality (Saito et al. 2002). Thus, a thinner body wall may indicate reduced collagen content, which could infer reduced quality and lower value product.

With ongoing improvements in sandfish mariculture (Raison 2008, Purcell et al. 2012b, Robinson 2013) and a growing interest in sea ranching of this species, it is of critical importance to investigate potential quality discrepancies. There are no published records for recovery rates of cultured and wild sandfish processed concurrently using the same method. This report provides size, recovery rates and compositional information for ocean-cultured sandfish and wild-harvested sandfish from New Ireland Province. They were processed to obtain directly comparable data and address the question of whether BDM processed from ocean-cultured sandfish is any different to that processed from wild-harvested sandfish.

6.2 Materials and methods

6.2.1 Sample collection

Adult cultured sandfish were collected from a sea pen at Limanak, a village grow-out site for community-based sea cucumber mariculture research in Kavieng, PNG (Chapters 1 and 3). These sandfish were hatchery produced, reared for one month at the Nago Island Mariculture and Research Facility (NIMRF), on-grown in ocean bag nets for two months, and then stocked into the sea pen at an average weight of around 5 g (for the grow-out experiment described in Chapter 3). They were grown in the sea pen for 15 months before collection for this study at 18-months old. Fifty individuals, representing the full size range of sandfish in the pen, were removed from the water and allowed to drain for several minutes before fresh whole weight (referred to as whole weight) was recorded to the nearest 1 g. At collection, the individual whole weights of the cultured sandfish ranged from 174 to 594 g, with a mean (± SD) weight of 423.8 ± 103.4 g. The sandfish were transferred to a raceway (without substrate) at NIMRF and provided with aeration and flow-through unfiltered seawater until processing.

Adult wild sandfish were collected from a shallow sand-seagrass habitat approximately 2 km from the sea pen location to avoid the possibility of collecting cultured escapees closer to the trial sea pens. Modelling has indicated that sandfish are unlikely to move outside a 1-ha area in the first two years after release (Purcell and Kirby 2006, Lee et al. 2018a). This is also supported by data from this study sites in PNG which show that the maximum distance covered by sandfish six months after release was 100 m (C. Hair, unpublished data). Furthermore, recruitment of the progeny of cultured sea cucumbers into the 'wild' population sampled, and their growth to the size sampled, was not possible within the timeline of culture activities at these sites. Fifty wild individuals were collected and measured in the same way as cultured individuals. To reduce the influence of size difference, which can affect the recovery rate (Skewes et al. 2004), wild sandfish of similar whole weight (i.e., ± 10 g) of the sampled cultured sandfish were collected. At collection, the individual whole weights of the wild sandfish ranged from 180–590 g, with a mean (± SD) weight of 424.5 ± 103.3 g. The wild-harvested sandfish were transported to NIMRF and transferred into a separate raceway (without substrate) with aeration and flow-through unfiltered seawater until processing.

6.2.2 Processing and data collection

Processing began approximately 20 h after collection of the cultured sandfish and 3 h after collection of the wild sandfish. Initial treatment and handling was identical for all sandfish. Individuals were removed from their holding tank, allowed to drain for 2 min, then fresh whole weight to the nearest 1 g and length to the nearest 1 mm were recorded. After evisceration to remove the internal organs and coelomic fluid, a 7–8-cm slit was made in the dorsal surface and the body cavity cleaned. Note that the usual BDM processing for sandfish entails a small cut on the underside of the animal (Anon 1994, Purcell 2014a); however, a large dorsal incision was made to enable measurement of each side of the fresh body wall to the nearest 0.1 mm with dial callipers. While carrying out these measurements, difficulties were experienced due to observable shrinking of the body wall during handling and the presence of naturally thick and thin body wall sections ('wrinkles'). Fresh gutted weight was recorded and then each sandfish was labelled with a numbered plastic tag on a coloured cable tie threaded through the body cavity and anus. A unique tag number and cable tie colour were used for each sandfish to enable identification of individuals through subsequent processing steps. However, when processing began it became apparent that gutted weights of the cultured and wild groups varied more than whole weights at collection. Since Skewes et al. (2004) had found that gutted weight was a more reliable estimate of true body weight, paired individuals of similar gutted weight from the sandfish available were used for the experiment. Thus, 23 pairs of sandfish consisting of a wild and cultured individual were selected to be approximately matched in weight, so that starting condition of each group was similar (cultured 230.9 ± 11.1 g, wild 232.5 ± 13.2 g; mean ± se).

The subset of 46 sandfish was processed to a fully dry state using a modified basic BDM processing method, similar to those used in PNG and the Pacific (Anon 1994, Ram et al. 2016b). Sandfish were cooked in a large pot of 50ºC seawater and the water heated further while stirring for 15 min (this is referred to as the first 'boil', even though the water does not reach boiling point). Boiled sandfish were held in a bag in running seawater for 12 h, then brushed with a coarse scrubbing brush to remove the outer skin layer of calcareous ossicles before a second boil in 50ºC seawater for 15 min while stirring. The sandfish were partly dried in the sun before completing the drying process in a drying oven at 55ºC until they were stone dry after approximately three days. Weight and length of all individuals were recorded following the first boil, second boil, and oven drying stages.

The dry body wall thickness was measured after lateral slicing of the fully dried sandfish BDM at the midline with an electric saw. The presence of external wrinkles that characterise sandfish integument, and the drying process itself, created thin and thick sections of body wall around this cross-section. A standardised method to determine dry body wall thickness was developed. Each individual cross-section was photographed together with a scale (Fig. 6.1). Four intersecting lines at 45º angles were superimposed on this image with the lines' centre within the body cavity and the 'south' direction line passing through the narrowest part of the ventral wall. Starting points for measurement of body wall thickness occurred where the lines intersected the outer body edge (or nearest point if no intersection). The body wall thickness was measured as the smallest distance from each start point into the inner edge of the wall, excluding any remnant dried viscera or calcareous layer (Fig. 6.1). Seven body width measurements per individual were obtained using *ImageJ* image analysis software (Abràmoff et al. 2004), and averaged to obtain a dry body wall width estimate. All data are repeated measurements of the same individual and presented as mean ± standard error (SE), except where specified.

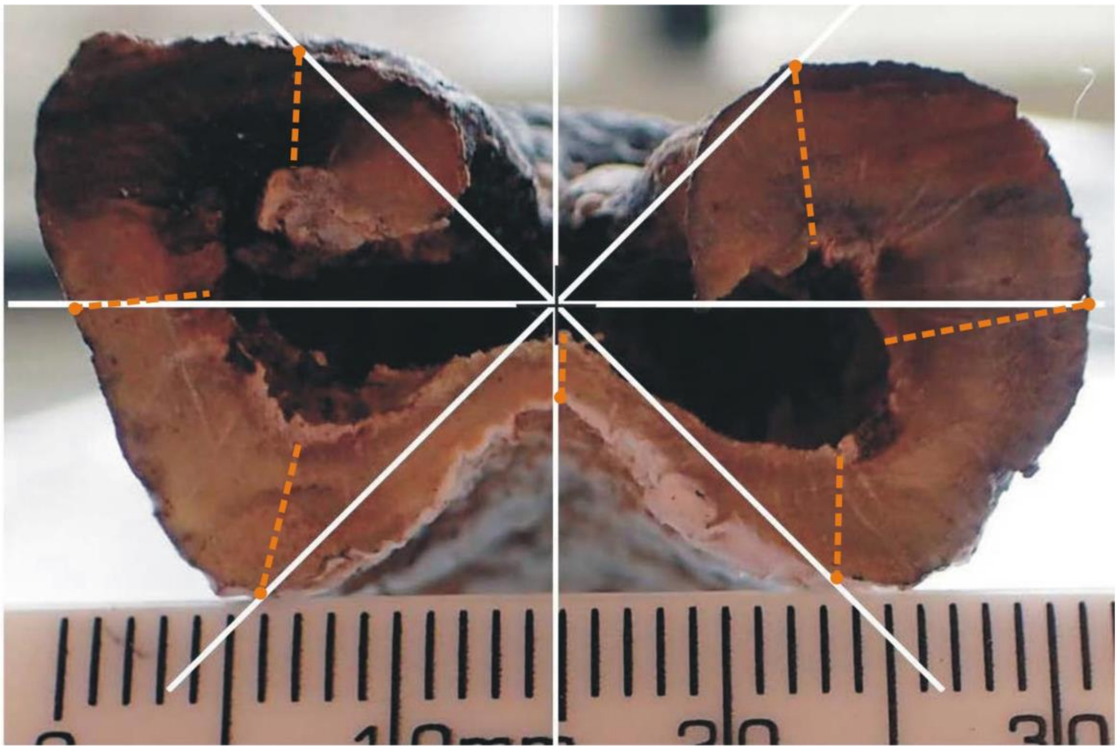


Figure 6.1 Method for selection of points for sandfish BDM body width measures. White lines indicate the seven outer body wall intercepts. Broken orange lines show the measurement path for each point.

The measured variables from ocean-cultured and wild-harvested sandfish were used for direct comparisons and also to calculate four derived variables, as follows: recovery rate from whole weight (RR_w), recovery rate from gutted weight (RR_g), ratio of dry length to fresh whole length (DLR) and body wall index (BWI) were calculated as:

RR_w = *dried weight / whole weight x 100*

RR_g = *dried weight / gutted weight x 100*

DLR = dried length / fresh length x 100

BWI = gutted weight / mean dry body wall thickness.

6.2.3 Body wall composition analysis

Subsamples of sandfish BDM (approximately 5 g) were heated in a muffle furnace for 24 h at 550°C to estimate ash content. Collagen content of dried body wall was determined for a representative size range of wild and cultured sandfish (n = 15 of each group; gutted weight 93–309 g for cultured individuals, and 87–350 g for wild individuals). Dried tissue samples were reconstituted, milled, freeze-dried, then hydrolysed using 6-Molar HCl. Hydroxyproline content of the samples was estimated spectrophotometrically (absorbance read at 558 nm), and collagen content (mg/g dry weight) was determined by applying a conversion coefficient of 11.1 (Chen et al. 2015).

6.2.4 Data analysis

One-way ANOVA and analysis of covariance (ANCOVA) were used to identify differences in the weight, length, body wall thickness, RR_w, RR_g, DLR, BWI, collagen content and ash content of ocean-cultured and wild sandfish at different stages of processing. ANCOVA was used where the initial size of the sandfish may have had an influence on the analysis outcome. Differences between groups were considered significant at $p \leq 0.05$. Prior to ANOVA all data were tested for normality and homogeneity of variance using Levene's test at $p \leq 0.05$, and additionally tested for homogeneity of regression prior to ANCOVA (IBM SPSS Statistics 22). Heterogeneous data were log transformed prior to analysis.

6.3 Results

There were no significant differences in weight and length parameters between ocean-cultured and wild-harvested sandfish immediately before or during processing (Table 6.1, Fig. 6.2). Wild sandfish had significantly thicker fresh body wall ($p = 0.040$), but there was no significant difference in dry body wall thickness ($p = 0.179$).

There was no significant difference in recovery rate from ocean-cultured or wild-harvested sandfish for gutted weight ($p = 0.055$) but there was a significant result for recovery from whole weight ($p = 0.047$) (Table 6.1). There was no significant difference in the ratio of dried length to fresh length ($p = 0.099$). The dry BWI was not significantly different between groups ($p = 0.121$). Collagen content was not significantly different between the two groups ($p = 0.420$) (Table 6.1). There was no significant difference between dried cultured and wild sandfish for ash content ($p = 0.468$).

Table 6.1 Mean, standard error, ANCOVA covariate where applicable, and *F* and *p* values for ANOVA/ANCOVA of key variables for ocean-cultured and wild sandfish (* denotes data were ln transformed prior to analysis to achieve homogeneity of variance).

Variable	Mean (±SE)		ANCOVA covariate	*F*	*p*
	Cultured	Wild			
Whole weight (g)	407.0 (±18.9)	400.6 (±21.7)	na	0.050	0.824
Gutted weight (g)	230.9 (±11.1)	232.5 (±13.2)	na	0.009	0.924
Whole length (mm)	196.7 (±5.1)	198.1 (±4.9)	na	0.420	0.839
Fresh body wall (mm)	5.6 (±0.3)	6.6 (±0.3)	Whole wt	4.633	0.037
			Gut. wt	4.497	0.040
Dry weight (g)*	20.2 (±1.0)	22.6 (±1.6)	na	0.525	0.473
Dry length (mm)	101.9 (±2.3)	98.3 (±2.6)	Whole lth	2.311	0.136
Dry body wall (mm)	2.7 (±0.1)	2.9 (±0.1)	Whole wt	2.158	0.149
			Gut. wt	1.864	0.179
Body wall index	86.9 (±3.7)	80. (±4.2)	Whole wt	1.715	0.197
			Gut. wt	2.508	0.121
RR whole (%)	5.0 (±0.2)	5.6 (±0.2)	Whole wt	4.168	0.047
RR gutted (%)	8.8 (±0.2)	9.6 (±0.3)	Gut. wt	3.887	0.055
Dry Length Ratio (%)	52.3 (±1.2)	49.7 (±1.0)	Whole lth	2.840	0.099
Collagen (mg g^{-1})	94.5 (±6.4)	104.0 (±9.7)	Whole wt	0.636	0.432
			Gut. wt	0.671	0.420
Ash (%)	15.2 (±1.1)	14.0 (±1.2)	Gut. wt	0.537	0.468

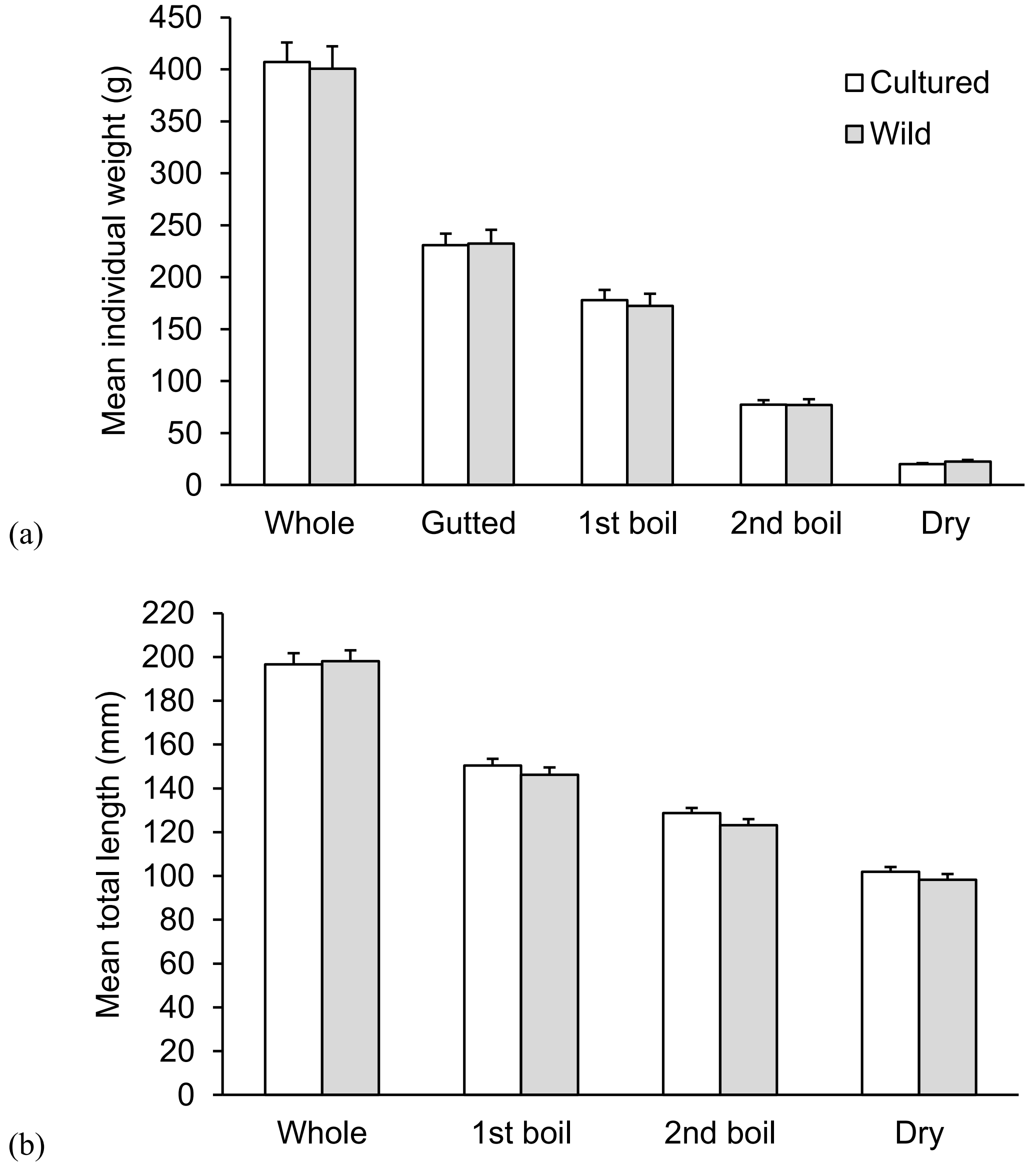


Figure 6.2 (a) Mean (±SE) weight (g), and (b) length (mm), of ocean-cultured (white bars) and wild-harvested (grey bars) sandfish at different stages of processing.

6.4 Discussion

Key attributes that affect the quality and value of ocean-cultured and wild sandfish BDM were compared. Minor differences in the recovery rates from fresh whole or gutted weight were found, with wild sandfish having slightly higher BDM yield (9–12%), although not of the magnitude of 2:1 suggested by Agudo (2012). Comparison to published results for cultured sandfish showed considerable variability to results from ocean-cultured sandfish from the Philippines and Madagascar, but lower than pond-reared sandfish from Vietnam (Table 6.2).

However, for wild sandfish, recovery rates from this study were very similar to those reported from PNG, northern Australia and the Pacific Islands region, except Fiji (Table 6.2).

Sea cucumbers are notoriously difficult animals to measure because their shape and size are plastic (Sewell 1991, Prescott et al. 2015). An individual's weight can also vary through the retention of water and sediment within the body and with seasonal changes (Sewell 1991, Battaglene et al. 1999, Pitt and Duy 2004, Skewes et al. 2004, Hannah et al. 2012). There are many examples of efforts to develop reproducible measuring techniques for fresh and processed sea cucumbers (e.g., Skewes et al. 2004, Laboy-Nieves and Conde 2006, Hannah et al. 2012, Prescott et al. 2015). However, even assuming accurate measurements are obtained, differences in BDM recovery rates are affected by factors such as: body size (Skewes et al. 2004, Pardua et al. 2018); species (Skewes et al. 2004, Purcell et al. 2009, Ngaluafe and Lee 2013, Ram et al. 2016b); processing methodology, such as the use of salt, which produces heavier BDM (Lavitra et al. 2008, Purcell 2014a, Purcell et al. 2016c, Pardua et al. 2018), and level of dryness (because moisture content equates to weight); and possibly even sea cucumber origin (Skewes et al. 2004). One or more of these factors may account for differences reported in the literature (Table 6.2).

Product size and thickness of the body wall are important determinants of commercial value of BDM (Skewes et al. 2004). The fresh body wall of ocean-cultured sandfish was significantly thinner than wild. However, problems with accurate recording of the fresh body wall were experienced because it became visibly thinner in response to evisceration and cutting during processing and measuring. Mechanical stimulation can cause sea cucumber dermis and body wall to undergo rapid changes in stiffness, resulting in up to 15% reduction in mass and volume (Wilkie 2002, Tamori et al. 2010). The body wall of sandfish also has transverse wrinkles (up to 3-mm deep) in the skin (Purcell et al. 2012a). In contrast, the body wall of dried individuals did not change with handling and dermal wrinkles were less deep. Further, by measuring seven points around the body wall, the influence of naturally thin or thick sections of body wall on the mean value was reduced. In this study, the dry body wall thickness is thus considered a more reliable and robust measure of this attribute. Development of a technique to measure consistent and accurate width of fresh sea cucumber body wall would benefit future studies of this nature. For example, measurements could be made after a fixed period of handling when the body wall has stabilised, and averaging values recorded from both 'thick' and 'thin' sections of the body wall.

Table 6.2 Comparison of average recovery rates from fresh whole weight (RR_w) and gutted weight (RR_g) for cultured and wild-harvested sandfish from the literature. NA denotes that data were not available.

Sandfish origin	Country	n	Mean fresh whole weight (g)	RR_w	RR_g	Author(s)
Wild	India	304	218–548	8.2–8.7%	NA	Bhaskar and James (1989)
Wild	Pacific	NA	370	5%	NA	Anon (1994)
Wild	PNG	42	366	5%	NA	Shelley (1985)
Wild	Australia	51		4.8%	9.4%	Skewes et al. (2004)
Cultured (ocean)	Madagascar	NA	280	~9%	~18%	Lavitra et al. (2008)
			430	~9%	~18%	
Cultured (pond)	New Caledonia	NA	400–600	Wild RR_F = 2 x Cultured RR_f	NA	Agudo (2012)
Cultured (ocean)	Philippines	2,407	240–397	2.3– 3.2%	NA	Juinio-Meñez et al. (2012b)
		18	839	NA	8.8%	Pardua et al. (2018)
		18	293	NA	6.2%	
Cultured (pond)	Vietnam	NA	300	~10%	NA	N.D.Q. Duy (pers. comm., May 2015)
		NA	500	~14%		
Wild	Fiji	51	129	8.1%	8.5 %	Ram et al. (2016b)
Wild	PNG	23	401	5.6%	9.6 %	This study
Cultured (ocean)	PNG	23	407	5.0%	8.8 %	This study

The dried body wall is the main edible part of the sea cucumber and an important source of collagen, which accounts for more than three-quarters of the total protein content (Xia and Wang 2015). Collagen is linked to the body wall thickness, texture and flesh quality of BDM (Saito et al. 2002, Lo 2004). BDM is known more for these qualities than flavour (Lo 2004), and they in turn influence the value of the final product. Collagen content was not significantly different between ocean-cultured and wild-harvested sandfish. Similarly, Wang et al. (2012) found no significant difference in collagen content of cultured and wild *Apostichopus japonicus*, the high-value, mass-produced temperate sea cucumber species (40.37% and 39.43%, respectively).

FAO statistics indicate that aquaculture production is the only way to address increasing demand for seafood in the future (FAO 2018). However, in the major BDM marketplace of China, 'wild' foods are considered superior since they are uncontaminated, more exclusive and also more '*bu*', i.e., typically exotic and favoured for health benefits (Fabinyi 2012, Fabinyi and Liu 2014). Despite this, cultured *A. japonicus* are reported to be rich in valuable bioactive nutrients (Bordbar et al. 2011, Zhang et al. 2015) and consumers in China accept that much seafood is farmed (Fabinyi and Liu 2014). A willingness to compromise while maintaining this preference is reflected in 20–50% higher prices for cultured *A. japonicus* grown in natural marine areas compared to pond- or cage-cultured animals (Zhang et al. 2015, Qinzeng et al. 2016). Putting aside consumer attitudes, inferior physical traits of products would pose a very real threat to the viability of sea cucumber mariculture. Recovery rate is a measure of the proportional weight of BDM produced from live sea cucumbers (Skewes et al. 2004), hence lower recovery rate equals less monetary return. The thickness and composition of the body wall is inextricably linked to the eating quality and therefore product price (Lo 2004).

6.5 Conclusion

Speculation that BDM processed from pond-cultured sandfish may have a lower recovery rate and thinner body wall than wild-harvested individuals (Agudo 2012, Purcell and Duy 2012) has not yet been examined. Comparison data for wild versus pond-cultured sandfish would be valuable. However, this study is the first to collect reliable data on differences between similarly sized ocean-cultured and wild-harvested sandfish, processed concurrently using the same methods. The recovery rate of BDM processed from ocean-cultured sandfish was slightly less than that from wild-harvested sandfish in this experiment (5% vs 5.6% from whole weight and 8.8% vs 9.6% from gutted weight) and much more favourable than that hypothesised for pond-cultured sandfish (Agudo 2012, Purcell and Duy 2012). The ratio of dried BDM length was slightly greater for ocean-cultured sandfish (52% vs 50 % of fresh length). Ocean-cultured BDM also had similar characteristics with respect to dry body wall thickness and collagen content. Furthermore, the cropping cycle is similar to that of *A. japonicus*, which reach harvestable size between 18 and 24 months, including an extended nursery period (Hagen 1996, Zhang et al. 2015). This information improves confidence in modelling the economic feasibility of sea ranching (Johnston 2012) and augers well for the future of sandfish sea ranching in PNG and other areas where mariculture of this species is being developed.

Chapter 7
Social and economic challenges to community-based sandfish mariculture development[18]

7.1 Introduction

7.1.1 Mariculture livelihoods and the wild sea cucumber fishery in PNG

There is an acknowledged need for appropriate fisheries and aquaculture livelihood activities that meet the cash needs and aspirations of Indo-Pacific rural coastal dwellers without negatively impacting future food security, income and resilience (Allison and Ellis 2001, Stevenson and Irz 2009, Mills et al. 2011a, Aslan et al. 2015, Béné et al. 2016). Improved livelihood options can be achieved through enhancing existing livelihoods, diversifying the range of livelihoods available or developing alternative livelihoods (Campbell et al. 2006, Salayo et al. 2012). Many coastal and island communities in Papua New Guinea (PNG) have limited livelihood options and rely heavily on marine resources for food security and cash income (Kronen et al. 2010, Purdy et al. 2017). One of the most important and lucrative of these is BDM, the dried body wall of sea cucumber (Kinch et al. 2008b, Barclay et al. 2016, Chapters 1 and 2). In 2009, the PNG National Fisheries Authority (NFA) imposed a nationwide moratorium on sea cucumber harvest and BDM sale because stocks were severely overfished. The moratorium was in place for seven years until it was lifted in April 2017.

A high-value commercial sea cucumber in PNG is sandfish, *Holothuria scabra*. Sandfish were heavily exploited in PNG in the late 1980s, and are a targeted species in the current, post-moratorium fishery (Hair et al. 2018, Chapters 1 and 2). This species exhibits boom and bust tendencies, dominating landings in the early stages of a fishery, then dwindling rapidly due to fishing pressure (Hamel et al. 2001, Hasan 2005, Chapter 1). It is also a promising commodity for mariculture (Purcell et al. 2012b, Robinson 2013, Chapter 1). Sandfish hatchery production has expanded rapidly since the lifecycle of this species was closed in the 1980s (James 1996). Presently, many countries within the circum-equatorial range of sandfish are commercially culturing this species, in the ocean (farming in enclosures or unfenced 'sea ranches') and in land-based systems (ponds, recirculation facilities) (see references in Hair et al. 2012, Purcell

[18] Data from this chapter were published as: Hair, C., Foale, S., Daniels, N., Minimulu, P., Aini, J. and Southgate, P.C. (2020). Social and economic challenges to community-based sea cucumber mariculture development in New Ireland Province, Papua New Guinea. *Marine Policy*, 117, 103940. https://doi.org/10.1016/j.marpol.2020.103940

et al. 2012b, Robinson 2013). In particular, community sea ranching appears to be economically, technically and culturally suited to PNG (Chapter 2), compared to other potential livelihood activities such as tourism and seaweed farming (Sievanen et al. 2005, Steenbergen et al. 2017a, Connell 2018, Fabinyi 2018). At the village level, this activity does not rely on wild seed, or require addition of food inputs, or negatively impact on ecosystem and community services if no enclosures are constructed. On the contrary, the deposit-feeding and burying habits of sandfish can provide ecological benefits leading to improved sediment, seagrass and water health (Wolkenhauer et al. 2010, Purcell et al. 2016b, Lee et al. 2018b). With responsible implementation (see Eriksson et al. 2012), sandfish sea ranching can also meet criteria for sustainable ecological aquaculture (Costa-Pierce 2010).

Sea ranching of sandfish has not been proposed as a substitute for the wild fishery or other existing livelihoods: such an approach has been shown to be unrealistic and potentially risky (Sievanen et al. 2005, Torell et al. 2010, Slater et al. 2013, Steenbergen et al. 2017a). Rather, it is intended as a means to provide additional income among a suite of livelihoods (see Chapter 2) and increase community economic resilience. This mariculture intervention can be seen as either enhancement of a familiar livelihood by what Torell et al. (2010) refers to as 'moving up the value chain', i.e., managing harvests for greater reliability, control and equity, or to provide an added income stream (diversification), albeit closely related to the existing wild fishery (Mills et al. 2011a). Uptake of any new livelihood technology is dependent on it being a good social and cultural fit for fisheries-dependent communities (Torell et al. 2010, Slater et al. 2013). It is also important to avoid top-down approaches, to consider unintended consequences and to involve communities at all stages of livelihood introduction, integration and implementation (Krause et al. 2015, Steenbergen et al. 2017a, Steenbergen et al. 2017b, Ateweberhan et al. 2018).

7.1.2 Engagement with the study community

Three communities in the Tigak and Tsoi islands collaborated in the mariculture research because of their dependence on marine resources, history of sea cucumber fishing, suitable ecological conditions for sandfish mariculture in their traditional fishing grounds and desire to participate (Chapter 1). Small numbers of cultured sandfish had been successfully reared to commercial size in sea pens in the fishing grounds of Enuk, Limanak and Ungakum (see Chapter 3) but technical and socio-economic data on a large-scale juvenile release in a realistic community situation had not been achieved. Community partnership and cooperation were critical to this goal; in turn, the information obtained would inform the community on viability of this livelihood and how to adopt it for their maximum benefit. An added advantage was the inclusion of a potential sea ranching community early in the research phase.

Engagement with the specific community that is the subject of this chapter began in 2014 (refer to research described in Chapters 2, 3, 4 and 5). Liaison was conducted predominantly with the marine resources committee (MRC) that managed the community marine resources, and to a lesser degree with the local level government (LLG) body and the village planning committee (VPC), noting a degree of overlap of members across these three committees. The MRC had been formed in the mid-2000s with support from a conservation NGO. The study community did not have a strong tradition of using *tambu* (i.e., fishing prohibition) as a means of conservation or stockpiling (sensu Foale et al. 2011). However, the community-NGO co-management arrangement had led to the declaration of a tambu coral reef area in 2006 that reportedly functioned well for more than a decade. As a result of this experience with the NGO and then, the present study, the community was familiar with concepts pertaining to fisheries management, including community-based management of an MPA. Indeed, one of the primary reasons for engaging this particular community in research into sandfish mariculture was their perceived superior capacity for community-based fisheries management (CBFM). Over the course of their involvement with the present study (2014-2018), various community members also assisted with surveys, cultured juvenile sandfish releases, and in maintaining cages and pens containing sandfish. In addition, educational activities had been conducted in the wider community, including hatchery tours, the provision of research updates, videos, booklets and posters on fishery management, sea cucumber mariculture and BDM processing (Figs 7.1, 7.2, 7.3). Although this study was concerned with sandfish mariculture, the sustainable fishing of wild sea cucumber and extraction of maximum value from the sandfish resource (via harvest of large individuals and quality BDM processing) were emphasised as integral to both a sustainable wild fishery and viable mariculture.

A trial sea ranch was established by the MRC in late-2016, after discussions with the author of this thesis and other researchers and following consultation with the wider community and LLG. The ranch comprised a 5-ha area of suitable sandfish habitat within the community's traditional sea cucumber fishing grounds, which were in excess of 500 ha. The trial sandfish sea ranch would be stocked with cultured juvenile sandfish (≥ 3 g), the timing of which was contingent on supply of cultured juvenile sandfish from NIMRF. Both the MRC and LLG pledged that the trial sea ranch would be protected from fishing (i.e., tambu) for one year from the completion of stocking, to allow collection of technical data on survival, growth and movement of cultured sandfish. Following a final survey to generate the technical data, it was agreed that all remaining cultured sandfish in the trial sea ranch would become community property. A target date for handover to the community was not set because of a paucity of data on which to base such a target and the potential to create unrealistic expectations within the community.

The trial sea ranch was an unfenced area of shallow (maximum 2-m depth) sand and seagrass habitat that was accessible by canoe or wading from shore. It was located about 300–400 m offshore from the nearest houses (in line-of-sight) but at least 1 km (and out-of-sight) from the main village. The location was selected to facilitate informal community-based security and deter poaching during the data-collection phase, noting that no formal security was established. Also, to ensure that the sea ranch was accessible to community members once it became a community responsibility. The prohibition on fishing within the trial sea ranch was prescribed in the community's marine management plan. A noticeboard, outlining the rules of the ranch and related information, was erected onshore, adjacent to the ranch (Fig. 7.3), and the sea ranch tambu was explained in project presentations and announced at community meetings. Independently, the MRC declared a fishing tambu on a separate 15-ha area of their fishing grounds that was not related to this study.

A baseline survey of wild sandfish within the trial sea ranch was conducted prior to stocking any juvenile sandfish (these results are presented in Chapter 4), and then again in June 2017 after the NFA had lifted the sea cucumber fishing moratorium. Results indicated that the ranch had been unfished and the community had upheld the agreement at that point in time. In the 2017 open season, an enumerator spent two weeks in the community to record and measure sea cucumber landings for a separate study on the post-moratorium status of wild stocks (see Hair et al. 2018).

The goal of 5,000 stocked cultured juvenile sandfish was attained in August 2018, the final batch of 300 juveniles were released three weeks after the 2018 sea cucumber fishing season opened. Prior to the fishery opening, border posts decorated with reflective tape and flags were installed to make the trial sea ranch boundary conspicuous and to limit accidental entry.

Figure 7.1 Detail from a poster describing how a community sea cucumber sea ranch would function.

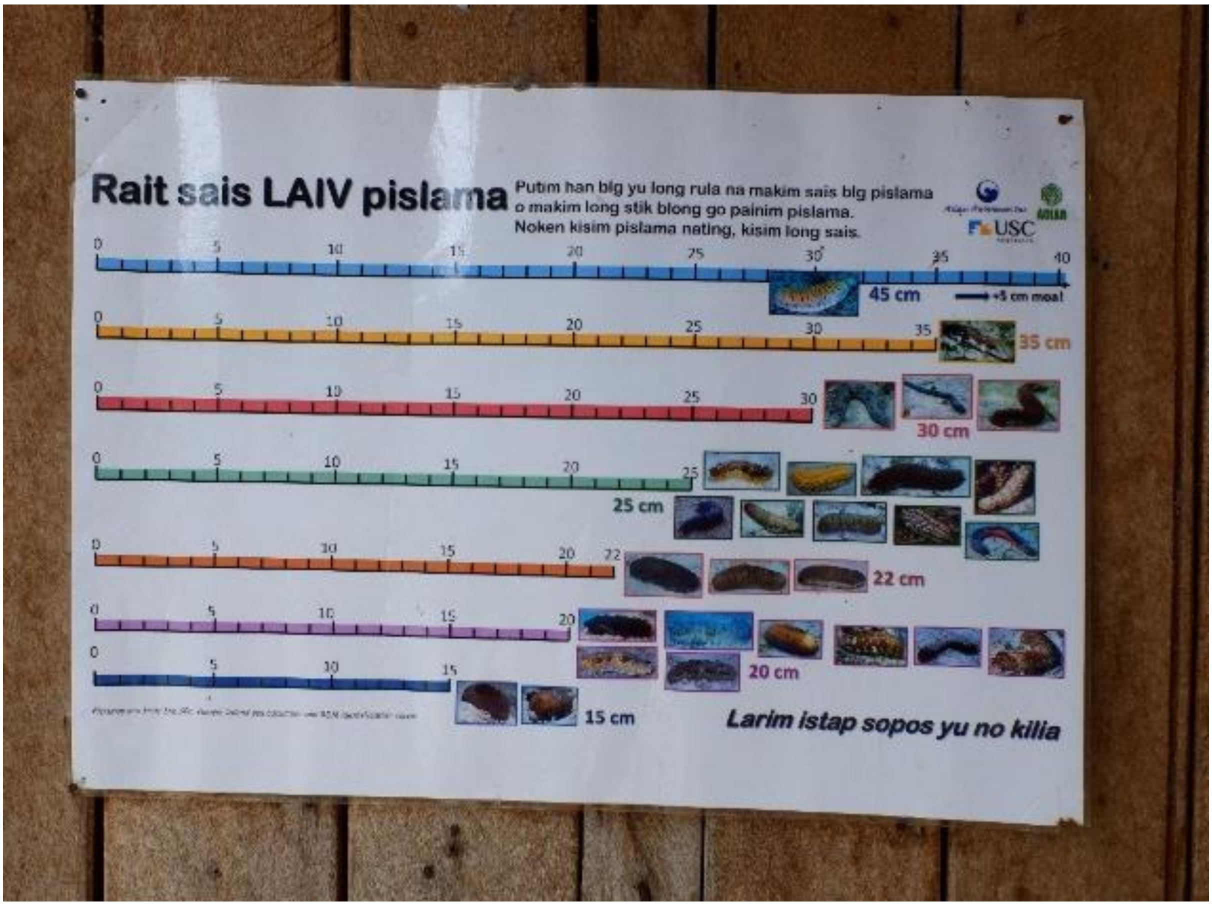


Figure 7.2 Poster demonstrating the legal minimum lengths of live sea cucumbers.

Figure 7.3 Community noticeboard used to display sea ranch regulations and sea cucumber fishery-related information.

7.1.3 Impact of the 2018 sea cucumber fishing season on mariculture research

The trial sea ranch was established in 2016 during the nationwide sea cucumber fishing moratorium, described in Chapter 1. However, the final two years of research were conducted after the moratorium was lifted, during a period when the fishery was opened for limited annual seasons. The first open sea cucumber season occurred in April-May 2017 (Hair et al. 2018, Chapter 2) and the second was in August-September 2018. During both open seasons, gear restrictions included bans on underwater breathing apparatus and use of lights at night. However, the primary fishery management measures were minimum size limits for all sea cucumber species, and designated open/closed seasons that were further regulated by a total allowable catch (TAC) of BDM, monitored at the point of export (Barclay et al. 2016, NFA 2018, noting that NFA released a second revised BDM Plan prior to the 2018 season). Under the latter measure, traders' purchase records were to be monitored in real time until a pre-determined TAC was reached, at which point the fishing season would be closed. Several aspects of the 2018 sea cucumber season in the provincial context were key to the events that occurred in the study area, including:

1. The 2018 provincial TAC of 80 tonnes (t) was exceeded by 120 t (the previous season's TAC had also been exceeded, Hair et al. 2018);

2. There were 24 licensed BDM exporters in New Ireland Province in 2018 (compared to eight in 2017), which was the highest number in any PNG province. Many of these traders were newcomers to the trade in PNG;

3. Record prices were paid for BDM, with sandfish of highest value; and

4. The 2018 season was notable for widespread targeting of undersized sea cucumber.

This chapter investigates the impact of the 2018 sea cucumber fishing season on the trial community sandfish sea ranch, where the community agreement to enforce a fishing ban in the area was broken. Community attitudes and actions are discussed in the context of internal factors (within the community) and external pressures that contributed to the breakdown, including those from the fishery and the research itself. The potential of sandfish mariculture research and livelihood development in the PNG context are assessed and lessons from this experience are presented.

7.2 Methods

7.2.1 Ethical statement

This study was carried out under James Cook University Human Research Ethics Committee approval H4930. All interviewees gave consent to participate, verbal consent was usually sought because of low levels of literacy. Prior to being interviewed, each respondent was informed of the purpose of the interview, the confidentiality of information provided and the right to omit questions or end the interview at any stage. The study community is not named in this chapter as they requested anonymity.

7.2.2 Data collection

Data were collected using a mixed-methods approach consisting of oral, semi-structured interviews with community members (n = 20 interviews in the main village and eight nearby hamlets[19]), focus group discussions (n = 2; a mix-gendered group at one of the larger hamlets and a women-only group at the main village), and informal conversations with sea cucumber fishers and other community members over a five-day period in November 2018, which was

[19] Small household clusters at least 200 m from the main village that identified with the overarching village/community name.

three months after the 2018 sea cucumber fishing season closed. Interviews were conducted in *Tokpisin*, a National lingua franca. A local assistant translated questions into local language (*Tokples*) and provided clarification when required. Questions revolved around the 2018 season as experienced in the community, knowledge of the trial sea ranch and how it was viewed by community members, events leading to the failure of the ranch, how community members viewed development (i.e., definition and examples), and lessons learned related to the role of researchers, government fisheries officers and community members in the failure of the trial sea ranch (Appendix 5).

Participant observation during regular field work associated with this study between 2014 and 2018 also generated substantial knowledge of community attitudes, perceptions and sea cucumber harvest/processing practices. All sources were examined for key themes and responses were coded for presentation (Bernard 2006). Information was also collected from other Tigak and Tsoi Islands' fishers, local traders and others who had knowledge or experience of the 2018 sea cucumber fishing season in New Ireland Province.

7.3 Results

7.3.1 Comparison of the 2017 and 2018 sea cucumber fishing seasons

When asked about the 2018 sea cucumber season, most fishers reported differences to the 2017 season in harvesting and BDM trade (Table 7.1). Around ten licensed exporters operated in the community during the 2018 season, including one that established a buying premises on the beachfront of the main village. The high price offered in 2018 compared to 2017 was referred to frequently in interviews, focus groups and informal discussions. Competition was fierce, and prices varied depending on how many traders were present in the community at any time and the level of BDM processing (Table 7.2). This contrasted with the 2017 season when most fishers in this community travelled to Kavieng to sell their BDM, did not sell fresh sea cucumber, mostly obeyed the size limits, and high quality sandfish BDM sold for maximum price of PGK 200 per kg [20].

Illegal and 'questionable' harvesting and buying practices that occurred during the 2018 season were reported in all interviews and informal conversations. For example, Asian traders

[20] At the time of this study, PGK 1 was approximately equal to USD 0.29

purchased BDM and sea cucumber from fishers in contravention of the NFA regulation that prohibits non-PNG nationals from direct involvement in the industry. Some traders actively encouraged fishers, including young children, to harvest undersized sea cucumber (e.g., fresh sandfish as small as 12 cm). Some Asian traders bought small and damaged BDM, claiming it was for their own consumption. Processing gear was provided to fishers and other goods were supplied on credit, on the proviso that fishers then sold BDM back to them. Coarse salt was also freely supplied; use of salt in processing benefits both fishers and traders because it produces a well-preserved and heavier BDM (Purcell 2014a). Receipts were not always provided for sales, and inconsistent weighing and grading of BDM were commonplace. Some traders paid slightly more than the quoted catch value to ingratiate themselves with fishers (*grisim man*). Fishers harvested sea cucumber at night using torches, and BDM were still being purchased for several months after the season closure.

Table 7.1 Number of responses (and % of total interviews) for reported factors differentiating the 2017 and 2018 sea cucumber open seasons. Most respondents cited more than one difference.

Factor	2017	2018	No (%)
Traders bought undersized BDM	No	Yes	15 (75%)
Price	Lower	Higher	9 (45%)
Income	Lower	Higher	6 (30%)
Traders in village	Few	Many (Asian)	6 (30%)
Intensity of fishing	Less	More	6 (30%)
Outsiders (poachers / insider-outsiders)	None or very few	Many	5 (25%)
Overall harvest	Smaller	Bigger	4 (20%)
	Bigger	Smaller	2 (10%)
Night fishing (torches)	No	Yes	4 (20%)
Deep water diving conditions	-	Poor visibility	3 (15%)
Buying practices different	-	Yes	3 (15%)
Processing level	BDM	BDM, boiled, fresh	2 (10%)
Sea ranch tambu respected	Yes	No	2 (10%)
External monitors	Yes	No	2 (10%)
Tradestore goods on boats	No	Yes	2 (10%)
Sandfish size	Bigger	Smaller	1 (5%)
	Smaller	Bigger	1 (5%)
Season duration	Short season	-	1 (5%)

Table 7.2 Level of processing and price paid for sandfish (legal length of ≥ 22 cm live, ≥ 10 cm BDM, unless noted), as reported by fishers.

Processing level	Price paid	Comments
Fresh, whole	PGK 17–20 (per piece)	Fresh sandfish, not processed.
Partly processed	PGK 150/kg	Sandfish boiled and calcareous skin layer removed.
'Wet' BDM	PGK 250/kg	Sandfish BDM with high moisture content. Usual village processing level. Higher prices for larger specimens.
'Stone' dry BDM	PGK 280-350/kg	Well dried sandfish BDM with low moisture content. Higher prices for larger specimens.
Undersized BDM	PGK 100/kg	Illegal

Most respondents noted that sandfish were abundant at the start of the season, with large individuals present both inside and outside the trial sea ranch. More than half (55% of respondents) said sandfish were still plentiful after the season closed. There was a common perception that small sandfish were abundant in shallow areas while large sandfish were abundant in deep water (more than 50% of respondents), because poor visibility had restricted the use of lead bombs[21] to harvest large sandfish from deeper fishing grounds. Two respondents thought that sandfish hide or move away during intense harvesting and return when fishing pressure eases (cf. Carrier 1987).

7.3.2 The trial sea ranch

Interview data confirmed that the entire community was aware of, and supportive of, the trial sea ranch and the tambu on it, and that this was also well-known to visitors and people in neighbouring villages. The removal of the tambu, therefore, caught most people by surprise. Some respondents (20%) were personally informed that the tambu had been lifted but most became aware when they noticed (65%) or heard (15%) that people were fishing in the sea ranch. The main reason provided for this was that one or two people 'poached' sandfish from the ranch, others then followed, and the situation intensified until there was widespread poaching (80%) to the point where the tambu was assumed to no longer be operational. A common variation on this scenario was as follows – an LLG official saw men fishing in the

[21] A 3-4 kg weight tied to a rope, with a 3-cm barbed spike, which is used from a boat or snorkeling to spear and collect sea cucumber in depths greater than 20 m when the water is clear (SPC 1994).

ranch, then angrily declared both tambu areas open without any consultation of the MRC (a third of respondents gave this version, including some who claimed to be eyewitnesses). Following this quasi-official opening, harvesting sandfish from the ranch cannot be considered as poaching because the community believed they had legitimate permission to fish there. The remaining 20% of respondents were unsure why the tambu was lifted.

All respondents claimed to be unhappy with the decision to lift the tambu and thought the sea ranch should have remained closed to fishing. The reasons varied, but the most common invoked the future of sandfish stocks in their fishing grounds (Table 7.3). Community members mostly thought the ranch was beneficial to them, often in a general sense, e.g., *em i halivim mipela* (it helped us) but also more specifically as a sandfish 'supply', *em i saplaim pislama*, referring to the spillover effect (large sandfish migrating out of the ranch) and to increased juvenile recruitment to areas outside the ranch as a result of spawning within the ranch (Foale and Manele 2004, Purcell 2010a). One respondent suggested that the ranch attracted wild sandfish from the outside, a case of 'reverse' spillover. Others cited ecological benefits, including attracting fish into the ranch area, and maintaining water depth by sandfish burying. Some respondents regretted that the hard work of the researchers was wasted. Most respondents (85%) thought that the ranch contained more and larger sandfish than outside areas. However, as noted above, sandfish were also believed to be abundant outside the ranch prior to the season opening and only half of those who fished in the ranch reported good sandfish catches.

Table 7.3 Reasons and number of responses for dissatisfaction with removal of the ranch tambu. Some respondents cited more than one reason.

Response	No
Sea cucumbers for the future	8
Sea cucumber 'supply' (juvenile recruitment)	6
Sea cucumber 'supply' (adult spillover)	5
Helping the community	3
Important to respect the tambu	3
Hard work of researchers	2
Ecological benefits	2
Convenient for nearby harvest	1
Because it is 'our' ranch	1
Development	1
Not specified	1

Of those who provided a time estimate for when the sea ranch tambu was broken, most said either mid or late in the season, i.e., late August. This time corresponds with reports from the community liaison officer and researchers. Sandfish within the ranch were probably undisturbed for the first two weeks of the season at least, while intense fishing occurred in non-tambu areas. This also suggests that the initial poaching occurred after large sandfish had been removed from the community fishing grounds, at which point the presence of large individuals inside the ranch provided strong temptation.

After the trial sea ranch was declared ‘open’, 50% of those interviewed did not fish there (either out of respect for the tambu or fear of punishment), 40% admitted to fishing in the ranch, and 10% were non-fishers. On the advice of the community warden and after consultation with the MRC chairman, researchers removed all project research equipment from the ranch site, including grow-out cages, a sea pen and the noticeboard. This occurred after the official season closure and disheartened those in the community who had continued to respect the trial sea ranch, even as it was fished by others. The unequivocal message that the mariculture research was officially terminated resulted in increased sea cucumber harvesting in the ranch, even though the 2018 season was closed.

All respondents mentioned the issue of outsider fishing, as described in Chapter 2. The majority reported poachers from neighbouring communities (80%), while a smaller number reported ‘insider-outsiders’. Many community members were unhappy with the presence of up to 30 insider-outsiders who resided in the village for the 2018 season. Despite this discontent, respondents said they had limited success in preventing poachers from stealing sea cucumbers at night and were powerless to prevent insider-outsiders from taking up temporary residence and fishing. The MRC tried to address the issue but there was strong reluctance to confront this group, or the community members they stayed with. However, it was noted that insider-outsiders donated to the church as a token of appreciation, also that they respected the ranch tambu and departed when the fishing season officially closed.

7.3.3 Community expectations of development

Respondents’ most common definition of development was to have enough money to meet needs (n = 11), i.e., ‘*gutpela sindaun*’, defined as a comfortable life, provision of food and other items (often store-bought) to make life easier and reduce stress. Next was the concept of things happening and change for the better (n = 10) expressed as ‘*senis long ples*’ and ‘*wok kamap*’. Less common responses were fairness, educating people and improving healthcare

($n = 1$ each). Tangible examples of development were roofing iron, water tanks and permanent houses, all of which contribute to a more secure water supply and reduce the work associated with traditional housing (Foale 2001, Chapter 2). Household items (e.g., pots, mattresses, knives, etc.), boat, school expenses, store food, savings, road and toilets were also mentioned.

Some anecdotal information on spending patterns was obtained, but this was not a survey question. Purchase of bicycles with 2018 BDM earnings, and permanent house construction was also noted by the survey team (Fig. 7.4). One middle-aged woman noted, "Older people bought iron roofing, chainsaw, and so on. Young people spent money on beer, tobacco, betelnut. Young women spent money on nice clothes and grooming, and some house stuff too. Women spent better than men". There were increased opportunities for spending in 2018 compared to 2017; several canteens established in the main village and boats from Kavieng brought store goods to the beachfront (e.g., rice, fresh-frozen chicken and sausage, soft drinks and beer). Store-bought food is very desirable when funds permit; purchase of comparatively expensive fresh sausage and chicken was reported in the 2018 season (compared with increased tinned fish consumption recorded in 2017, Chapter 2). The study community also reported a substantial increase in drunkenness in the 2018 season (as did many other local communities). The store-goods boats and some canteens ceased operation when the flow of BDM money ceased, as noted in many communities with sudden influxes of cash from sea cucumber (e.g., Foale 2005, Christensen 2011, Kinch 2020).

Figure 7.4 A permanent house (with water tank) being constructed with BDM earnings.

7.3.4 Divisions in the community

Numerous divisions were observed or reported in the community. Serious rifts existed between the elected LLG leaders and traditional leaders, and also between LLG and the MRC. Despite some LLG members also holding positions on the MRC, officers from the former were implicated in lifting the ranch tambu (*section 7.3.2*) and also in allowing various illegal or unsustainable fishing activities. Clan, family and generational disputes were reported. At one point, an argument over disrespect of the sea ranch tambu escalated to a physical fight between two groups of women. The mariculture project itself appears to have revealed pre-existing fracture-lines within the community (cf Filer 1990), including jealousy over perceived economic and/or political benefit from project activities. Respondents were also asked if and how the various parties involved in the fishery and research may have prevented failure of the ranch (Table 7.4).

Table 7.4 Range and number of responses as to how the community, the researchers or government fisheries officers might have prevented failure of the trial sea ranch.

Response	Community	Researchers	Fisheries
Obeyed the tambu in the trial sea ranch	7	-	-
Improved community leadership	3	-	-
Provided security for the trial sea ranch	2	3	-
Improved community unity	1	-	-
Empowered younger men	1	-	-
Improved clarity on trial sea ranch responsibility	-	4	-
Left the community noticeboard in place	-	2	-
Visited the community more frequently	-	1	3
Marked the trial sea ranch boundary more clearly	-	1	-
Researchers should stay with other clan groups	-	1	-
Selected a different trial sea ranch site	-	1	-
Enforced fishery regulations (size limits, season opening and closing times)	-	-	5
Exerted more control on traders	-	-	4
Nothing more could have been done	1	4	3
No response	6	8	12

7.4 Discussion

This study presents the outcomes of a community-based sea ranch trial – a 'put, grow and take' activity with potential as a sustainable livelihood for communities in New Ireland Province, PNG. Unfortunately, the trial sandfish ranch failed due to widespread poaching of sandfish during the 2018 sea cucumber fishing season, despite community agreement to protect the area. The events described had two major consequences for the development of this livelihood activity. First, the opportunity to generate technical data necessary for proof of concept of this activity was lost. Second, local management systems failed to protect the *trial* sea ranch and may be assumed to be inadequate in managing an *actual* ranch were this livelihood activity to develop. Technical issues that constrain hatchery production, survival and growth of cultured juvenile sandfish in ocean mariculture, or economic viability of sea cucumber mariculture, may be considered manageable based on research presented in this study (see Chapters 3, 4, 5 and 6), and elsewhere (see Purcell et al. 2012b, Juinio-Meñez et al. 2013, Rougier et al. 2013). The principal impediments to the development of sea cucumber mariculture in New Ireland Province, PNG, are, therefore, associated with a divided community and fragmented, conflict-ridden local leadership, resulting in a weak communal management system. Overlaying these social and cultural factors, exacerbating external forces were witnessed in the 2018 season including record BDM prices, strong pressure from traders, a short open season and absence of control by government regulators.

7.4.1 Effectiveness of community-based fisheries management

Community-based fisheries management (CBFM), whereby communities manage their marine resources according to their local customary knowledge and technology, is accepted as a valuable management tool that should be better integrated with a broader governance approach that includes formal fisheries management (Asafu-Adjaye 2000, Jentoft 2000, Cinner et al. 2012, Léopold et al. 2013, Baker-Médard and Ohl 2019, Barclay et al. 2019). In the Indo-Pacific region, CBFM operates within complex and dynamic local contexts in fisheries, conservation and mariculture (Ruddle 1993, Foale et al. 2011, Glaser et al. 2015, Beyerl et al. 2016, Aswani et al. 2017). The remoteness, geographical extent, number of landing points and number of sea cucumber fishers in PNG preclude the NFA from exerting effective control of the fishery at community level. A transition to greater provincial regulation and local management for the fishery have been advocated (Barclay et al. 2016, NFA 2018), although there was little evidence of this in the 2018 season. Valuable support for CBFM initiatives can also result from co-management regimes with external agencies (e.g., local and international NGOs, external governments, researchers) (Léopold et al. 2013, Cohen and Steenbergen 2015).

However, CBFM also regularly fails to live up to promises, and customary management does not always produce sustainable outcomes (Polunin 1984, Filer 1997, Foale et al. 2011, Barclay and Kinch 2013, Sulu et al. 2015, Hamilton et al. 2019). Where fisheries are important for customary exchange (Carrier 1987) or have increased commodity value (Otto 1998, Foale et al. 2011), greater proprietary behaviour (tenure and taboo systems) has been commonly observed. However, the widespread weakening of traditional authority and increased possessive individualism (Macpherson 1962), combined with elevated commodity prices render customary management institutions increasingly ineffective (Ruddle 1993, Foale et al. 2011, Kinch 2020). Record prices and intense fishing (including the taking of undersized sea cucumber) created a highly lucrative and egalitarian open season in 2018, although arguably at the expense of the future productivity of the sea cucumber fishery.

A community sandfish sea ranch is a minimal input aquaculture intervention but CBFM is required to maximise returns and ensure equitable distribution of benefits (Purcell et al. 2018b, Chapter 2). Increased concern over outsider fishing was reported in 2018 compared to 2017 (Chapter 2), due to the 'honeypot' effect (Owen and Kemp 2017) which attracted non-resident fishers seeking easy money from sea cucumber fishing. This is a source of conflict in many sea cucumber fishing communities (Barclay et al. 2016, Chapter 2). Poaching is also a common problem with sandfish mariculture (Robinson and Pascal 2012, Glaser et al. 2015). In this study, a minor poaching event in the ranch escalated to free-for-all harvesting due to the community's inability to transcend what are, by now, well-documented and analysed tendencies to political fragmentation and disunity (Filer 1990, Schoeffel 1997, Foale 2001, Connell 2018). The community lacked capacity to prevent (by sanction or confrontation) its own members or outsiders fishing in the ranch and community fishing grounds, despite strong disapproval of both practices. Our observations confirm reports of stated CBFM rules that are routinely unheeded or surreptitiously dropped from management plans (Léopold et al. 2013, Cohen and Steenbergen 2015), and non-compliance with two of Ostrom's (1990) 'Design Principles' (i.e., graduated sanctions and conflict resolution mechanisms). These results, along with most anthropological work in similar contexts (e.g., Filer 1990, Wagner 2007, Allen 2013), also stand in stark contrast to claims of the efficacy of these institutions in coastal communities elsewhere in PNG (Cinner et al. 2012, Purdy et al. 2017).

7.4.2 Project outcomes

Despite the sea ranch research not proceeding to conclusion and not generating data on the viability of this activity in PNG, is there a basis to claim some success? Can anecdotal evidence of increased sandfish abundance and size in the ranch, positive perceptions of the ranch and enhanced CBFM capacity be interpreted as positive outcomes of this project?

There was agreement that, prior to the 2018 open season, there were many large sandfish in the sea ranch but it is not clear whether this differed from non-ranch areas. However, with no sea cucumber harvested at the sea ranch site since 2009, and supplementation with 5,000 cultured individuals released there[22], it would be expected to be more productive. Reported satisfaction with sandfish catches from the trial sea ranch was variable, and may have been dependent on how quickly individual fishers accessed the area after the tambu was lifted. Sampling of the central juvenile release zone of the trial ranch, six months after the season closure, recovered some cultured sandfish (unpublished data), however, this only proves that not all of the released juveniles died or were lost. Survival and growth of cultured sandfish cannot, unfortunately, be gauged from these disparate elements.

There was strong positive perception of the value of the ranch, it was widely believed to represent an important future supply of sandfish (via spillover and/or recruitment). This notion led many fishers to place disproportionate value on the sea ranch (5 ha) compared to the extensive wild fishery grounds (> 500 ha), when the latter had greater potential to supply sandfish if managed sustainably. Education on sustainable management of a future sandfish sea ranch and a broader message about sustainable management of wild stocks focused on promoting the harvest of large sandfish in order to increase financial returns and maximise spawning potential. Nonetheless, many fishers were unconcerned about the impacts of overfishing and expressed seemingly contradictory ideas regarding the harvest of undersized sandfish. Fishers claimed that good harvests in the 2018 season resulted from observance of minimum size limits in the 2017 season. They admitted that it was wrong to harvest undersized sandfish in the 2018 season, but that the traders were to blame by 'forcing' them (with money!) to ignore size limits. Furthermore, there was no indication that this behaviour might change in the future; compare this to the 2017 season when undersized BDM were rejected by traders,

[22] How many of the 5,000 sandfish remained in the ranch is not known, but research in 2016 indicated that >70% of stocked cultured juvenile sandfish survived in the ranch location (unpublished data).

leading to a change in fishing communities' attitudes, as reported in Chapter 2. It was concluded that knowledge dissemination was ineffective, or at least insufficient, to change unsustainable harvest practices, to correct ecological misconceptions or prevent breakdown of the ranch tambu.

7.4.3 Lessons learned

Notwithstanding our conclusion that protection of the trial sea ranch had a low chance of success within the context of the 2018 season, there were some lessons learned that should be considered in future attempts to undertake similar research:

1. Unexpected changes can dramatically alter governance dynamics. The community's long and mostly successful engagement with conservation efforts (on the coral reef tambu) and successful CBFM of the sea ranch in 2017 suggested that they had capacity to enforce the sea ranch tambu but the 2018 season events diminished this capacity (see *section 7.3.1*). In hindsight, researchers' expectations of ongoing cooperation from the entire community and stable governance might be regarded as naïve. Researchers should remain vigilant and maintain an awareness of local politics and existing (as well as potential) divisions in the community in order to anticipate and potentially avert problems.

2. Frequent communication and site visits are essential. The breakdown of the local telecommunications tower, midway through the project, and less frequent visits (due to high fuel costs and researchers' time availability) prevented timely action when poaching of the sea ranch first occurred.

3. The mismatch between what rural coastal peoples and external agencies (scholars, aid donors, NGOs, etc.), respectively, regard as development was highlighted in this study. The latter look primarily to education, health, community wellbeing or social justice, but our study found that the grassroots definition of 'development' was very simply (and quite reasonably) – the ability to purchase goods to make life more comfortable (also see Barclay et al. 2016, Chapter 2). However, there is no denying the prevalent use of BDM earnings for items that do not produce long-term community benefits and contribute to social problems (e.g., alcohol) (Foale 2005, Christensen 2011, Barclay et al. 2016).

4. There is some tension between avoiding a top-down approach and allowing a group to fail. Researchers played a strong role in technical and education aspects of the trial sea ranch but CBFM was a community responsibility to foster community ownership. Furthermore, shirking of project duties and incidences of interpersonal conflict arose when key community management roles were not well defined and supervised. A stronger and more defined co-management arrangement might better empower communities.

5. Security of high-value marine resources is a wider issue and would be necessary if community-based sandfish mariculture becomes a reality (Juinio-Meñez et al. 2012a, Robinson and Pascal 2012, Glaser et al. 2015). Notably, fishers observed fishery regulations when they believed they were being monitored by a data collector in the 2017 season. Outside enforcement is not the most desirable (or affordable) solution to security for a community sea ranch but co-management may be helpful.

6. There may be scope for improving the science communication regarding the functions (and benefits) of the sea ranch model. Providing training in areas such as aquaculture technology and community empowerment may be beneficial (Baticados et al. 2014, Sulu et al. 2015).

7.4.4 A different approach?

The popularity of sandfish mariculture is growing, with Madagascar, Vietnam, The Philippines, New Caledonia, Australia, China, Saudi Arabia, Maldives and other countries involved in sea ranching, stock enhancement, or farming (ocean or pond) of this species (Purcell et al. 2012b, Robinson 2013, Purcell and Wu 2017). Specific approaches vary from place to place but commonalities in the successful mariculture ventures include one or more of the following elements: (a) depleted wild sea cucumber stocks; (b) local communities with very limited alternative livelihood options; (c) exclusive use rights; and (d) commercial company control over the mariculture activity. There are two key points of difference in the PNG study community. First, they have abundant wild sea cucumber stocks that have sustained intense, lucrative fishing seasons in 2017 and 2018. Further, the customary marine tenure (CMT) arrangement allows any community member to fish in the communal fishing grounds (Otto 1998, Chapter 1).

Sea ranching (i.e., no enclosures) of sandfish was judged to be the most efficacious and equitable mariculture model in terms of cost, potential profitability, and compatibility with prevailing CMT and environmental conditions in the PNG research location (Eriksson et al. 2019, Table 7.5). However, as highlighted by the research outcomes, it was also a risky option in the complex and dynamic socio-economic setting of a PNG village. Is the answer, therefore, to adopt a pen farming model such as that practiced in Madagascar? General features of this approach include: grow-out of sandfish in family- or clan-operated sea pens; purchase of large sandfish juveniles from a commercial hatchery; security infrastructure; buy-back of commercial-size sandfish by the hatchery; and a community-managed lease system (Pascal and Robinson 2011, Klückow et al. 2017). Increasing levels of possessive individualism in PNG have heightened the appeal of privately-owned mariculture pens. However, some aspects of the farm model may be problematic to implement in the CMT context of the Tigak and Tsoi islands (Table 7.5), and potential negative consequences of shifting away from communal-access must be carefully appraised (Luttrell 2006, Steenbergen et al. 2017b, Eriksson et al. 2019). In addition, specific environmental conditions were found to be necessary in order for successful sea pen installation and retention of sandfish in the study area (refer to Table 7.5, Environmental conditions, based on experience gained in experiments described in Chapter 3).

7.5 Conclusions

Failure of the trial community-based sea ranch was unsurprising in the context of the 2018 sea cucumber open fishing season. Sustainable management of a high-value commodity like sea cucumber in a low-income village situation presents great challenges for all stakeholders (Baker-Médard and Ohl 2019, Barclay et al. 2019). This study highlights the importance of understanding the human dimension, including but not limited to, existing livelihoods and activities, formal fisheries governance, CBFM capacity, income and purchasing patterns, fishing practices, community relationship and attitudes, in the development phase of a potential new mariculture livelihood (Lorenzen et al. 2010, Krause et al. 2015, Sulu et al. 2015, Chapter 2). It was concluded that technical research into community sea cucumber mariculture in New Ireland Province will be problematic as long as there is no effective local control of the annual sea cucumber fishing season. The study identified important social constraints, but a crucial unfulfilled objective was to investigate if, and how, benefits of a communal sea ranch would be distributed within the community and if it could meet requirements for equitable mariculture, as characterised by Eriksson et al. (2019).

Table 7.5 Comparison of private farm and community sea ranch models for sea cucumber mariculture in New Ireland Province.

Factor	Private farm	Community sea ranch
Technical factors		
Per-capita cost	High	Low
Initial / ongoing time / labour requirements	High (with risk of stock loss from lax pen maintenance)	Low
Social factors		
Requisite CBFM capacity	Mostly unnecessary (individual pen ownership)	Highly functional (community ranch ownership)
Requisite community leadership capacity	Moderately functional (e.g., to manage conflict)	Highly functional (e.g., distribution of benefits)
External support/co-management	High (equipment cost and management assistance)	Medium to high (management assistance)
Benefit to women, elderly	Potentially high (improved access)	Potentially high (improved access)
Ownership and distribution of benefits	1. Clear individual ownership 2. Hard work rewards individual farmer/s 3. Potential for intra-family disputes 4. Risk of stock loss from lax pen maintenance	1. Potential for disputes over distribution of benefits 2. Opportunity for free-rider behaviour and harvest by outsiders 3. Risk of stock migration beyond ranch borders
Risk of stock theft	High (security needed)	High (security needed)
Overlapping technical and social factors		
Environmental conditions	1. Suitable sandfish grow-out habitat necessary 2. Owner access necessary 3. Suitable for sea pen stability (shallow depth, low energy / currents / tidal flow, suitable sediment profile)	1. Suitable sandfish grow-out habitat necessary 2. Community access necessary
Infrastructure impacts and potential for increased community conflict/discord	1. Inconvenience to motor boat traffic and accident risk (small tidal range, pen damage, compensation claims) 2. Loss of fishing grounds (i.e., impacting livelihoods and food security) 3. Sea tenure disputes	None

It is of concern that, regardless of the technical outcomes, community capacity to manage a sea ranch was inadequate. Other studies and our observations from many communities in PNG suggest that the internal factors and external pressures acting on the study community were not unique (Barclay et al. 2016, Barclay et al. 2019). It is also clear that successful sandfish mariculture livelihoods, as proposed in Chapter 2, would require reduced collective fishing effort, increased local leadership and cohesion, and/or stronger support from government and/or external agencies. Further depletion of the sea cucumber resource may eventually galvanise communities into developing more effective CBFM, but this is not guaranteed. An accurate understanding of the conditions for effective collective management at this scale will always require detailed knowledge of culture, history and politics, in the context of ongoing social and economic change.

Chapter 8
General discussion

8.1 Introduction

This study addressed factors influencing the potential for development of community-based sea cucumber mariculture in New Ireland Province, PNG. The initial objective of this study was to assess the potential of sea ranching of the high-value, tropical sea cucumber, sandfish (*Holothuria scabra*) as a livelihood activity for coastal communities in the Tigak and Tsoi Islands. However, a seven-year moratorium on the PNG sea cucumber fishery was lifted during the study and provided unexpected opportunities to assess the reopened fishery and the potential for sandfish mariculture alongside it. The focus of this study shifted, as a result, to include assessment of social aspects of the sea cucumber fishery and the technical and social factors that may influence uptake of sandfish mariculture as a potential livelihood activity. The major outputs of this study and their potential applications are summarised in Table 8.1 and, while acknowledging potential overlap, described below within four broad themes related to: (1) the PNG wild sea cucumber fishery; (2) new information relating to mariculture of sandfish; (3) consideration of the culture environment for sandfish mariculture; and (4) social aspects relating to both the wild sea cucumber fishery and the adoption of sandfish sea ranching.

8.2 The wild sea cucumber fishery considerations

A review of patterns of wild sea cucumber exploitation in the Tigak and Tsoi Islands study area was a logical starting point to explore whether sandfish mariculture may be an appropriate livelihood activity and to identify issues that might influence its chances of successful uptake. The socio-economic aspects of the wild sea cucumber fishery were highly relevant to mariculture development because the communities most likely to adopt this activity are fishing communities and because the sandfish sea ranching model relies on established fishery management strategies to be sustainable. Re-opening of the sea cucumber fishery during the study provided an opportunity to investigate these aspects in a contemporary setting in collaborating island communities (Enuk, Limanak and Ungakum) that engaged in the wild sea cucumber fishery and that also had suitable habitat for sandfish mariculture in their traditional fishing grounds.

Table 8.1 Major outputs from this study and their potential applications.

Prior knowledge/practice	Outputs of this study	Application(s) of outputs
Fishery considerations: • Limited knowledge of the past status of sandfish in the New Ireland Province sea cucumber fishery. • No knowledge of the socio-economic effects of reopening the sea cucumber fishery on potential sandfish farming communities.	• Sandfish are a good candidate for community-based mariculture, due to its high value, fishers' familiarity, established markets and historical role in the New Ireland fishery (Chapter 1). • Increased household income, spending and dietary changes resulted from the reopened fishery; and • Sandfish were targeted; poor quality BDM was rejected; community-based management was ineffectual in the reopened fishery (Chapter 2).	• Poor-quality BDM and harvest of undersized sandfish reduce income from sea cucumber fishing and threaten stock sustainability, impacting the wild sea cucumber fishery and future mariculture potential. • Outputs from this study may assist NFA policy development to support sandfish mariculture, e.g., training in sustainable CBFM, BDM processing, community co-management, and improved governance under the BDM Management Plan.
Mariculture considerations: • No knowledge of differences between cultured and wild sandfish regarding: (1) 'fitness' of cultured juveniles due to hatchery rearing or transport stress; and (2) BDM quality. • Need for improved juvenile sandfish release strategies.	• •Cage protection of juvenile sandfish post-release is only warranted when predators are present; and, if so, one week may be inadequate (Chapter 3). • Survival and growth of cultured juveniles was similar to wild. However, cultured juveniles buried less for 30 hours after release, potentially exposing them to increased predation (Chapter 5). • Cultured sandfish BDM does not differ from wild in fresh:dry conversion ratio, length, body wall thickness or collagen content (Chapter 6).	• No need for cage protection of juveniles when predation risk is low, saving time, effort and funds. • Lack of hatchery-induced deficits supports mariculture efforts. • Differences in cultured juveniles' burying behaviour indicate a need for research into better transportation / release methods. • The results increase confidence in market acceptance/value of hatchery-produced, ocean-cultured BDM from New Ireland. • Cropping cycle and survival from PNG sites indicate viability. • Pilot-scale grow-out of cultured juvenile sandfish in potential culture locations is recommended prior to scaling up mariculture activities.
Culture environment: • Limited knowledge of biophysical parameters that influence sandfish performance in ocean mariculture. • Limited knowledge of GIS/remote sensing potential for sea cucumber mariculture.	• Survival and growth varied between four seagrass sites; the best site had more coarse grain, epiload and chlorophyll-a, and less fine grain (Chapter 3). • Remote sensing cannot pre-assess optimal sandfish habitat without field data but has potential within a broader GIS approach (Chapter 4).	• Identification of biophysical features conducive to sandfish survival and growth assist in optimal habitat selection for mariculture and indicate promising areas for further research. • A 3-stage GIS/remote sensing protocol for sandfish culture site selection is proposed. Outputs from this and other chapters recommend inclusion of novel socio-economic factors (e.g., traditional knowledge and CBFM capacity).
Social considerations: • No knowledge of social and cultural factors affecting adoption of sandfish sea ranching as a livelihood activity by Tigak/Tsoi Islands fishing communities.	• A trial sandfish sea ranch failed due to internal factors (weak leadership, community disunity) and external pressures (fishery, study factors). • Development of this potential livelihood is hindered by the high value of sandfish, and ineffective governance at all levels (Chapter 7).	• More research into the human aspects of community-based sandfish mariculture, capacity building and stronger co-management is recommended because mariculture adoption may increase as wild sandfish stocks become depleted.

8.2.1 History of the sea cucumber fishery in New Ireland Province

Chapter 1 established that sandfish drove early development of the sea cucumber fishery and BDM trade in the Tigak and Tsoi Islands in the late 1980s and early 1990s, before being overfished. By the time the moratorium was imposed on the fishery and BDM trade in 2009, sandfish had dwindled to less than 5% of provincial sea cucumber production, but they remained the most valuable and preferred species for fishers. There appeared to be an opportunity for a sandfish sea ranching within the existing fishery structure, noting that this activity bears similarities to the existing wild fishery (i.e., hatchery-reared juvenile sandfish would be stocked in open, unfenced sea ranches and protected under community stewardship until they reached commercial size). Fishers were familiar with harvesting and processing sandfish and markets were well established. Moreover, husbandry inputs should be minimal in suitable habitat with few predators (this aspect is explored further in mariculture and culture environment considerations below). It was predicted that regular stocking of juveniles from NFA or private hatcheries could provide a predictable harvest and sustain a modest but regular income stream, assuming large individuals were harvested and processed well. However, Chapter 1 also revealed that many unsustainable sandfish harvest practices occurred in the late 1980s, continuing up to the moratorium in 2009, and that government fishery regulations were mostly ignored. For sandfish, the harvest of undersized specimens not only threatened future supply by removing animals before they can spawn, but is economically unsound because larger sandfish are disproportionately more valuable than smaller specimens (Purcell et al. 2018b). It was found that fishers in close proximity to town often produced poor quality and 'wet' BDM of lower value, opting for immediate but smaller income, i.e., more sea cucumbers were harvested to generate the same income. Through the necessity imposed by greater distance from traders and the risk of wet product spoiling, fishers based further from town were more likely to produce better quality BDM that fetched higher prices.

8.2.2 The re-opened (post-moratorium) sea cucumber fishery

The results of Chapter 2 confirmed that sandfish remained the most targeted and high-value species in the first post-moratorium wild sea cucumber open season in 2017. Sea cucumber harvest and processing/selling of BDM were intense in the three study communities. Sandfish was targeted early in the season and became less common in landings by the time the fishery closed (Hair et al. 2018). The issues of concern inferred in Chapter 1, such as unsustainable harvesting practices, disregard for fishery regulations and substandard BDM processing, were observed. During the 2017 fishing season, traders rejected large quantities of undersized, damaged and incompletely dried BDM, as directed by the NFA (NFA 2016). This led to waste of unmarketable BDM and discontent among fishers who received nil or lower income for their efforts. There did appear, however, to be an attitudinal shift in fishers who expressed willingness to change their practices in future fishing seasons (i.e., to harvest larger sea cucumber and produce high-quality BDM). Limanak community had problems with poachers harvesting sea cucumbers in their fishing grounds and they were unable to enforce a fishing *tambu* (ban) or protect a trial sea ranch from poaching. The other two communities had fewer issues with outsider fishing, with Ungakum successfully enforced a fishing tambu on their trial sea ranch in the 2017 fishing season.

8.2.3 The 2018 sea cucumber fishing season

The 2018 sea cucumber season was set apart from the 2017 season by remarkably strong demand for BDM; traders travelled to the villages to buy direct from fishers, similar to the frenzied buying reported in Limanak during the lead-up to the moratorium in 2009. Sandfish prices were at an unprecedented high, accompanied by a market for undersized sea cucumber, leading to intense fishing effort. The emerging attitudinal shift toward better harvest and processing practices reported in 2017 promptly dissolved as many traders accepted (and openly encouraged) any size or quality BDM that was offered for sale. New Ireland Province recorded its highest BDM production since the start of the commercial sea cucumber fishery in 1988, and the total allowable catch (TAC) of BDM was exceeded by a record amount (Fig. 8.1). The proportion and amount of sandfish BDM produced in New Ireland Province dropped (from 33% to 12%, and from 26 t to 18.6 t, respectively) in just two post-moratorium fishing seasons (Fig. 8.1).

8.2.4 NFA policy development

Chapters 2 and 7 confirmed that communities had limited capacity for effective CBFM of the sea cucumber fishery, or commitment to extracting maximum economic benefit through sale of large, well-processed BDM. This has serious repercussions for sea cucumber mariculture interventions because a viable and equitable sandfish sea ranching livelihood activity relies on maximising economic returns from cultured sandfish, strong CBFM capacity and a system for distribution of benefits to all community members (e.g., see Eriksson et al. 2019). The NFA's revised BDM Plans (NFA 2016, 2018) were well designed but not enforced effectively in the post-moratorium fishery; overshooting of the TACs (Fig. 8.1), licensing law breaches, and fishing of undersized sea cucumber occurred in both seasons. Lax enforcement by government fisheries departments also contributed to poor outcomes of research into community-based sandfish sea ranching (Chapter 7). There was no evidence of the NFA's stated goal to decentralise management of the sea cucumber fishery to lower levels (provincial, LLGs and community) in the study communities (see also Kinch 2020). The events of two post-moratorium open seasons highlighted that fishing communities did not have the capacity to achieve strong CBFM without assistance, particularly under intense pressure from the extremely lucrative sea cucumber fishery.

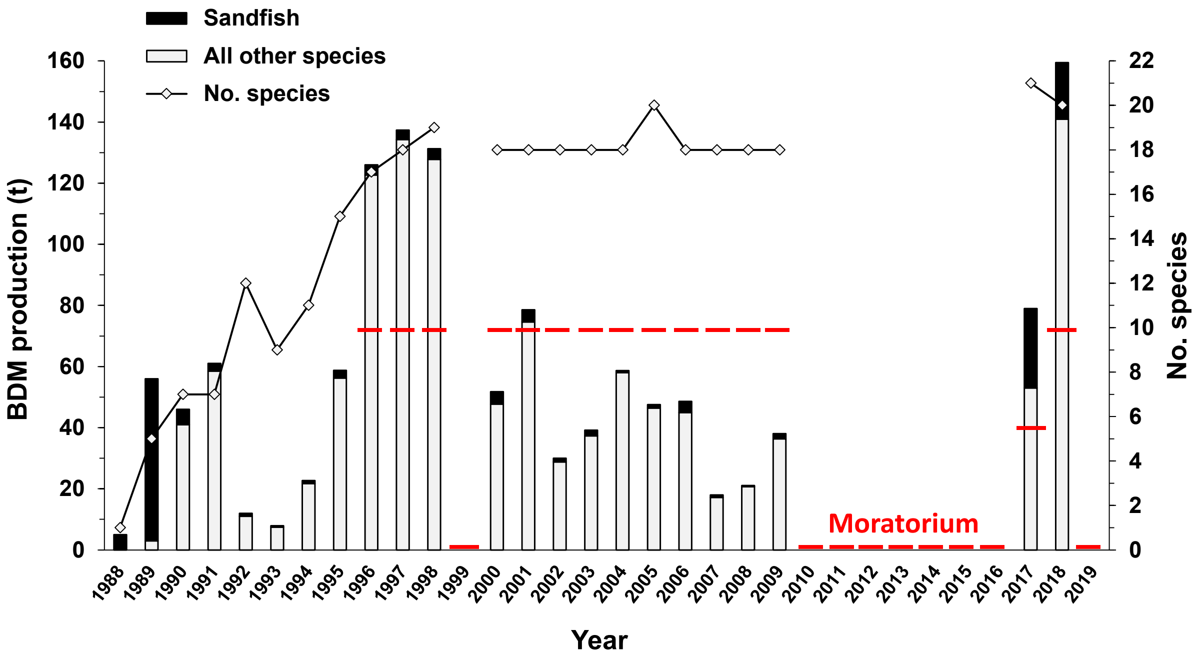


Figure 8.1 New Ireland Province BDM production quantity (t) and species diversity from 1988 to 2018 (black bar = sandfish, grey bar = all other sea cucumber species, line = no. species). Red lines indicate quota (t) since the introduction of TACs in 1996. The national sea cucumber fishery did not open in 2019. Sources: Lokani 1996a (1988-1992); NFA database (1993-2009, 2017-2018). Figure revised from Fig. 1.6 to include TACs and 2017-2018 BDM production.

The revised post-moratorium BDM Plans (NFA 2016, 2018) added regulations for sea cucumber Aquaculture, where ranching was defined as 'stocking reefs with sea cucumber hatched and raised in a hatchery and released to the natural environment to enable natural feeding and growth to take place'. The 2018 BDM Plan stipulated that mariculture proponents must apply for an aquaculture licence, with various conditions that may be considered (Table

8.2). Outputs from this study can provide useful input to most of these conditions with respect to community-based sandfish sea ranching (Table 8.2).

Table 8.2 NFA 2018 BDM Plan aquaculture conditions and relevant study outputs.

BDM Plan condition	Study outputs
1. Minimum standards for hatchery operations	Highlighted the importance of: high-quality cultured juvenile sandfish (i.e., healthy, appropriate genetic stock, sand-conditioned prior to distribution) (Chapter 5)
2. Access to brood stock	A well-managed sea ranch can be a source of broodstock of same genetic stock as that of the community sandfish (Chapter 7)
3. Movement of juveniles	Improved transport and release strategies described (Chapters 3, 5) (more research is needed).
4. Acquiring sea area for sea ranching	Improved selection of the most suitable sandfish mariculture habitat, and management of community expectations regarding survival and growth parameters (Chapters 3, 4)
5. Boundary determination of sea ranching areas	Improved selection of the most suitable sandfish mariculture habitat (Chapters 3, 4) (large-scale research will be useful).
6. Ownership of sea cucumber stocks inside sea ranching areas	Identified need for capacity building in CBFM, increased co-management by government fisheries departments or NGOs, and better fisheries regulations enforcement, in order to define and enforce ownership (Chapter 7).
7. Dealing with conflicts arising from sea ranching	Identified actual sources of conflict and mitigation measures (lessons learned); identified additional potential sources of conflict (Chapters 2, 7)
8. Harvesting periods for aquacultured sea cucumbers	Generated data on growth rates and time to harvest after stocking to improve success rate of sea ranching and manage community expectations (Chapter 3) (more research is needed, e.g., large-scale sea ranching or farming operations).
9. Culture of F2 generation for export	Not applicable
10. Impacts of aquacultured sea cucumbers on annual Provincial TACs	Generated data on survival and growth of cultured sandfish, in a range of habitats, and BDM conversion ratio, to improve estimates of sea ranch productivity to adjust TACs (Chapters 3, 6) (more research is needed, e.g., large-scale sea ranching or farming operations).

8.3 Mariculture considerations

8.3.1 Improved release strategies for cultured juvenile sandfish

Knowledge of the level of husbandry required to minimise mortality and loss of cultured juvenile sandfish is critical to viability of sea ranching. Chapter 3 found that cage protection of juvenile sandfish for up to 7-days post-release did not improve survival or early growth in four different seagrass habitats. However, the loss of all released juveniles from one site was a clear warning about attention to site suitability, in terms of predation risk and biophysical features. Notwithstanding, this outcome will save time, effort and expense associated with providing unnecessary protection in low predation-risk areas. Chapter 5 compared, for the first time, growth and behaviour of cultured juvenile sandfish to that of wild conspecifics following release into the wild. Despite the unavoidable handling and transport of wild collected juveniles while setting up experiments, two field experiments yielded valuable insights into performance of cultured juvenile sandfish in ocean mariculture. First, survival and growth of cultured sandfish did not differ from that of wild conspecifics reared in sea pens after a 3-month grow-out period. A prior long-term growth study of cultured sandfish at the same site (Chapter 3) showed that mortality rates stabilised after two months and that growth rates remained positive until they attained commercial size. A second experiment on post-release burying responses found that, despite high survival for both cultured and wild-collected sandfish, cultured juveniles were slower to bury after release, less likely to be buried at most times, and more likely to be buried in seagrass habitat, although burying behaviour converged more after 1.5 days. The behavioural differences were attributed to transportation stress. Given that diurnal burying of small sandfish juveniles is their principal defence against predation, these differences could potentially increase mortality in areas with abundant predators. Interpretation of this result with the Chapter 3 findings that cage protection had no effect on survival of newly-released cultured sandfish over that period revealed apparent contradictions. This discrepancy may have been due to site-specific factors, i.e., seven days of protection may be inadequate in high-predation risk areas, whereas protection is unnecessary in low-predation risk areas, (also see Lavitra et al. 2015, Klückow et al. 2017).

The take home message for sandfish sea ranching (or ocean pen farming) is that precautions will be needed at high-predation sites. Juveniles may need to remain at the hatchery or be protected at the release site until they are larger and less vulnerable to predation. Alternatively, predators will need to be managed. Any mitigation measures or increased husbandry effort will incur additional costs (Raison 2008, Purcell et al. 2012b). Results therefore highlight the need for reduction of stress through adherence to best practice transportation techniques, release into optimal habitat, and pilot studies prior to committing to large-scale releases, as recommended more broadly for aquaculture developments (Southgate and Lucas 2019). Observations of burying behaviour after release, and monitoring of survival and growth of cultured juvenile sandfish (≥ 3 g) for at least two months in small sea pens (some with no cover, and some with a predator-exclusion mesh cover that allows sunlight in), should be conducted in areas where sandfish mariculture is planned.

8.3.2 Comparison of BDM produced from cultured and wild sandfish

Chapter 6 presented results from another unique set of like-sized mature ocean-cultured (hatchery bred) and wild-harvested sandfish that were processed concurrently with the same BDM production method. Perceptions of inferior BDM from cultured sandfish (Agudo 2012, Purcell and Duy 2012) could negatively impact profitability of mariculture due to lower value or longer grow-out duration to attain comparable recovery rates to wild-collected sandfish. The key determinants of BDM quality (i.e., recovery rate from fresh gutted weight, and BDM length ratio, body wall thickness and collagen content) were not significantly different for hatchery-produced, ocean-cultured sandfish BDM, signalling confidence in market acceptance. The study also developed a standardised method to measure BDM that accounted for natural variations in the width of the body wall of sandfish BDM.

8.3.3 Overall mariculture potential

The research indicated that the cropping cycle of sandfish in the study area was similar to that of *A. japonicus*, which attains harvestable size between 18 and 24 months. The best PNG site produced commercial sandfish in less than 12 months after release of 3-g juvenile sandfish. Although sites with unsuitable habitat will not produce commercial sandfish within that time-frame, survival of sandfish at three sea pen sites was greater than 50%, considerably better than the 10–20% benchmark for sea ranching operations (Purcell et al. 2012b). When considering key determinants of sandfish mariculture potential (i.e., survival and growth of cultured juveniles released into the wild, productivity of various habitat types, and quality of cultured sandfish BDM), the potential for ocean mariculture of this species in PNG was positive. With respect to sea pen farming, the mariculture and the culture environment (*section 8.4*) considerations discussed here are equally applicable. Adoption of pen farming would, however, introduce the need for purchase and maintenance of fences. For PNG communities, this would negatively affect profitability of the mariculture activity or require subsidisation. Study results also indicate that the NFA sea cucumber mariculture policy should take into account the potential impacts of installing these structures in traditional marine tenure areas.

8.4 Culture environment considerations

8.4.1 Optimal sandfish mariculture habitat

A culture environment with unacceptably high juvenile mortality or one that is unable to support growth of all sandfish life stages to commercial size, will stymie the development of sea ranching. Chapter 3 reported on grow-out of cultured sandfish in sea pens at four sites within partner community marine tenure areas that conformed to the best information available for 'suitable' sandfish habitat: presence of moderate seagrass cover, recommended sediment grain profile (≤ 2 mm), immersed at lowest tides, nil or minimal freshwater input, low wave energy, presence of varied invertebrate fauna, and conspecifics. Survival and growth rate of sandfish, and carrying capacity (i.e., pen biomass), were outstanding at the Limanak-1 site compared to the other three PNG sites, and also to overseas studies of sandfish grow-out in the ocean. PCA clearly differentiated the Limanak-1 site from the other three sites because it had higher sediment chlorophyll-*a* content, seagrass epiphyte load and coarse sediment fraction, and less fine sediment. Sandfish at another of the sea pen sites, Ungakum, experienced total mortality. More predators were observed at Ungakum, but it was also differentiated by a very high fine sediment fraction that may have affected the capacity of juveniles to bury and resurface. Moderate to high juvenile survival and more modest growth performance were recorded from two other sea pen sites. Reported higher burial rates of cultured juvenile sandfish in seagrass habitat (Chapter 5 and *section 8.3.1*) also suggested that this was better habitat for mariculture releases.

Due to experimental design issues related to working in a village setting, sandfish performance cannot be definitively attributed to the measured habitat features. Nonetheless, the Chapter 3 results present one of the longest size-at-age datasets available for cultured sandfish in sea pens where biophysical variables were monitored. Chapter 5 found that transportation-stressed cultured sandfish juveniles spent more time buried in habitat with sparse seagrass, but was unable to identify the biophysical driver behind this finding, acknowledging that there may be some combination of features associated with seagrass meadows that promote burial. The results contribute to knowledge of cultured sandfish habitat requirements and indicate worthwhile areas for further sea ranching site selection research, discussed below in future research opportunities. The results of Chapter 3 also provide a cautionary lesson against assuming that the biophysical parameters controlling sandfish survival and growth can be neatly or discretely defined, and lend further support for carrying out pilot studies before committing to full-scale mariculture activities.

8.4.2 Assessment of GIS and remote sensing techniques

GIS applications for planning and site selection for sea cucumber mariculture are uncommon and the capacity of remote sensing to identify optimal habitat for sandfish had not been previously reported. Chapter 4 provided a preliminary assessment of the capacity of spatial planning tools to pre-assess suitable sandfish mariculture sites. Traditional ground scouting is expensive and time consuming, especially in the Pacific Islands region where ocean exceeds land mass by orders of magnitude. The major findings of Chapter 4 were that remote sensing techniques, such as supervised classification and NDVI, can represent marine habitat classes reasonably well. At one site, they showed promise in differentiating juvenile and adult sandfish habitat. Unfortunately, remote sensing cannot be used as a standalone pre-assessment tool because of the need for ground-truthing data from each specific site for supervised classification. Nonetheless, remote sensing could be integrated into a broader GIS application to access data quickly and easily, early in project development, to improve sea cucumber mariculture site selection while reducing costs associated with on-site travel and activity.

Chapter 4 outlined a three-stage GIS approach for sandfish mariculture site selection that can be adapted to individual project aims and the available GIS capacity. Stage 1 applies a desk-top spatial multi-criteria evaluation process, integrating environmental and socio-economic factors that may influence sandfish mariculture (e.g., depth, salinity, seagrass cover, population density, and distance to the sandfish hatchery), and fisheries data on sea cucumber abundance and past BDM exports, where available. Basic remote sensing analysis (e.g., green band, NDVI, unsupervised classification) can also be done at Stage 1. Stage 2 involves a site visit to promising locations to obtain site-specific information, consult with potential mariculture proponents and other stakeholders on the Stage 1 output, and to collect field data for more advanced remote sensing analysis. Community input into the site selection process might include local knowledge of fishing history and sandfish distribution, as well as their priority areas for mariculture, tambu areas, disputed fishing zones, and fishing ground boundaries. Stage 3 is reached once the GIS model indicates that a particular location satisfies the technical and socio-economic criteria for successful sandfish mariculture. Stage 3 involves a pilot grow-out trial of cultured juvenile sandfish already discussed (*section 8.3.1*). This final stage is necessary because data presented in Chapters 3 and 7, and in available literature, demonstrate that sites may appear to meet the criteria for suitability but can fail due to known, unknown or unforeseen factors, e.g., unacceptably high predation, community discord, sabotage, disputed fishing grounds, unknown biophysical factors, or unexpected weather events.

8.5 Social considerations

The success of a new livelihood activity depends on it being a good cultural fit as well as being technically and economically feasible (Hambrey et al. 2011, Krause et al. 2015, Steenbergen et al. 2017a, Ateweberhan et al. 2018). Three thesis chapters were concerned with social considerations, primarily with the socio-economic aspects of the wild sea cucumber fishery but there were many parallels with a sandfish sea ranching livelihood activity. Findings of Chapters 1, 2 and 7 supported the basic notion that sandfish sea ranching would be socially and culturally compatible with coastal communities in the Tigak and Tsoi Islands area. The wild fishery provides substantial benefits to participants with high income compared to other livelihood activities, and sandfish are the highest value species. Fishers within the study communities and other maritime provinces in PNG are familiar with sea cucumber harvest and processing, and with selling BDM. Chapters 3 and 5 found that sea ranching of sandfish would require minimal and part-time husbandry inputs, allowing time for other subsistence, income-generating and social activities. Sea ranches situated close to villages in shallow water would provide better access for women, as well as older and younger community members, the groups that are disadvantaged when wild sea cucumber stocks are heavily-fished and are confined to deep and more distant fishing grounds These sea cucumber stocks are only accessible to those with strength and diving skill (often young men), and/or those with motorised dinghies. Mariculture is likely to sustain a more modest, regular and equitably distributed income; however, it is also likely that the high earnings reported in Chapter 2, which resulted from a partially-recovered post-moratorium sea cucumber fishery, may fall if stocks become depleted again as seen prior to the 2009 moratorium (see Fig. 8.1).

There is potential for community conflict arising from sandfish mariculture. It was theorised in Chapter 7 that the CMT arrangements in the Tigak and Tsoi Islands were more suited to a sea ranching model due to all community members holding rights to fish throughout their respective fishing grounds. Attempts to fence off areas for sandfish farms might lead to problems if fishing rights are affected. Further, the marine environment of many sites in the study area (i.e., limited extensive, shallow areas with suitable sandfish habitat, boat traffic, high-energy environment) was not suited to installation of barriers to enclose sandfish (C. Hair unpublished data). There is no one-size-fits-all model of mariculture, however, and the findings of this study do not dismiss the potential of sea ranching or a pen farming model for communities in the study area or elsewhere.

8.5.1 Cross-cutting issues

Cross-cutting issues between fishery and social considerations are deserving of brief mention here. Sustainable fishery and mariculture livelihood activities depend on CBFM. In particular, delaying harvest of sandfish until they reach large size is important for ecological and economic outcomes. Analysis of the early (Chapter 1) and contemporary (Chapters 2 and 7) fishery did not provide evidence of strong CBFM in the study area. Examination of the failed sea ranch and wild fishery management in Chapter 7 revealed a lack of good fishery governance at national, provincial, and local level governments, compounded by a conflict-ridden and disunited community. Poaching is a problematic issue for both wild sea cucumber resources and sandfish mariculture. Harvest of sea cucumbers in tambu areas by poachers, 'insider-outsiders' and community members was reported to varying degrees by all communities. CBFM was revealed to be weak in the community studied in Chapter 7; however, for a high value product like sandfish, even strong CBFM in a cohesive community may be inadequate to control poaching in a sea ranch. There was limited capacity to provide co-management in this study, but stronger support may be necessary in early stages of development of community-based sea cucumber mariculture, particularly for security measures.

8.5.1.1 Optimal processing level for sea cucumber and BDM

Results from Chapter 7 also challenged the popular view that high-quality sandfish BDM in mariculture operations will capture more of the monetary value (Purcell 2014b, Ram et al. 2014, Barclay et al. 2016, Chapter 1). Data on average BDM weight (Chapter 6) and prices offered by traders in 2018 (Chapter 7) indicated that fishers earned more by selling fresh smaller sandfish and partly processed larger sandfish because the higher prices for well-dried BDM do not fully offset the weight loss (Fig. 8.2). This is also a fishery and mariculture consideration, but is discussed under social considerations because it is people who do the processing and, in the context of community-based mariculture, the optimal level of processing is an important socio-economic issue. Selling partly-processed BDM is only possible when traders come to the fisher, fishers that are distant from markets always need to produce non-perishable, well-dried BDM. Nonetheless, it is clear that sandfish farmers will have improved opportunities to maximise returns by negotiating with traders on the best price for size and processing stage.

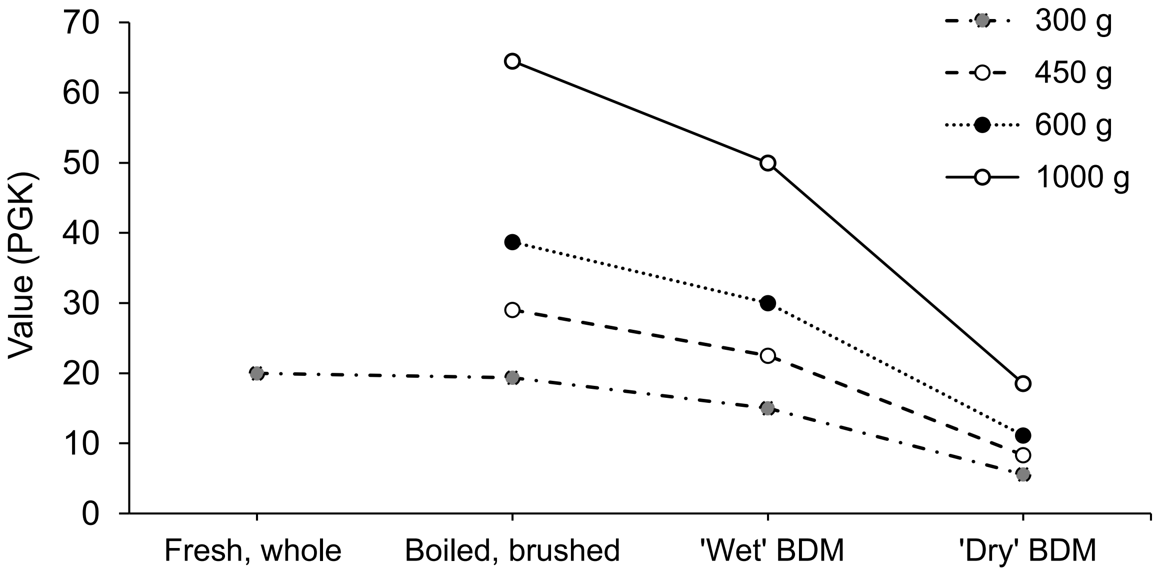


Figure 8.2 Value (PGK) of a range of sandfish sizes (300, 450, 600 and 1,000 g) at four processing stages, based on reported 2018 season prices at Ungakum (see Table 7.2): fresh sandfish (100% of live size, PGK 20/piece, minimum legal size); boiled with calcareous layer brushed off (43%, PGK 150/kg); 'wet' BDM[23] (20%, PGK 250/kg) and fully dried BDM (5.3%, PGK 350/kg).

Another consideration is that less processing means fewer steps between harvest and sale and this may increase the speed and equality of the distribution of benefits. The effort required to process fully-dried BDM brings into play cultural issues of labour value, fair remuneration, unequal labour contribution by individuals and potential conflict. Analogous examples of the socio-political complications that can arise when PNG communities are forced to factor labour into the cost-benefit equation for commodity production can be found in the cocoa (Curry et al. 2015) and forestry industries (Foale et al. 2016). Specific circumstances (e.g., preferred BDM processing stage, local prices, distance to market, CBFM capacity, distribution of benefits, etc.) will dictate what works best for individual communities.

[23] Moisture content of partly dried or 'wet' village BDM is assumed here to be 20% (Barclay et al. 2016; p. 46).

8.6 Future research and recommendations

The scope of the research presented in this thesis is very broad, and it identified a number of potential topics for follow-on and future research, described below under the same general themes as the outputs summary above.

8.6.1 Sea cucumber fishery considerations

If community-based sandfish mariculture becomes established, there is potential for black market trade of wild sandfish because of the inability to distinguish ocean-cultured product from wild-caught by direct observation. This poses a problem for enforcement agencies if wild sandfish (fresh or BDM) are marketed as cultured sandfish, and should be considered in the development of sandfish mariculture in PNG communities. Research into simple and easily observable tagging techniques would help to address this issue but sea cucumbers are very difficult to tag. Strict chain of custody arrangements could be applied to mariculture operations but these would be difficult to administer, and may create problems for remote communities that attempt a sandfish mariculture livelihood activity. A possible solution may be to not try to distinguish cultured and wild sandfish but to control the quantity traded by adjusting the allowable quota. For example, communities involved in sandfish mariculture might be permitted to sell both wild and cultured sandfish but only during the fishing season. They could be provided with an exemption from the TAC that is based on the number of juveniles they have stocked (expected production estimated from predicted survival and growth at their sea ranch site). This or other ways to achieve the same aim, will require further investigation as sea cucumber mariculture develops.

This study concluded that coastal and island communities urgently require improved capacity in CBFM and sustainable management strategies of their sea cucumber resources (wild stocks and cultured sandfish). With regard to BDM processing practices, there is a need for: (1) government regulation of the industry to ensure that traders pay consistent and fair prices for BDM of appropriate quality, thereby providing financial incentives to process large sandfish to high quality; (2) awareness of the need for high-quality BDM processing to whatever level is most profitable (refer to *section 8.5.1.1*); and (3) training in improved and updated BDM processing skills (e.g., for inexperienced fishers, use of salt in processing, etc.). The NFA is in the best position to develop these areas, in partnership with traders, although there may also be a role for NGOs in co-management support and education.

8.6.2 Mariculture considerations

More work is needed to develop improved release protocols for cultured sandfish juveniles; for example, to confirm if the differences observed in post-release behaviour reported in Chapter 5 were due to transportation stress. Survival from field experiments, where juveniles subjected to different levels of stress are released into high and low predation risk areas, will be valuable in development of improved release strategies that are site specific. Monitoring physiological responses of cultured juveniles at different stages of transportation could identify critical stress points. Research could then be directed towards improved transport and release methods in order to minimise stress.

Size of sandfish at release is a priority research area since it is an important predictor of post-release survival and growth (Purcell and Simutoga 2008, Lavitra et al. 2015, Ceccarelli et al. 2018). Predators pose a great threat to sea cucumber juveniles below refuge size (Dance et al. 2003), and a greater range of habitat types may be available to larger juveniles (Dumalan et al. 2019, Chapter 3). Juveniles can be held at the hatchery or protected after release until they reach refuge size but this entails additional effort, expense, and potential for other complications. The size refuge for sandfish has not been established and, as shown in this study, is likely to be site-specific, although cultured juveniles > 50-g can be killed by starved crabs (Lavitra et al. 2009, Eeckhaut et al. 2020). Knowledge of the relative survival and growth profiles of juveniles released at different sizes with and without protection would be valuable to mariculture development, and a cost-benefit analysis of various options would be invaluable to current and prospective stakeholders.

8.6.3 Culture environment considerations

8.6.3.1 Optimal habitat

The biggest current knowledge gap relates to our understanding of the relationship between sandfish and the marine habitat they occupy. Gray (1974) noted that '…*consideration of the relationship of organisms to sediments is complex, since a number of subsidiary parameters are influenced by sediment characters and the subsidiary factors may in fact be the limiting ones*'. Anderson (2008) further emphasised the difficulty of characterising these relationships from field data '…*due to the existence of multiple other potentially important and interacting factors, some of which are inevitably unmeasured*.' The task of describing the relationship of sandfish to their habitat is not straightforward; results presented in this thesis supported some findings from the literature, with equally as many instances of disagreement. A number of biophysical parameters were not considered in this study but have been identified by others as important for sandfish growth. Priority variables are:

1. **Redox potential** – the outstanding Limanak-1sea pen site was the only site with an obvious anoxic layer, and Robinson et al. (2015) reported high growth rates of sandfish in anoxic sediment in recirculation systems; and
2. **Bacteria** – bacteria are important as both a food for sea cucumbers and as intermediaries between organic matter and compounds that provide nutrition for sea cucumbers (Yingst 1982, Plotieau et al. 2014b).

Primary production (microalgae) is another factor worth further research as it was also a feature of the Limanak-1 sea pen substrate, and has been noted in the literature as important in the diet of sandfish (Battaglene et al. 1999, Plotieau et al. 2013, Gorospe et al. 2019); it is notable that sandfish juvenile growth becomes negative when deprived of light (C. Hair unpublished data). In order to disentangle the biophysical drivers of survival and growth, field research using a replicated multifactorial experimental approach (e.g., Ceccarelli et al. 2018) is recommended, in tandem with laboratory experiments where variables of particular interest can be isolated and manipulated. The results of Chapter 3 indicate that a 4–6-month grow-out period using sea pens can yield useful field results. More research is needed to determine whether the cause of sandfish mortality at the Ungakum sea pen site was due to predation or related to the very high percentage of fine sediment, and what growth rates could be expected from a habitat type characterised by a high fine-sediment fraction. Additional information on which habitat and sediment features lead to high survival and support strong growth would also be valuable in improving husbandry of juvenile sandfish in sand nursery systems in hatcheries.

8.6.3.2 Impacts of sandfish mariculture on the environment

An area barely touched upon in this study was potential impacts of sandfish mariculture on the environment. Sea cucumbers in general and sandfish in particular are regarded as beneficial to the marine environment (Purcell et al. 2016b). Negative impacts of sandfish sea ranching would not be anticipated since past, unexploited sandfish populations were of greater density than likely future sea ranching densities (Shelley 1985, Lokani 1996b, Chapter 1). Nonetheless, there may be ecological impacts if natural habitat is modified to enhance ocean mariculture production (e.g., Tsiresy et al. 2011, Eriksson et al. 2012). Moreover, temporal changes in biophysical parameters have been noted in sea pens where sandfish were grown (Plotieau et al.

2013, Chapter 3). Finally, if an enclosed farming model is adopted instead of an open sea ranch, there may be environmental consequences (in addition to possible social impacts discussed in Chapter 7). Therefore, while not a priority research area, it is recommended that a habitat monitoring program be established if and when ocean mariculture of sandfish commences, in order to assess potential environmental impacts.

8.6.3.3 GIS applications

Assessment of the potential of GIS and remote sensing in identifying suitable habitat for sandfish mariculture undertaken in this study was preliminary but provided a logical entry point into this field for PNG and elsewhere in the Pacific Islands region. Follow-on research should involve completing Stage 1 of the three-stage GIS model proposed in Chapter 4. This research comprises a relatively simple desk-top MCE using available empirical maps, numerical models, field data, fisheries data and basic remote sensing (e.g., green band or NDVI) to identify suitable areas for sandfish mariculture. There may be value in using alternative classification methods. For example, object-based image analysis (OBIA) differs from the traditional pixel-based analysis by taking into account contextual information around the satellite image pixels (Phinn et al. 2012). OBIA has gained popularity for marine habitat mapping (Hedley et al. 2016, Purkis et al. 2019), but also requires considerable expertise, time and field data compared with the pixel-based approach. Suitable GIS technical capacity and access to available data sources will be required (see Powers et al. 2019). Additional improvements to spatial planning capacity could be gained by determining the best way to incorporate habitat descriptors into Stage 2 of the proposed GIS model. Sea cucumber site selection requires more emphasis on substrate conditions than for suspended shellfish farming and fish cage culture, where oceanographic conditions are the major factors influencing site suitability. Furthermore, sediment features are more important for sandfish than for reef dwelling, non-burying sea cucumbers (e.g., *A. japonicus*). There is a need to develop simple and fit-for-purpose seafloor/sediment descriptors that can be collected with relative ease and integrated into GIS modelling.

8.6.4 Social considerations

The failure of the trial sea ranch reported in Chapter 7 clearly indicated that many future research priorities lie in the social and cultural realm. Education, training and capacity building are essential for communities wishing to participate in mariculture livelihood activities. Chapters 2 and 7 showed that key ecological concepts central to sustainable marine resource management were not well understood. Education and training in producing high-quality BDM are needed to ensure that mariculture livelihood activities generate maximum income (noting the optimal processing issues raised in *section 8.5.1.1*). Training in business and financial management may assist in ensuring that income from sandfish mariculture contributes to long-term community well-being, and would also enhance benefits from other livelihood activities. Chapter 7 showed that communities are likely to need greater co-management in the early development phase of a sandfish mariculture intervention. But the failure of the trial sea ranch also showed that weak and/or unstable leadership and political disunity, that are common to many rural Melanesian communities, can quickly undermine attempts to communally manage such a high-value, easy-to-access commodity. Support from government fisheries agencies, NGOs and research projects may help to strengthen community capacity to collectively manage their resources through effective CBFM. Security of cultured sandfish must be guaranteed, from outsiders and the community itself, while the industry is developing. Unsustainable harvest within mariculture ranches or farms will reduce profits and threaten economic viability. Failure and disappointment are damaging to any fledgling mariculture industry (Hambrey et al. 2011, von Essen et al. 2013).

Monitoring and evaluation are also necessary to establish whether benefits accrue to communities who undertake sandfish sea ranching compared to, for example, the sea cucumber fishery or other mariculture livelihood activities, along with the nature and distribution of those benefits. Communities may have to develop a management plan and demonstrate adequate capacity (e.g., leadership, cohesion) to manage a sea ranch before they are provided a licence and can receive cultured juveniles. These considerations also apply to alternative sandfish farming approaches, such as individual sea pen farming (Robinson and Pascal 2009, Klückow et al. 2017). The desire for individual private sea farms was expressed by many community members during field work for this thesis. Putting aside the motives for those requests, it is appropriate to question whether a different model might be warranted, given the significant social and cultural barriers to community-based sandfish sea ranching revealed in Chapter 7, and the potential for individual or family ventures to have more success than group ventures (Torell et al. 2010). Community marine tenure arrangements differ widely within PNG and the Pacific Islands region, as do the features of sandfish mariculture habitat (depth, exposure, grain size, etc.). The potential for individual or clan-based sea pen farming should be investigated if local conditions (social and environmental) are conducive to this model. Well-designed social, cultural and economic research should be done in order to identify the factors that contribute to community (or individual) success and adoption, of either model. This information will greatly facilitate future sea cucumber mariculture livelihood development.

As suggested in *section 8.5.1.1*, dried BDM may not be the most profitable option for all sandfish mariculture operations (Fig. 8.2). Determination of the water content of 'wet' BDM from the study area is needed to compare against the estimated 20% conversion rate suggested by Barclay et al. (2016). Chapters 1 and 2 reported low prices or outright rejection of badly processed BDM, resulting from either an inability to process well, or desire for 'quick money'. Training on high-quality processing accompanied by a cost-benefit analysis of selling at different stages of processing (e.g., sandfish that have been boiled once and the calcareous skin layer removed versus well-dried BDM) will prepare sandfish mariculture proponents for trade negotiations in order to maximise economic returns. More research is needed, however, because of the unique circumstances of the 2018 sea cucumber fishing season when these data were collected. Strong competition for BDM resulted in volatile prices and the interview data may be unreliable since neither the BDM condition nor the transactions were witnessed. Validation of these data may also be difficult due to the lack of transparency in traders' dealings with fishers, maintained deliberately by some traders for market advantage.

Socio-economic investigation into the most profitable BDM processing stage, local buying price, distance to market, distribution of benefits, labour value, conflict and CBFM are useful inputs for economic modelling (e.g., Johnston 2012) and further research in these areas would assist communities and the facilitating agencies to develop optimal mariculture strategies.

8.7 Conclusion

This thesis presents the first evaluation of an extensive range of social and technical factors that are likely to affect development of a community-based sandfish mariculture sector in New Ireland Province, PNG. The research was conducted primarily within the sea cucumber fishing communities that the research was designed to benefit. Changes in the status of the fishery (i.e., lifting of a moratorium on sea cucumber harvest) significantly affected livelihood activities within partner communities and the focus of the study necessarily shifted not only to accommodate those changes, but to take advantage of them. The broad and comprehensive approach adopted in this study and reported in this thesis generated valuable new information for prospective sandfish sea ranchers and farmers, funding bodies, policy makers and other stakeholders. It also provides valuable information for use in extension activities to support further development of sandfish mariculture specifically, and related mariculture developments in PNG and the broader Indo-Pacific region. Importantly, this thesis provides a foundation for future research into the further development of sustainable community-based sandfish mariculture.

References

Abràmoff, M. D., Magalhães, P. J. and Ram, S. J. 2004. Image Processing with ImageJ. *Biophotonics International,* 11**,** 36-42.

Agudo, N. 2007. *Sandfish hatchery techniques*. Secretariat of the Pacific Community, Noumea (New Caledonia), 49 pp.

Agudo, N. 2012. Pond grow-out trials for sandfish (*Holothuria scabra*) in New Caledonia. *In:* Hair, C., Pickering, T. and Mills, D. (eds.) *Asia–Pacific tropical sea cucumber aquaculture symposium. ACIAR Proceedings 136.* Canberra: Australian Centre for International Agricultural Research, pp. 104-112.

Alkhatlan, A., Bannari, A., El-Battay, A., Al-Dawood, T. and Abahussain, A. 2018. Potential of Landsat-Oli for Seagrass and Algae Species Detection and Discrimination in Bahrain National Water Using Spectral Reflectance. *IEEE International Geoscience and Remote Sensing Symposium.* pp. 4043-4046.

Allen, M. G. 2013. Melanesia's violent environments: Towards a political ecology of conflict in the western Pacific. *Geoforum,* 44**,** 152-161. https://doi.org/10.1016/j.geoforum.2012.09.015

Allison, E. H. and Ellis, F. 2001. The livelihoods approach and management of small-scale fisheries. *Marine Policy,* 25**,** 377-388. https://dx.doi.org/10.1016/S0308-597X(01)00023-9

Altamirano, J. P., Recente, C. P. and Rodriguez, J. C. J. 2017. Substrate preference for burying and feeding of sandfish *Holothuria scabra* juveniles. *Fisheries Research,* 186**,** 514-523. https://doi.org/10.1016/j.fishres.2016.08.011

Anderson, M. J. 2008. Animal-sediment relationships re-visited: Characterising species' distributions along an environmental gradient using canonical analysis and quantile regression splines. *Journal of Experimental Marine Biology and Ecology,* 366**,** 16-27. https://doi.org/10.1016/j.jembe.2008.07.006

Anderson, M. J., Gorley, R. N. and Clarke, K. R. 2008. *PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods,* Plymouth, UK, PRIMER-E.

Anderson, S. C., Flemming, J. M., Watson, R. and Lotze, H. K. 2011. Serial exploitation of global sea cucumber fisheries. *Fish and Fisheries,* 12**,** 317-339. https://doi.org/10.1111/j.1467-2979.2010.00397.x

Anon 1994. *Sea cucumbers and beche-de-mer of the tropical Pacific – A handbook for fishers*. Noumea: Secretariat of the Pacific Community, 51 pp.

Anuchiracheeva, S., Demaine, H., Shivakoti, G. P. and Ruddle, K. 2003. Systematizing local knowledge using GIS: fisheries management in Bang Saphan Bay, Thailand. *Ocean and Coastal Management,* 46**,** 1049-1068. https://doi.org/10.1016/j.ocecoaman.2004.01.001

Asafu-Adjaye, J. 2000. Customary marine tenure systems and sustainable fisheries management in Papua New Guinea. *International Journal of Social Economics,* 27**,** 917-927. https://doi.org/10.1108/03068290010336856

Aslan, L. O. M., Iba, W., Bolu, L. O. R., Ingram, B. A., Gooley, G. J. and de Silva, S. S. 2015. Mariculture in SE Sulawesi, Indonesia: Culture practices and the socio economic aspects of the major commodities. *Ocean and Coastal Management,* 116**,** 44-57. https://doi.org/10.1016/j.ocecoaman.2015.06.028

Aswani, S. and Lauer, M. 2006. Incorporating fishermen's local knowledge and behavior into geographical information systems (GIS) for designing marine protected areas in Oceania. *Human Organization,* 65**,** 81-102. https://doi.org/10.17730/humo.65.1.4y2q0vhe4l30n0uj

Aswani, S., Albert, S. and Love, M. 2017. One size does not fit all: Critical insights for effective community-based resource management in Melanesia. *Marine Policy,* 81**,** 381-391. https://doi.org/10.1016/j.marpol.2017.03.041

Ateweberhan, M., Hudson, J., Rougier, A., Jiddawi, N. S., Msuya, F. E., Stead, S. M. and Harris, A. 2018. Community based aquaculture in the western Indian Ocean: challenges and opportunities for developing sustainable coastal livelihoods. *Ecology and Society,* 23. https://doi.org/10.5751/ES-10411-230417

Baker-Médard, M. and Ohl, K. N. 2019. Sea cucumber management strategies: challenges and opportunities in a developing country context. *Environmental Conservation***,** 1-11. https://doi.org/10.1017/S0376892919000183

Barclay, K. and Kinch, J. 2013. *Local Capitalisms and Sustainability in Coastal Fisheries: Cases from Papua New Guinea and Solomon Islands*, Emerald Insight.

Barclay, K., Kinch, J., Fabinyi, M., EDO-NSW, Waddell, S., Smith, G., Sharma, S., Kichawen, P., Foale, S. and Hamilton, R. H. 2016. *Interactive Governance Analysis of the Bêche-de-Mer 'Fish Chain' from Papua New Guinea to Asian Markets*. Sydney: University of Technology Sydney, 167 pp.

Barclay, K., Fabinyi, M., Kinch, J. and Foale, S. 2019. Governability of high-value fisheries in low-income contexts: A case study of the sea cucumber fishery in Papua New Guinea. *Human Ecology,* 47**,** 381-396. https://doi.org/10.1007/s10745-019-00078-8

Barillé, L., Robin, M., Harin, N., Bargain, A. and Launeau, P. 2010. Increase in seagrass distribution at Bourgneuf Bay (France) detected by spatial remote sensing. *Aquatic Botany,* 92**,** 185-194. https://doi.org/10.1016/j.aquabot.2009.11.006

Bartley, D. M. and Bell, J. D. 2008. Restocking, stock enhancement, and sea ranching: arenas of progress. *Reviews in Fisheries Science,* 16**,** 357-365. https://doi.org/10.1080/10641260701678058

Basir, A. P., Andayani, S. and Sambah, A. B. 2017. Spatial multi criteria analysis to determine the suitability of the area for sea cucumber cultivation (*Holothuria* sp.) in the waters of Hatta Island, Banda Neira, Maluku. *Research Journal of Pharmaceutical, Biological and Chemical Sciences,* 8**,** 291-299.

Baticados, D. B., Agbayani, R. F. and Quinitio, E. T. 2014. Community-based technology transfer in rural aquaculture: The case of mudcrab *Scylla serrata* nursery in ponds in northern Samar, Central Philippines. *AMBIO,* 43**,** 1047-1058. https://doi.org/10.1007/s13280-014-0528-5

Battaglene, S. C. 1999. Culture of tropical sea cucumbers for stock restoration and enhancement. *Naga, the ICLARM Quarterly,* 22**,** 4-11.

Battaglene, S. C., Seymour, J. E. and Ramofafia, C. 1999. Survival and growth of cultured juvenile sea cucumbers, *Holothuria scabra*. *Aquaculture,* 178**,** 293-322. https://doi.org/10.1016/S0044-8486(99)00130-1

Bell, J. D., Rothlisberg, P. C., Munro, J. L., Loneragan, N. R., Nash, W. J., Ward, R. D. and Andrew, N. L. 2005. Restocking and stock enhancement of marine invertebrate fisheries. *Advances in Marine Biology,* 49**,** 1-374. https://doi.org/10.1016/S0065-2881(05)49002-1

Bell, J. D., Leber, K. M., Blankenship, H. L., Loneragan, N. R. and Masuda, R. 2008. A new era for restocking, stock enhancement and sea ranching of coastal fisheries resources. *Reviews in Fisheries Science,* 16**,** 1-9. https://doi.org/10.1080/10641260701776951

Bell, J. D., Kronen, M., Vunisea, A., Nash, W. J., Keeble, G., Demmke, A., Pontifex, S. and Andréfouët, S. 2009. Planning the use of fish for food security in the Pacific. *Marine Policy,* 33**,** 64-76. https://doi.org/10.1016/j.marpol.2008.04.002

Béné, C., Arthur, R., Norbury, H., Allison, E. H., Beveridge, M., Bush, S., Campling, L., Leschen, W., Little, D., Squires, D., Thilsted, S. H., Troell, M. and Williams, M. 2016. Contribution of fisheries and aquaculture to food security and poverty reduction: Assessing the current evidence. *World Development,* 79**,** 177-196. https://doi.org/10.1016/j.worlddev.2015.11.007

Bernard, H. R. 2006. *Research Methods in Anthropology; Qualitative and Quantitative Approaches,* Oxford, Altamira Press.

Beyerl, K., Putz, O. and Breckwoldt, A. 2016. The role of perceptions for community-based marine resource management. *Frontiers in Marine Science,* 3**,** 1-17. https://doi.org/10.3389/fmars.2016.00238

Bhaskar, B. K. and James, P. S. R. B. 1989. Size and weight reduction in *Holothuria scabra* processed as beche-de-mer. *Marine Fisheries Information Service Trend and Environment Series,* 100**,** 13-16.

Bordbar, S., Anwar, F. and Saari, N. 2011. High-value components and bioactives from sea cucumbers for functional foods—A review. *Marine Drugs,* 9**,** 1761-1805. https://doi.org/10.3390/md9101761

Bowman, W. M. 2012. Sandfish production and development of sea ranching in northern Australia. *In:* Hair, C., Pickering, T. and Mills, D. (eds.) *Asia–Pacific tropical sea cucumber aquaculture symposium. ACIAR Proceedings 136.* Canberra: Australian Centre for International Agricultural Research, pp. 75-78.

Branch, T. A., Lobo, A. S. and Purcell, S. W. 2013. Opportunistic exploitation: an overlooked pathway to extinction. *Trends in Ecology & Evolution,* 28**,** 409-413. https://doi.org/10.1016/j.tree.2013.03.003

Brokordt, K. B., Fernández, M. and Gaymer, C. F. 2006. Domestication reduces the capacity to escape from predators. *Journal of Experimental Marine Biology and Ecology,* 329**,** 11-19. https://doi.org/10.1016/j.jembe.2005.08.007

Buitrago, J., Rada, M., Hernández, H. and Buitrago, E. 2005. A single-use site selection technique, using GIS, for aquaculture planning: Choosing locations for mangrove oyster raft culture in Margarita Island, Venezuela. *Environmental Management,* 35**,** 544-556. https://doi.org/10.1007/s00267-004-0087-9

Calamia, M. A. 1999. A methodology for incorporating traditional ecological knowledge with geographic information systems for marine resource management in the Pacific. *SPC Traditional Marine Resource Management and Knowledge Information Bulletin,* 10**,** 2-12.

Campbell, J., Whittingham, E. and Townsley, P. 2006. Responding to Coastal Poverty: Should we be Doing Things Differently or Doing Different Things? *In:* Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds.) *Environment and livelihoods in tropical coastal zones; Managing agriculture-fishery-aquaculture conflicts.* Oxfordshire: CABI, pp. 274-292.

Carleton, C., Hambrey, J., Govan, H., Medley, P. and Kinch, J. 2013. Effective management of sea cucumber fisheries and the beche-de-mer trade in Melanesia. *SPC Fisheries Newsletter,* 140**,** 24-42.

Carrier, J. G. 1987. Marine tenure and conservation in Papua New Guinea. *In:* McCay, B.J. and Acheson, J.M. (eds.) *The Question of the Commons: The Culture and Ecology of Communal Resources.* Tucson: The University of Arizona Press, pp. 142-167.

Carrier, J. G. and Carrier, A. H. 1989. *Wage, Trade, and Exchange in Melanesia: A Manus Society in the Modern State,* Berkeley, University of California Press.

Caulier, G., Van Dyck, S., Gerbaux, P., Eeckhaut, I. and Flammang, P. 2011. Review of saponin diversity in sea cucumbers belonging to the family Holothuriidae. *SPC Beche-de-mer Information Bulletin,* 31**,** 48-54.

Ceccarelli, D. M., Logan, M. and Purcell, S. 2018. Analysis of optimal habitat for captive release of the sea cucumber *Holothuria scabra*. *Marine Ecology Progress Series,* 588**,** 85-100. https://doi.org/10.3354/meps12444

Chambers, J. M. and Hastie, T. J. 1992. *Statistical Models in S,* California, Wadsworth and Brooks.

Chen, J. 2004. Present status and prospects of sea cucumber industry in China. *In:* Lovatelli, A., Conand, C., Purcell, S., Uthicke, S., Hamel, J.F. and Mercier, A. (eds.) *Advances in Sea Cucumber Aquaculture and Management. FAO Fisheries Technical Paper No. 463.* Rome, Italy: FAO, pp. 25-37.

Chen, T., Peng, Z., Lu, J., Li, B. and Hou, H. 2015. Self-degradation of sea cucumber body wall under 4C storage condition. *Journal of Food Processing and Preservation***,** 1-9. https://doi.org/10.1111/jfpp.12652

Cheyne, A. 1852. *A Description of the Islands in the Western Pacific Ocean, North and South of the Equator, Together with their Productions: Manners and Customs of the Natives, and Vocabularies of their Various Languages,* London, Potter.

Christensen, A. E. 2011. Marine gold and atoll livelihoods: The rise and fall of the bêche-de-mer trade on Ontong Java, Solomon Islands. *Natural Resources Forum,* 35**,** 9-20. https://doi.org/10.1111/j.1477-8947.2011.01343.x

Ciccia Romito, V. 2012. *Remote sensing and GIS techniques as a pre-assessment tool for sea cucumber mariculture site selection and economic appraisal in Tanzania.* Masters Research, Newcastle University.

Cinner, J. E., McClanahan, T. R., MacNeil, M. A., Graham, N. A. J., Daw, T. M., Mukminin, A., Feary, D. A., Rabearisoa, A. L., Wamukota, A., Jiddawi, N., Campbell, S. J., Baird, A. H., Januchowski-Hartley, F. A., Hamed, S., Lahari, R., Morove, T. and Kuange, J. 2012. Comanagement of coral reef social-ecological systems. *Proceedings of the National Academy of Sciences of the United States of America,* 109**,** 5219-5222. doi: 10.1073/pnas.1121215109

Clarke, K. R. and Gorley, R. N. 2006. *PRIMER v6: User Manual/Tutorial PRIMER-E,* Plymouth.

Cohen, P., Tapala, S., Rikio, A., Sori, F., Hilly, Z., Alexander, T. J. and Foale, S. 2014. Developing a common understanding of taxonomy for fisheries management in north Vella Lavella, Solomon Islands. *SPC Traditional Marine Resource Management and Knowledge Information Bulletin,* 33**,** 3-12.

Cohen, P. and Steenbergen, D. 2015. Social dimensions of local fisheries co-management in the coral triangle. *Environmental Conservation,* 42**,** 278-288. https://doi.org/10.1017/S0376892914000423

Conand, C. 1990. *The Fishery Resources of Pacific Island Countries*. 272.2. Rome: FAO, 143 pp.

Conand, C. and Byrne, M. 1993. A review of recent developments in the world sea cucumber fisheries. *Marine Fisheries Review,* 55**,** 1-13.

Conand, C. 2018. Tropical sea cucumber fisheries: Changes during the last decade. *Marine Pollution Bulletin,* 133**,** 590-594. https://doi.org/10.1016/j.marpolbul.2018.05.014

Connell, J. 2018. Islands: balancing development and sustainability? *Environmental Conservation***,** 1-14. https://doi.org/10.1017/S0376892918000036

Costa-Pierce, B. A. 2010. Sustainable ecological aquaculture systems: The need for a new social contract for aquaculture development. *Marine Technology Society Journal,* 44**,** 88-112. https://dx.doi.org/10.4031/MTSJ.44.3.3

Curry, G. N. and Koczberski, G. 2012. Relational economies, social embeddedness and valuing labour in agrarian change: An example from the developing world. *Geographical Research,* 50**,** 377-392. https://doi.org/10.1111/j.1745-5871.2011.00733.x

Curry, G. N., Koczberski, G., Lummani, J., Nailina, R., Peter, E., McNally, G. and Kuaimba, O. 2015. A bridge too far? The influence of socio-cultural values on the adaptation responses of smallholders to a devastating pest outbreak in cocoa. *Global Environmental Change,* 35**,** 1-11. https://doi.org/10.1016/j.gloenvcha.2015.07.012

Dalzell, P. J., Adams, T. J. H. and Polunin, N. V. C. 1996. Coastal fisheries in the Pacific Islands. *Oceanography and Marine Biology: An Annual Review,* 34**,** 395 - 531.

Dance, S. K., Lane, I. and Bell, J. D. 2003. Variation in short-term survival of cultured sandfish (*Holothuria scabra*) released in mangrove-seagrass and coral reef flat habitats in Solomon Islands. *Aquaculture,* 220**,** 495-505. https://doi.org/10.1016/s0044-8486(02)00623-3

Davis, J. L. D., Eckert-Mills, M. G., Young-Williams, A. C., Hines, A. H. and Zohar, Y. 2005. Morphological conditioning of a hatchery-raised invertebrate, *Callinectes sapidus,* to improve field survivorship after release. *Aquaculture,* 243**,** 147-158. https://doi.org/10.1016/j.aquaculture.2004.09.027

de Sousa, F. E. S., Moura, E. A. and Marinho-Soriano, E. 2012. Use of geographic information systems (GIS) to identify adequate sites for cultivation of the seaweed *Gracilaria birdiae* in Rio Grande do Norte, Northeastern Brazil. *Revista Brasileira de Farmacognosia,* 22**,** 868-873. https://doi.org/10.1590/S0102-695X2012005000087

Dobson, G. 2001. An improved method of packing to minimise mortality in juvenile trochus during transport. *SPC Trochus Information Bulletin,* 8**,** 22-23.

Dumalan, R. J. P., Bondoc, K. G. V. and Juinio-Meñez, M. A. 2019. Grow-out culture trial of sandfish *Holothuria scabra* in pens near a mariculture-impacted area. *Aquaculture,* 507**,** 481-492. https://doi.org/10.1016/j.aquaculture.2019.04.045

Duy, N. D. Q. 2010. *Seed production of sandfish (Holothuria scabra) in Vietnam*. Iloilo, Philippines: SEAFDEC, 12 pp.

Duy, N. D. Q. 2012. Large-scale sandfish production from pond culture in Vietnam. *In:* Hair, C., Pickering, T. and Mills, D. (eds.) *Asia–Pacific tropical sea cucumber aquaculture symposium. ACIAR Proceedings 136.* Canberra: Australian Centre for International Agricultural Research, pp. 34-39.

Duy, N. D. Q., Francis, D., Pirozzi, I. and Southgate, P. C. 2016. Use of micro-algae concentrates for hatchery culture of sandfish, *Holothuria scabra*. *Aquaculture,* 464**,** 145-152. https://doi.org/10.1016/j.aquaculture.2016.06.016

Eeckhaut, I., Février, J., Todinanahary, G. and Delroisse, J. 2020. Impact of *Thalamita crenata* (Decapoda; Portunidae) predation on *Holothuria scabra* juvenile survival in sea farming pens. *SPC Beche-de-mer Information Bulletin,* 40.

Eriksson, B. H., Troell, M., Brugere, C., Chadag, M., Phillips, M. J. and Andrew, N. 2019. *A diagnostic framework for equitable mariculture development in the Western Indian Ocean*. ACIAR monograph No. 204. Canberra: Australian Centre for International Agricultural Research, 36 pp.

Eriksson, H. 2012. Sandfish (*Holothuria scabra*) farming in a social–ecological context: conclusions from Zanzibar. *In:* Hair, C., Pickering, T. and Mills, D. (eds.) *Asia–Pacific tropical sea cucumber aquaculture symposium. ACIAR Proceedings 136.* Canberra: Australian Centre for International Agricultural Research, pp. 196-202.

Eriksson, H., Robinson, G., Slater, M. and Troell, M. 2012. Sea cucumber aquaculture in the Western Indian Ocean: Challenges for sustainable livelihood and stock improvement. *AMBIO,* 41**,** 109-121. https://doi.org/10.1007/s13280-011-0195-8

Eriksson, H. and Clarke, S. 2015. Chinese market responses to overexploitation of sharks and sea cucumbers. *Biological Conservation,* 184**,** 163-173. https://doi.org/10.1016/j.biocon.2015.01.018

Eriksson, H., Österblom, H., Crona, B., Troell, M., Andrew, N., Wilen, J. and Folke, C. 2015. Contagious exploitation of marine resources. *Frontiers in Ecology and the Environment,* 13**,** 435-440. https://doi.org/10.1890/140312

ESRI 2020. *https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/how-maximum-likelihood-classification-works.htm* [Online]. [Accessed 11 January 2020].

Fabinyi, M. 2012. Historical, cultural and social perspectives on luxury seafood consumption in China. *Environmental Conservation,* 39**,** 83-92. https://doi.org/10.1017/S0376892911000609

Fabinyi, M. and Liu, N. 2014. Seafood banquets in Beijing: Consumer perspectives and implications for environmental sustainability. *Conservation and Society,* 12**,** 218-228. https://doi.org/10.4103/0972-4923.138423

Fabinyi, M., Dressler, W. H. and Pido, M. D. 2017. Fish, trade and food security: Moving beyond 'availability' discourse in marine conservation. *Human Ecology,* 45**,** 177-188. https://doi.org/10.1007/s10745-016-9874-1

Fabinyi, M. 2018. Environmental fixes and historical trajectories of marine resource use in Southeast Asia. *Geoforum,* 91**,** 87-96. https://doi.org/10.1016/j.geoforum.2018.02.033

FAO 2018. *State of the World Fisheries and Aquaculture (SOFIA)*. Rome: Food and Agriculture Organization, 210 pp.

Feary, D. A., Hamilton, R., Matawai, M., Molai, C., Karo, M. and Almany, G. 2015. *Assessing sandfish population stocks within the south coast of Manus, and a summary report of sandfish connectivity field research*. The Nature Conservancy, National Fisheries Authority, 60 pp.

Filer, C. 1990. The Bougainville Rebellion, The Mining Industry And The Process Of Social Disintegration In Papua New Guinea. *Canberra Anthropology,* 13**,** 1-39. https://doi.org/10.1080/03149099009508487

Filer, C. 1997. Logging and resource dependency in Papua New Guinea: a response to Henderson. *In:* Burt, B. and Clerk, C. (eds.) *Environment and Development in the Pacific Islands.* Canberra: National Centre for Development, Research School of Pacific and Asian Studies, The Australian National University, UPNG Press, pp. 69-77.

Foale, S. 1998. What's in a name? An analysis of the West Nggela (Solomon Islands) fish taxonomy. *SPC Traditional Marine Resource Management and Knowledge Information Bulletin,* 9**,** 2-19.

Foale, S. and Macintyre, M. 2000. Dynamic and flexible aspects of land and marine tenure at West Nggela: Implications for marine resource management. *Oceania,* 71**,** 30-45.

Foale, S. 2001. 'Where's our development?' Landowner aspirations and environmentalist agendas in Western Solomon Islands. *The Asia Pacific Journal of Anthropology,* 2**,** 44-67. https://doi.org/10.1080/14442210110001706105

Foale, S. and Manele, B. 2004. Social and political barriers to the use of marine protected areas for conservation and fishery management in Melanesia. *Asia Pacific Viewpoint,* 45**,** 373-386. https://doi.org/10.1111/j.1467-8373.2004.00247.x

Foale, S., Cohen, P., Januchowski-Hartley, S., Wenger, A. and Macintyre, M. 2011. Tenure and taboos: origins and implications for fisheries in the Pacific. *Fish and Fisheries,* 12**,** 357-369. https://doi.org/10.1111/j.1467-2979.2010.00395.x

Foale, S., Dyer, M. and Kinch, J. 2016. The value of tropical biodiversity in rural Melanesia. *Valuation Studies,* 4**,** 1-29. https://doi.org/10.3384/VS.2001-5992.164111

Foale, S. J. 2005. *Sharks, sea slugs and skirmishes : managing marine and agricultural resources on small, overpopulated islands in Milne Bay, PNG*. Canberra: ANU, 55 pp.

Francour, P. 1997. Predation on holothurians: a literature review. *Invertebrate Biology,* 116**,** 52-60. https://doi.org/10.2307/3226924

Friedman, K., Kronen, M., Pinca, S., Magron, F., Boblin, P., Pakoa, K., Awiva, R. and Chapman, L. 2008a. *Papua New Guinea Country Report: Profiles and results from survey work at Andra, Tsoilaunung, Sideia and Panapompom*. Noumea: Secretariat of the Pacific Community, 435 pp.

Friedman, K., Purcell, S., Bell, J. D. and Hair, C. A. 2008b. *Sea Cucumber Fisheries: A Manager's Toolbox.* Canberra: Australian Centre for International Agricultural Research, 32 pp.

Friedman, K., Eriksson, H., Tardy, E. and Pakoa, K. 2011. Management of sea cucumber stocks: patterns of vulnerability and recovery of sea cucumber stocks impacted by fishing. *Fish and Fisheries,* 12**,** 75-93. https://doi.org/10.1111/j.1467-2979.2010.00384.x

Froehlich, H. E., Gentry, R. R. and Halpern, B. S. 2017. Conservation aquaculture: Shifting the narrative and paradigm of aquaculture's role in resource management. *Biological Conservation,* 215**,** 162-168. https://doi.org/10.1016/j.biocon.2017.09.012

Fyfe, S. K. 2003. Spatial and temporal variation in spectral reflectance: Are seagrass species spectrally distinct? *Limnology and Oceanography,* 48**,** 464-479. https://doi.org/10.4319/lo.2003.48.1_part_2.0464

Giap, D. H., Yi, Y. and Yakupitiyage, A. 2005. GIS for land evaluation for shrimp farming in Haiphong of Vietnam. *Ocean and Coastal Management,* 48**,** 51-63. https://doi.org/10.1016/j.ocecoaman.2004.11.003

Glaser, M., Breckwoldt, A., Deswandi, R., Radjawali, I., Baitoningsih, W. and Ferse, S. C. A. 2015. Of exploited reefs and fishers – A holistic view on participatory coastal and marine management in an Indonesian archipelago. *Ocean and Coastal Management,* 116**,** 193-213. https://doi.org/10.1016/j.ocecoaman.2015.07.022

Gordon, H. S. 1954. The economic theory of a common-property resource: The fishery. *Journal of Political Economy,* 62**,** 124-142. https://doi.org/10.1086/257497

Gorospe, J. C., Juinio-Meñez, M. A. and Southgate, P. C. 2019. Effects of shading on periphyton characteristics and performance of sandfish, *Holothuria scabra* Jaeger 1833, juveniles. *Aquaculture,* 512**,** 1-8. 10.1016/j.aquaculture.2019.734307

Govan, H. 2017. A review of sea cucumber fisheries and management in Melanesia. *SPC Fisheries Newsletter,* 154**,** 31-42.

Grant, J., Bacher, C., Joao G. , Ferreira, J. G., Groom, S., Morales, J., Rodriguez-Benito, C., Saitoh, S.-I., Sathyendranath, S. and Stuart, V. 2009. Remote Sensing Applications in Marine Aquaculture. *In:* Forget, M.-H., Stuart, V. and Platt, T. (eds.) *Remote Sensing in Fisheries and Aquaculture.* pp. 77-88.

Gray, J. S. 1974. Animal-Sediment Relationships. *Oceanography and Marine Biology: An Annual Reveiw,* 12**,** 223-261.

Green, E. P., Mumby, P. J., Edwards, A. J. and Clark, C. D. 2000. *Remote Sensing Handbook for Tropical Coastal Management. Coastal Management Sourcebooks 3*. Paris: UNESCO, 316 pp.

Guo, B., Gong, C., Shao, P. and Jia, L. 2014. The changes of enzymes involved in metabolism and immunity of *Apostichopus japonicus* (Selenka) after short-term transportations. *Aquaculture International,* 22**,** 379-389. https://doi.org/10.1007/s10499-013-9645-6

Hagen, N. T. 1996. Echinoculture: from fishery enhancement to closed cycle cultivation. *World Aquaculture,* 27**,** 6-19.

Hair, C., Pickering, T., Semisi, M., Vereivalu, T., Hunter, J. and Cavakiqali, L. 2011. Sandfish culture in Fiji Islands. *SPC Beche-de-mer Information Bulletin,* 31**,** 3-11.

Hair, C. A. and Aini, J. W. 1995. *1994 Fisheries Statistics Report New Ireland Province*. Port Moresby: PNG National Fisheries Authority, 39 pp.

Hair, C. A. and Aini, J. W. 1996. *1995 Fisheries Statistics Report, New Ireland Province*. Port Moresby: PNG National Fisheries Authority, 66 pp.

Hair, C. A., Pickering, T. D. and Mills, D. J. 2012. Asia–Pacific tropical sea cucumber aquaculture. 15-17 February 2011. Noumea, New Caledonia. Australian Centre for International Agricultural Research, Canberra, 209 pp.

Hair, C. A., Bitalen, P., Kanawi, P., Leini, E. and Southgate, P. 2016. Multi-species sea cucumber spawning at Limellon Island, New Ireland Province, Papua New Guinea. *SPC Beche-de-mer Information Bulletin,* 36**,** 87-89.

Hair, C. A., Kinch, J., Galiurea, T., Kanawi, P., Mwapweya, M. and Noiney, J. 2018. Re-opening of the sea cucumber fishery in Papua New Guinea: A case study from the Tigak Islands in the New Ireland Province. *SPC Beche-de-mer Information Bulletin,* 38**,** 3-10.

Hamano, T., Kondo, M., Ohhashi, Y., Tateishi, T., Fujimura, H. and Sueyoshi, T. 1996. The whereabouts of edible sea cucumber *Stichopus japonicus* juveniles released in the wild. *Aquaculture Science,* 44**,** 249-254. https://doi.org/10.11233/aquaculturesci1953.44.249

Hambrey, J., Govan, H. and Carleton, C. 2011. *Opportunities for the development of the Pacific islands' mariculture sector: report to the Secretariat of the Pacific Community*. Noumea: SPC, 139 pp.

Hamel, J.-F., Conand, C., Pawson, D. L. and Mercier, A. 2001. The sea cucumber *Holothuria scabra* (Holothuroidea: Echinodermata): Its biology and exploitation as beche-de-mer. *Advances in Marine Biology.* pp. 129-223.

Hamel, J.-F., Mercier, A., Conand, C., Purcell, S., Toral-Granda, M. V. and Gamboa, R. U. 2013. *Holothuria scabra. The IUCN red list of threatened species 2013: e.T180257A1606648.* [Online]. [Accessed 9 December 2019].

Hamel, J.-F., Sun, J., Gianasi, B. L., Montgomery, E. M., Kenchington, E. L., Burel, B., Rowe, S., Winger, P. D. and Mercier, A. 2019. Active buoyancy adjustment increases dispersal potential in benthic marine animals. *Journal of Animal Ecology,* 88**,** 820-832. https://doi.org/10.1111/1365-2656.12943

Hamel, J. F. and Mercier, A. 2000. Cuvierian tubules in tropical holothurians: Usefulness and efficiency as a defence mechanism. *Marine and Freshwater Behaviour and Physiology,* 33**,** 115-139. https://doi.org/10.1080/10236240009387085

Hamel, M. A. and Andréfouët, S. 2010. Using very high resolution remote sensing for the management of coral reef fisheries: Review and perspectives. *Marine Pollution Bulletin,* 60**,** 1397-1405. https://doi.org/10.1016/j.marpolbul.2010.07.002

Hamilton, R. J., Hughes, A., Brown, C. J., Leve, T. and Kama, W. 2019. Community-based management fails to halt declines of bumphead parrotfish and humphead wrasse in Roviana Lagoon, Solomon Islands. *Coral Reefs,* 38**,** 455-465. https://doi.org/10.1007/s00338-019-01801-z

Hammond, L. S. 1981. An analysis of grain size modification in biogenic carbonate sediments by deposit-feeding holothurians and echinoids (Echinodermata). *Limnology and Oceanography* 26**,** 898-906.

Hammond, L. S. 1982. Patterns of feeding and activity in deposit-feeding holothurians and echinoids (Echinodermata) from a shallow back-reef lagoon, Discovery Bay, Jamaica. *Bulletin of Marine Science,* 32**,** 549-571.

Hannah, L., Duprey, N., Blackburn, J., Hand, C. M. and Pearce, C. M. 2012. Growth rate of the California sea cucumber *Parastichopus californicus*: Measurement accuracy and relationships between size and weight metrics. *North American Journal of Fisheries Management,* 32**,** 167-176. https://doi.org/10.1080/02755947.2012.663455

Hasan, M. H. 2005. Destruction of a *Holothuria scabra* population by overfishing at Abu Rhamada Island in the Red Sea. *Marine Environmental Research,* 60**,** 489-511. https://doi.org/10.1016/j.marenvres.2004.12.007

Hastie, T. and Tibshirani, R. 1987. Generalized additive models: Some applications. *Journal of the American Statistical Association,* 82**,** 371-386. https://doi.org/10.1080/01621459.1987.10478440

Hatanaka, H., Uwaoku, H. and Yasuda, T. 1994. Experimental studies on the predation of juvenile sea cucumber, *Stichopus japonicus* by sea star, *Asterina pectinifera*. *Aquaculture Science,* 42**,** 563-566. https://doi.org/10.11233/aquaculturesci1953.42.563

Hedley, J. D., Harborne, A. R. and Mumby, P. J. 2005. Technical note: Simple and robust removal of sun glint for mapping shallow-water benthos. *International Journal of Remote Sensing,* 26**,** 2107-2112. https://doi.org/10.1080/01431160500034086

Hedley, J. D., Roelfsema, C. M., Chollett, I., Harborne, A. R., Heron, S. F., Weeks, S., Skirving, W. J., Strong, A. E., Eakin, C. M., Christensen, T. R. L., Ticzon, V., Bejarano, S. and Mumby, P. J. 2016. Remote sensing of coral reefs for monitoring and management: A review. *Remote Sensing,* 8. https://doi.org/10.3390/rs8020118

Hines, A. H., Johnson, E. G., Young, A. C., Aguilar, R., Kramer, M. A., Goodison, M., Zmora, O. and Zohar, Y. 2008. Release strategies for estuarine species with complex migratory life cycles: Stock enhancement of Chesapeake blue crabs (*Callinectes sapidus*). *Reviews in Fisheries Science,* 16**,** 175-185. https://doi.org/10.1080/10641260701678090

Hossain, M. S., Bujang, J. S., Zakaria, M. H. and Hashim, M. 2015. The application of remote sensing to seagrass ecosystems: an overview and future research prospects. *International journal of remote sensing,* 36**,** 61-114. https://doi.org/10.1080/01431161.2014.990649

Hou, S., Jin, Z., Jiang, W., Chi, L., Xia, B. and Chen, J. 2019. Physiological and immunological responses of sea cucumber *Apostichopus japonicus* during desiccation and subsequent resubmersion. *PeerJ,* 7:e7427**,** 1-19. https://doi.org/10.7717/peerj.7427

Hulberg, L. W. and Oliver, J. S. 1980. Caging manipulations in marine soft-bottom communities: Importance of animal interactions or sedimentary habitat modifications. *Canadian Journal of Fisheries and Aquatic Sciences,* 37**,** 1130-1139. https://doi.org/10.1139/f80-145

Hwang, C., Chang, C. H., Kildea, T., Burch, M. and Fernandes, M. 2019. Effects of epiphytes and depth on seagrass spectral profiles: Case study of Gulf St. Vincent, South Australia. *International Journal of Environmental Research and Public Health,* 16. https://doi.org/10.3390/ijerph16152701

Hyndman, D. 1993. Sea tenure and the management of living marine resources in Papua New Guinea. *Pacific Studies,* 16**,** 99-114.

ISO 1992. Water quality, measurement of biochemical parameters; spectrometric determination of the chlorophyll-a concentration. *Water quality.* GmbH Berlin- Vien – Zürich: Beuth Verlag.

James, C. M. 2012. Sea cucumber in the Maldives. *Aquaculture Asia Pacific Magazine,* Sept-Oct**,** 43-44.

James, D. B. 1996. Culture of sea cucumber. *Bulletin of the Central Marine Fisheries Research Institute,* 48**,** 120-126.

Jayanthi, M., Thirumurthy, S., Muralidhar, M. and Ravichandran, P. 2018. Impact of shrimp aquaculture development on important ecosystems in India. *Global Environmental Change,* 52**,** 10-21. https://doi.org/10.1016/j.gloenvcha.2018.05.005

Jentoft, S. 2000. The community: a missing link of fisheries management. *Marine Policy,* 24**,** 53-60. https://doi.org/10.1016/S0308-597X(99)00009-3

Jimmy, R., Pickering, T. and Hair, C. 2012. Overview of sea cucumber aquaculture and stocking research in the Western Pacific region. *In:* Hair, C., Pickering, T. and Mills, D.J. (eds.) *Asia–Pacific tropical sea cucumber aquaculture symposium. ACIAR Proceedings 136.* Canberra: Australian Centre for International Agricultural Research, pp. 12-21.

Johannes, R. 1982. Implications of traditional marine resource use in coastal fisheries in Papua New Guinea. *In:* Mourata, L., Pernetta, J. and Heaney, W. (eds.) *Traditional Conservation in Papua New Guinea: Implications for Today.* Boroko: Institute of Applied Social and Economic Research, pp. 239-249.

Johnston, B. L. 2012. Applying economic decision tools to improve management and profitability of sandfish industries in the Asia–Pacific region. *In:* Hair, C., Pickering, T. and Mills, D. (eds.) *Asia–Pacific tropical sea cucumber aquaculture symposium. ACIAR Proceedings 136.* Canberra: Australian Centre for International Agricultural Research, pp. 205-209.

Juinio-Meñez, M. A., Pana, M. A. S., Peralta, G. M. d., Catbagan, T. O., Olavides, R. D. D., Edullantes, C. M. A. and Rodriguez, B. D. R. 2012a. Establishment and management of communal sandfish (*Holothuria scabra*) sea ranching in the Philippines. *In:* Hair, C., Pickering, T. and Mills, D. (eds.) *Asia–Pacific tropical sea cucumber aquaculture symposium. ACIAR Proceedings 136.* Canberra: Australian Centre for International Agricultural Research, pp. 121-127.

Juinio-Meñez, M. A., Peralta, G. M. d., Catbagan, T. O. and Casilagan, I. L. N. 2012b. *Sea Ranching and Restocking Sandfish (Holothuria scabra) in Asia-Pacific - Luzon Node*. ACIAR, 29 pp.

Juinio-Meñez, M. A., Peralta, G. M. d., Dumalan, R. J. P., Edullantes, C. M. A. and Catbagan, T. O. 2012c. Ocean nursery systems for scaling up juvenile sandfish (*Holothuria scabra*) production: ensuring opportunities for small fishers. *In:* Hair, C., Pickering, T. and Mills, D. (eds.) *Asia–Pacific tropical sea cucumber aquaculture symposium. ACIAR Proceedings 136.* Canberra: Australian Centre for International Agricultural Research, pp. 57-62.

Juinio-Meñez, M. A., Evangelio, J. C., Olavides, R. D. D., Pana, M. A. S., de Peralta, G. M., Edullantes, C. M. A., Rodriguez, B. D. R. and Casilagan, I. L. N. 2013. Population dynamics of cultured *Holothuria scabra* in a sea ranch: Implications for stock restoration. *Reviews in Fisheries Science,* 21**,** 424-432. https://doi.org/10.1080/10641262.2013.837282

Juinio-Meñez, M. A., Tech, E. D., Ticao, I. P., Gorospe, J. R. C., Edullantes, C. M. A. and Rioja, R. A. V. 2017. Adaptive and integrated culture production systems for the tropical sea cucumber *Holothuria scabra*. *Fisheries Research,* 186**,** 502-513. https://doi.org/10.1016/j.fishres.2016.07.017

Kailola, P. J. 1995. *Fisheries Resources Profiles: Papua New Guinea*. Honiara: Forum Fisheries Agency, 389 pp.

Kaly, U. 2005. *Small-scale-fisheries related socio-economic survey of New Ireland Province, Papua New Guinea*. Coastal Fisheries Management and Development Project and the Papua New Guinea National Fisheries Authority, 86 pp.

Kaly, U., Preston, G., Opnai, J. and Aini, J. 2007. *Sea Cucumber Survey, New Ireland Province*. Port Moresby: Coastal Fisheries Management and Development Project and the Papua New Guinea National Fisheries Authority, 37 pp.

Kapetsky, J. M. and Aguilar-Manjarrez, J. 2008. *Geographic information systems, remote sensing and mapping for the development and management of marine aquaculture*. Rome: FAO, 125 pp.

Kapetsky, J. M. and Aguilar-Manjarrez, J. 2013. From estimating global potential for aquaculture to selecting farm sites: perspectives on spatial approaches and trends. *In:* Ross, L.G., Telfer, T.C., Falconer, L., Soto, D. and Aguilar-Manjarrez, J. (eds.) *Site selection and carrying capacities for inland and coastal aquaculture.* Stirling: FAO, pp. 129-146.

Kawarazuka, N. and Béné, C. 2010. Linking small-scale fisheries and aquaculture to household nutritional security: an overview. *Food Security,* 2**,** 343-357. https://doi.org/10.1007/s12571-010-0079-y

Kennedy, G., Ballard, T. and Dop, M. 2011. *Guidelines for Measuring Household and Individual Dietary Diversity*. Rome: FAO, 53 pp.

Kinch, J. 2002. Overview of the beche-de-mer fishery in Milne Bay Province, Papua New Guinea. *SPC Beche-de-mer Information Bulletin,* 17**,** 2-16.

Kinch, J., James, M., Thomas, E., Lauhi, P. and Gabiobu, R. 2007. *Socio-economic Assessment of the Beche-de-mer Fisheries in the Western, Central and Manus Provinces, Papua New Guinea*. Port Moresby: National Fisheries Authority, 132 pp.

Kinch, J., Purcell, S., Uthicke, S. and Friedman, K. 2008a. Population status, fisheries and trade of sea cucumbers in the western central Pacific. *In:* Toral-Granda, V., Lovatelli, A. and Vasconcellos, M. (eds.) *Sea Cucumbers: A Global Review of Fisheries and Trade. FAO Fisheries Technical Paper, No. 516.* Rome, Italy: FAO, pp. 7-55.

Kinch, J., Purcell, S., Uthicke, S. and Friedman, K. 2008b. Papua New Guinea: A hot spot of sea cucumber fisheries in the western central Pacific. *In:* Toral-Granda, V., Lovatelli, A. and Vasconcellos, M. (eds.) *Sea Cucumbers: A Global Review of Fisheries and Trade. FAO Fisheries Technical Paper, No. 516.* Rome, Italy: FAO, pp. 57-77.

Kinch, J. 2020. *Changing lives and livelihoods: Culture, capitalism and contestation over marine resources in island Melanesia.* PhD Dissertation, Australian National University.

Klückow, T. 2017. Effect of biomas density, handling stress, and non-fallowing of sediment on the growth and survival of *Holothuria scabra* (abstract). *World Aquaculture Society Conference.* Capetown, South Africa.

Klückow, T., Gough, C. and Humber, F. 2017. Farming model changes and their rationale after experimental trials and seven years project history farming *Holothuria scabra* in sea pens in south-west Madagascar (abstract). *World Aquaculture Society Conference.* Cape Town, South Africa.

Krause, G., Brugere, C., Diedrich, A., Ebeling, M. W., Ferse, S. C. A., Mikkelsen, E., Pérez Agúndez, J. A., Stead, S. M., Stybel, N. and Troell, M. 2015. A revolution without people? Closing the people–policy gap in aquaculture development. *Aquaculture,* 447**,** 44-55. https://doi.org/10.1016/j.aquaculture.2015.02.009

Kristensen, E. 1990. Characterization of biogenic organic matter by stepwise thermogravimetry (STG). *Biogeochemistry,* 9**,** 135-159. https://doi.org/10.1007/BF00692169

Kronen, M., Vunisea, A., Magron, F. and McArdle, B. 2010. Socio-economic drivers and indicators for artisanal coastal fisheries in Pacific island countries and territories and their use for fisheries management strategies. *Marine Policy,* 34**,** 1135-1143. https://doi.org/10.1016/j.marpol.2010.03.013

Kropp, R. K. 1982. Responses of five holothurian species to attacks by a predatory gastropod, *Tonna perdix*. *Pacific Science,* 36**,** 445-452.

Kumara, A. and Dissanayake, C. 2017. Preliminary study on broodstock rearing, induced breeding and grow-out culture of the sea cucumber *Holothuria scabra* in Sri Lanka. *Aquaculture Research,* 48**,** 1058-1069. https://doi.org/10.1111/are.12948

Kunzmann, A., Beltran-Gutierrez, M., Fabiani, G., Namukose, M. and Msuya, F. E. 2018. Integrated seaweed – sea cucumber farming in Tanzania. *Western Indian Ocean Journal of Marine Science,* 17**,** 35-50. https://doi.org/10.4314/wiojms.v17i2.4

Laboy-Nieves, E. N. and Conde, J. E. 2006. A new approach for measuring *Holothuria mexicana* and *Isostichopus badionotus* for stock assessments. *SPC Beche-de-mer Information Bulletin,* 24**,** 39-44.

Lafrance, M., Cliche, G., Haugum, G. A. and Guderley, H. 2003. Comparison of cultured and wild sea scallops *Placopecten magellanicus*, using behavioral responses and morphometric and biochemical indices. *Marine Ecology Progress Series,* 250**,** 183-195.

Lavitra, T. 2008. *Caractérisation, contrôle et optimalisation des processus impliqués dans le développement postmétamorphique de l'holothurie comestible Holothuria scabra.* PhD Dissertation, Université de Mons-Hainaut.

Lavitra, T., Rachelle, D., Rasolofonirina, R., Jangoux, M. and Eeckhaut, I. 2008. Processing and marketing of holothurians in the Toliara region, southwestern Madagascar. *SPC Beche-de-mer Information Bulletin,* 28**,** 24-33.

Lavitra, T., Rasolofonirina, R., Jangoux, M. and Eeckhaut, I. 2009. Problems related to the farming of *Holothuria scabra* (Jaeger, 1833). *SPC Beche-de-Mer Information Bulletin***,** 20-30.

Lavitra, T., Rasolofonirina, R. and Eeckhaut, I. 2010. The effect of sediment quality and stocking density on survival and growth of the sea cucumber *Holothuria scabra* reared in nursery ponds and sea pens. *Western Indian Ocean Journal of Marine Science,* 9**,** 153-164.

Lavitra, T., Tsiresy, G., Rasolofonirina, R. and Eeckhaut, I. 2015. Effect of nurseries and size of released *Holothuria scabra* juveniles on their survival and growth. *SPC Beche-de-mer Information Bulletin,* 35**,** 37-41.

Lawless, S. and Frijlink, S. 2016. *Socioeconomic Assessment of villages in the Tigak and Tsoi Islands, Northern New Ireland Province, Papua New Guinea*. Kavieng: Wildlife Conservation Society, 37 pp.

Le Vay, L., Carvalho, G. R., Quinitio, E. T., Lebata, J. H., Ut, V. N. and Fushimi, H. 2007. Quality of hatchery-reared juveniles for marine fisheries stock enhancement. *Aquaculture,* 268**,** 169-180. https://doi.org/10.1016/j.aquaculture.2007.04.041

Lee, S. 2016. *Sedimentary response to sea cucumber (Holothuria scabra) removal.* MSc, Bremen University.

Lee, S., Ford, A., Mungubhai, S., Wild, C. and Ferse, S. 2018a. Length-weight relationship, movement rates, and in situ spawning observations of *Holothuria scabra* (sandfish) in Fiji. *SPC Beche-de-mer Information Bulletin,* 38**,** 11-14.

Lee, S., Ford, A., Mungubhai, S., Wild, C. and Ferse, S. 2018b. Effects of sandfish (*Holothuria scabra*) removal on shallow-water sediments in Fiji. *PeerJ,* 6:e4773. https://doi.org/10.7717/peerj.4773

Léopold, M., Beckensteiner, J., Kaltavara, J., Raubani, J. and Caillon, S. 2013. Community-based management of near-shore fisheries in Vanuatu: What works? *Marine Policy,* 42**,** 167-176. https://doi.org/10.1016/j.marpol.2013.02.013

Lindholm 1978. *Beche-de-mer Fishery*. Port Moresby, PNG: DFMR, 7 pp.

Lo, T. H. 2004. Valuation of sea cucumber attributes through laddering. *SPC Beche-de-mer Information Bulletin,* 20**,** 34-37.

Loh, P. S., Reeves, A. D., Harvey, S. M., Overnell, J. and Miller, A. E. J. 2008. The fate of terrestrial organic matter in two Scottish sea lochs. *Estuarine, Coastal and Shelf Science,* 76**,** 566-579. https://doi.org/10.1016/j.ecss.2007.07.023

Lokani, P. 1990. Beche-de-mer research and development in Papua New Guinea. *SPC Beche-de-mer Information Bulletin,* 2**,** 8-11.

Lokani, P. 1996a. *Management of the New Ireland Beche-de-mer fishery*. Port Moresby: NFA Research, Surveys and Assessment Branch, 6 pp.

Lokani, P. 1996b. *Fishery dynamic and biology of beche-de-mer in the Tigak islands, Papua New Guinea*. Port Moresby: PNG National Fisheries Authority, 22 pp.

Longdill, P. C., Healy, T. R. and Black, K. P. 2008. An integrated GIS approach for sustainable aquaculture management area site selection. *Ocean and Coastal Management,* 51**,** 612-624. https://doi.org/10.1016/j.ocecoaman.2008.06.010

Lorenzen, K., Leber, K. M. and Blankenship, H. L. 2010. Responsible approach to marine stock enhancement: An update. *Reviews in Fisheries Science,* 18**,** 189-210. https://doi.org/10.1080/10641262.2010.491564

Lovatelli, A., Conand, C., Purcell, S., Uthicke, S., Hamel, J.-F. and Mercier, A. 2004. Advances in sea cucumber aquaculture and management. Rome. FAO, Rome, 425 pp.

Luttrell, C. 2006. Adapting to aquaculture in Vietnam: securing livelihoods in a context of change in two coastal communities. *In:* Hoanh, C.T., Tuong, T.P., Gowing, J.W. and Hardy, B. (eds.) *Environment and livelihoods in tropical coastal zones; Managing agriculture-fishery-aquaculture conflicts.* oxford: CABI, pp. 17-29.

Lyle, J. M., Coleman, A. P. M., West, L., Campbell, D. and Henry, G. W. 2002. New Large-Scale Survey Methods for Evaluating Sport Fisheries. *In:* Pitcher, T.J. and Hollingworth, C.E. (eds.) *Recreational Fisheries: Ecological, Economic and Social Evaluation.* Oxford: Blackwell Science, pp. 207-226.

Macintyre, M. and Foale, S. 2004. Global imperatives and local desires: competing economic and environmental interests in Melanesian communities. *In:* Lockwood, V. (ed.) *Globalisation and Culture Change in the Pacific Islands.* Upper Saddle River, New Jersey: Pearson Prentice Hall, pp. 149-164.

Macintyre, M. A. and Foale, S. J. 2007. Land and marine tenure, ownership and new forms of entitlement on Lihir: Changing notions of property in the context of a goldmining project. *Human Organization,* 66**,** 49-59. https://doi.org/10.17730/humo.66.1.g81616400585qk75

Macpherson, C. B. 1962. *Possessive Individualism and Liberal Democracy. The Political Theory of Possessive Individualism,* Oxford, Clarendon Press.

Marizal, D., Jaya, Y. V. and Irawan, H. 2012. *GIS application for suitability region growing cucumbers Holothuria scabra with penculture method Mantang Island, District Mantang, Bintan*. Indonesia: Raja Ali Haji Maritime University, 8 pp.

Masaki, K., Yamaura, K., Aoto, I. and Okuma, H. 2007. Factors decreasing the discovery rates of farm-raised juveniles of sea cucumber *Apostichopus japonicus* after release into artificial reef. *Aquaculture Science,* 55**,** 347-354. https://doi.org/10.11233/aquaculturesci1953.55.347

McElroy, S. 1990. Beche-de-mer species of commercial value—an update. *SPC Beche-de-Mer Information Bulletin,* 2**,** 2-7.

McKenzie, L. J. and Campbell, S. J. 2002. *Seagrass-Watch: Manual for Community (citizen) Monitoring of Seagrass Habitat. Western Pacific Edition* Cairns: QFS, NFC, 1-43 pp.

Meaden, G. J. 2009. Geographical Information Systems (GIS) in Fisheries Management and Research. *In:* Megrey, B.A. and Moksness, E. (eds.) *Computers in Fisheries Research.* 2nd ed.: Springer, pp. 93-120.

Meaden, G. J. and Aguilar-Manjarrez, J. 2013. *Advances in Geographic Information Systems and Remote Sensing for Fisheries and Aquaculture*. Rome: Food and Agriculture Organization of the United Nations, 425 pp.

Merchant, J. W. and Narumalani, S. 2009. Integrating Remote Sensing and Geographic Information Systems. *In:* Warner, T.A., Nellis, M.D. and Foody, G.M. (eds.) *The SAGE Handbook of Remote Sensing.* SAGE Publications.

Mercier, A., Battaglene, S. C. and Hamel, J.-F. 1999. Daily burrowing cycle and feeding activity of juvenile sea cucumbers *Holothuria scabra* in response to environmental factors. *Journal of Experimental Marine Biology and Ecology,* 239**,** 125-156. https://doi.org/10.1016/s0022-0981(99)00034-9

Mercier, A., Battaglene, S. C. and Hamel, J.-F. 2000a. Settlement preferences and early migration of the tropical sea cucumber *Holothuria scabra*. *Journal of Experimental Marine Biology and Ecology,* 249**,** 89-110. https://doi.org/10.1016/s0022-0981(00)00187-8

Mercier, A., Battaglene, S. C. and Hamel, J.-F. 2000b. Periodic movement, recruitment and size-related distribution of the sea cucumber *Holothuria scabra* in Solomon Islands. *Hydrobiologia,* 440**,** 81-100. https://doi.org/10.1023/A:1004121818691

Mercier, A. and Hamel, J. F. 2013. Sea cucumber aquaculture: Hatchery production, juvenile growth and industry challenges. *In:* Allan, G. and Burnell, G. (eds.) *Advances in Aquaculture Hatchery Technology.* oxford: Woodhead Publishing, pp. 431-454.

Mezali, K. and Soualili, D. L. 2013. The ability of holothurians to select sediment particles and organic matter. *SPC Beche-de-mer Information Bulletin,* 33**,** 38-43.

Micael, J., Costa, A. C., Aguiar, P., Medeiros, A. and Calado, H. 2015. Geographic information system in a multi-criteria tool for mariculture site selection. *Coastal Management,* 43**,** 52-66. https://doi.org/10.1080/08920753.2014.985178

Militz, T. A., Leini, E., Duy, N. D. Q. and Southgate, P. C. 2018. Successful large-scale hatchery culture of sandfish (*Holothuria scabra*) using micro-algae concentrates as a larval food source. *Aquaculture Reports,* 9**,** 25-30. https://doi.org/10.1016/j.aqrep.2017.11.005

Miller, L. P. and Gaylord, B. 2007. Barriers to flow: The effects of experimental cage structures on water velocities in high-energy subtidal and intertidal environments. *Journal of Experimental Marine Biology and Ecology,* 344**,** 215-228. https://doi.org/10.1016/j.jembe.2007.01.005

Mills, D. J., Gardner, C. and Oliver, M. 2005. Survival and movement of naïve juvenile spiny lobsters returned to the wild. *Journal of Experimental Marine Biology and Ecology,* 324**,** 20-30. https://doi.org/10.1016/j.jembe.2005.04.003

Mills, D. J., Adhuri, D. S., Phillips, M. J., Ravikumar, B. and Padiyar, A. P. 2011a. Shocks, recovery trajectories and resilience among aquaculture-dependent households in post-tsunami Aceh, Indonesia. *Local Environment,* 16**,** 425-444. https://doi.org/10.1080/13549839.2011.554804

Mills, D. J., Westlund, L., de Graaf, G., Kura, Y., Willman, R. and Kelleher, K. 2011b. Under-reported and Undervalued: Small-scale Fisheries in the Developing World. *In:* Pomeroy, R.S. and Andrew, N.L. (eds.) *Small-scale Fisheries Management.* CAB International, pp. 1-15.

Mulyani, L. F., Marsoedi, M. and Guntur, G. 2017. An application of geographic information system to identify the suitability of sea cucumbers (*Holothuria scabra*) in west Lombok waters. *Journal of Indonesian Tourism and Development Studies,* 5**,** 155-160. https://doi.org/10.21776/ub.jitode.2017.005.03.03

Nath, S. S., Bolte, J. P., Ross, L. G. and Aguilar-Manjarrez, J. 2000. Applications of geographical information systems (GIS) for spatial decision support in aquaculture. *Aquacultural Engineering,* 23**,** 233-278. https://doi.org/10.1016/S0144-8609(00)00051-0

NFA 2000. *Report on the New Ireland Province Beche-de-mer Management Workshop, National Fisheries College*. Kavieng: NFA and New Ireland Province Department of Primary Industries and Fisheries, 55 pp.

NFA 2007. *A Review of Fisheries and Marine Resources in New Ireland Province, Papua New Guinea*. National Fisheries Authority and Coastal Fisheries Management and Development Project, 36 pp.

NFA 2016. *National Beche-de-mer Fishery Management Plan*. Port Moresby: National Fisheries Authority, 20 pp.

NFA 2018. *National Beche-de-mer Fishery Management Plan*. Port Moresby: National Fisheries Authority, 23 pp.

Ngaluafe, P. and Lee, J. 2013. Change in weight of sea cucumbers during processing: Ten common commercial species in Tonga. *SPC Beche-de-mer Information Bulletin,* 33**,** 3-8.

Nowland, S. J., Southgate, P. C., Basiita, R. K. and Jerry, D. R. 2017. Elucidation of fine-scale genetic structure of sandfish (*Holothuria scabra*) populations in Papua New Guinea and northern Australia. *Marine and Freshwater Research,* 68**,** 1901-1911. https://doi.org/10.1071/MF16223

Nusch, E. A. 1980. Comparison of different methods for chlorophyll and phaeopigment determination. *Archives Hydrobiolical Beih. Ergeb. Limnolology,* 14**,** 14-36.

Olavides, R. D. D., Rodriguez, B. D. R. and Juinio-Meñez, M. A. 2011. Simultaneous mass spawning of *Holothuria scabra* in sea ranching sites in Bolinao and Anda municipalities, Philippines. *SPC Beche-de-mer Information Bulletin,* 31**,** 23-24.

Oliver, M. D., Stewart, R., Mills, D., MacDiarmid, A. B. and Gardner, C. 2005. Stock enhancement of rock lobsters (*Jasus edwardsii*): timing of predation on naïve juvenile lobsters immediately after release. *New Zealand Journal of Marine and Freshwater Research,* 39**,** 391-397. https://doi.org/10.1080/00288330.2005.9517320

Oliver, M. D., MacDiarmid, A. B., Stewart, R. A. and Gardner, C. 2006. Spiny lobster population enhancement: Moderation of emergence behaviour of juvenile *Jasus edwardsii* reared in captivity. *New Zealand Journal of Marine and Freshwater Research,* 40**,** 605-613. https://doi.org/10.1080/00288330.2006.9517449

Olofsson, P., Foody, G. M., Herold, M., Stehman, S. V., Woodcock, C. E. and Wulder, M. A. 2014. Good practices for estimating area and assessing accuracy of land change. *Remote Sensing of Environment,* 148**,** 42-57. https://doi.org/10.1016/j.rse.2014.02.015

Ostrom, E. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action,* Indiana, Cambridge University Press.

Ottinger, M., Clauss, K. and Kuenzer, C. 2016. Aquaculture: Relevance, distribution, impacts and spatial assessments – A review. *Ocean and Coastal Management,* 119**,** 244-266. https://doi.org/10.1016/j.ocecoaman.2015.10.015

Otto, T. 1998. Resource Management in Lavongai and Tigak Islands: changing practices, changing identities. *In:* Wassmann, J. (ed.) *Pacific Answers to Western Hegemony: Cultural Practices of Identity Construction.* Oxford, UK: Berg, pp. 229-252.

Owen, J. R. and Kemp, D. 2017. Social management capability, human migration and the global mining industry. *Resources Policy,* 53**,** 259-266. https://doi.org/10.1016/j.resourpol.2017.06.017

Pakoa, K., Ngaluafe, P., lotoahea, T., Matoto, S. V. and Bertram, I. 2013. *The status of Tonga's sea cucumber fishery, including an update on Vava'u and Tongatapu*. Noumea: Secretariat of the Pacific Community and Tonga Ministry of Agriculture and Food, Forests and Fisheries, 35 pp.

Pakoa, K., M., Bertram, I., Friedman, K. and Tardy, E. 2012. Sandfish (*Holothuria scabra*) fisheries in the Pacific region: present status, management overview and outlook for rehabilitation. *In:* Hair, C., Pickering, T. and Mills, D. (eds.) *Asia–Pacific tropical sea cucumber aquaculture symposium. ACIAR Proceedings 136.* Canberra: Australian Centre for International Agricultural Research, pp. 168-176.

Palomar-Abesamis, N., Juinio-Meñez, M. A. and Slater, M. J. 2017. Effects of light and microhabitat on activity pattern and behaviour of wild and hatchery-reared juveniles of *Stichopus* cf. *horrens*. *Journal of the Marine Biological Association of the United Kingdom,* 98**,** 1703-1713. https://doi.org/10.1017/S0025315417000972

Pardua, S. N., Lapitan, E. L. O., Deanon, J., Duque, J. A. C., Pangan, R. S. and Yaptenco, K. F. 2018. Product recovery after processing and drying of Philippine sandfish (*Holothuria scabra*) into trepang. *Philippine Journal of Agricultural and Biosystems Engineering,* 14**,** 31-44.

Parkes, L., Quinitio, E. and Le Vay, L. 2011. Phenotypic differences between hatchery-reared and wild mud crabs, *Scylla serrata*, and the effects of conditioning. *Aquaculture International,* 19**,** 361-380.

Pascal, B. and Robinson, G. 2011. *Handbook for Sandfish Farming*. Madagascar: Regional Programme for the Sustainable Management of the Coastal Zones of the Countries of the Indian Ocean (ReCoMaP). 29 pp.

Pauly, D. 1995. Anecdotes and the shifting baseline syndrome of fisheries. *Trends in Ecology & Evolution,* 10**,** 430. https://doi.org/10.1016/S0169-5347(00)89171-5

Pe'eri, S., Morrison, J. R., Short, F., Methieson, A. and Lippmann, T. 2016. Eelgrass and macroalgal mapping to develop nutrient criteria in New Hampshire's estuaries using hyperspectral imagery. *Journal of Coastal Research,* 76**,** 209-218. https://doi.org/10.2112/SI76-018

Perez, O. M., Telfer, T. C. and Ross, L. G. 2005. Geographical information systems-based models for offshore floating marine fish cage aquaculture site selection in Tenerife, Canary Islands. *Aquaculture Research,* 36**,** 946-961. https://doi.org/10.1111/j.1365-2109.2005.01282.x

Phinn, S. R., Roelfsema, C. M. and Mumby, P. J. 2012. Multi-scale, object-based image analysis for mapping geomorphic and ecological zones on coral reefs. *International Journal of Remote Sensing,* 33**,** 3768-3797. 10.1080/01431161.2011.633122

Pitt, R. and Duy, N. D. Q. 2004. Breeding and rearing of the sea cucumber *Holothuria scabra* in Viet Nam. *In:* Lovatelli, A., Conand, C., Purcell, S., Uthicke, S., Hamel, J.F. and Mercier, A. (eds.) *Advances in sea cucumber aquaculture and management. FAO Fisheries Technical Paper No. 463.* Rome, Italy: FAO, pp. 333-346.

Plotieau, T., Baele, J.-M., Vaucher, R., Hasler, C. A., Koudad, D. and Eeckhaut, I. 2013. Analysis of the impact of *Holothuria scabra* intensive farming on sediment. *Cahiers de Biologie Marine,* 54**,** 703-711.

Plotieau, T., Lepoint, G., Baele, J.-M., Tsiresy, G., Rasolofonirina, R., Lavitra, T. and Eeckhaut, I. 2014a. Mineral and organic features of the sediment in the farming sea pens of *Holothuria scabra* (Holothuroidea, Echinodermata). *SPC Beche-de-mer Information Bulletin,* 34**,** 29-33.

Plotieau, T., Lepoint, G., Lavitra, T. and Eeckhaut, I. 2014b. Isotopic tracing of sediment components assimilated by epibiontic juveniles of *Holothuria scabra* (Holothuroidea). *Journal of the Marine Biological Association of the United Kingdom,* 94**,** 1485-1490. https://doi.org/10.1017/S0025315414000502

Polon, P. 2004. The Papua New Guinea national beche-de-mer fishery management plan. *In:* Lovatelli, A., Conand, C., Purcell, S., Uthicke, S., Hamel, J.F. and Mercier, A. (eds.) *Advances in sea cucumber aquaculture and management. FAO Fisheries Technical Paper No. 463.* Rome, Italy: FAO, pp. 205-219.

Polunin, N. 1984. Do traditional marine "reserves" conserve? A view of Indonesian and New Guinean evidence. *In:* Ruddle, K. and Akimichi, T. (eds.) *Maritime Institutions in the Western Pacific.* Osaka: National Museum of Ethnology, pp. 267-283.

Pomeroy, R. S., Parks, J. E. and Balboa, C. M. 2006. Farming the reef: is aquaculture a solution for reducing fishing pressure on coral reefs? *Marine Policy,* 30**,** 111-130. https://doi.org/10.1016/j.marpol.2004.09.001

Powers, M., Begg, Z., Smith, G. and Miles, E. 2019. Lessons From the Pacific Ocean portal: Building Pacific Island capacity to interpret, apply, and communicate ocean information. *Frontiers in Marine Science,* 6. https://doi.org/10.3389/fmars.2019.00476

Prescott, J., Zhou, S. and Prasetyo, A. P. 2015. Soft bodies make estimation hard: correlations among body dimensions and weights of multiple species of sea cucumbers. *Marine and Freshwater Research,* 66**,** 857-865. https://doi.org/10.1071/MF14146

Preston, G. L. 1992. Study of the Aitutaki trochus fishery. *SPC Trochus Information Bulletin,* 1**,** 10-12.

Preston, G. L. 1993. Beche-de-mer. *In:* Wright, A. and Hill, L. (eds.) *Nearshore Marine Resources of the South Pacific.* Honiara: IPS, FFA and ICOD, pp. 371-407.

Purcell, S., Blockmans, B. and Agudo, N. 2006a. Transportation methods for restocking of juvenile sea cucumber, *Holothuria scabra*. *Aquaculture,* 251**,** 238-244. https://doi.org/10.1016/j.aquaculture.2005.04.078

Purcell, S., Blockmans, B. and Nash, W. 2006b. Efficacy of chemical markers and physical tags for large-scale release of an exploited holothurian. *Journal of Experimental Marine Biology and Ecology,* 334**,** 283-293. https://doi.org/10.1016/j.jembe.2006.02.007

Purcell, S., Gossuin, H. and Agudo, N. 2009. Changes in weight and length of sea cucumbers during conversion to processed beche-de-mer: Filling gaps for some exploited tropical species. *SPC Beche-de-mer Information Bulletin,* 29**,** 3-6.

Purcell, S. 2010a. *Managing sea cucumber fisheries with an ecosystem approach*. Rome: Food and Agriculture Organization of the United Nations, 157 pp.

Purcell, S. 2012. Principles and science of stocking marine areas with sea cucumbers. *In:* Hair, C., Pickering, T. and Mills, D. (eds.) *Asia–Pacific tropical sea cucumber aquaculture symposium. ACIAR Proceedings 136.* Canberra: Australian Centre for International Agricultural Research, pp. 92-103.

Purcell, S. and Duy, N. D. Q. 2012. Processing cultured tropical sea cucumbers into export product: Issues and opportunities (abstract). *In:* Hair, C., Pickering, T. and Mills, D. (eds.) *Asia–Pacific tropical sea cucumber aquaculture symposium. ACIAR Proceedings 136.* Canberra: Australian Centre for International Agricultural Research, pp. 195.

Purcell, S., Samyn, Y. and Conand, C. 2012a. Commercially Important Sea Cucumbers of the World. *FAO Species Catalogue for Fishery Purposes No. 6.*

Purcell, S., Choo, P. S., Akamine, J. and Fabinyi, M. 2014a. Alternative product forms, consumer packaging and extracted derivatives of tropical sea cucumbers. *SPC Beche-de-mer Information Bulletin,* 34**,** 47-52.

Purcell, S., Ngaluafe, P., Foale, S., Cocks, N., Cullis, B. and Lavavanua, W. 2016a. Multiple factors affect socioeconomics and wellbeing of artisanal sea cucumber fishers. *PLoS ONE,* 11(12): e0165633. https://doi.org/10.1371/journal.pone.0165633

Purcell, S., Crona, B., Lalavanua, W. and Eriksson, B. H. 2017. Distribution of economic returns in small-scale fisheries for international markets: A value-chain analysis. *Marine Policy,* 86**,** 9-16. https://doi.org/10.1016/j.marpol.2017.09.001

Purcell, S. and Wu, M. 2017. Large-scale sandfish (*Holothuria scabra*) aquaculture in multitrophic polyculture ponds in southern China. *SPC Beche-de-mer Information Bulletin,* 37.

Purcell, S. W. 2004. Criteria for release strategies and evaluating the restocking of sea cucumbers. *In:* Lovatelli, A., Conand, C., Purcell, S., Uthicke, S., Hamel, J.F. and Mercier, A. (eds.) *Advances in sea cucumber aquaculture and management. FAO Fisheries Technical Paper No. 463.* Rome, Italy: FAO, pp. 181-191.

Purcell, S. W. and Kirby, D. S. 2006. Restocking the sea cucumber *Holothuria scabra*: Sizing no-take zones through individual-based movement modelling. *Fisheries Research,* 80**,** 53-61. https://doi.org/10.1016/j.fishres.2006.03.020

Purcell, S. W. and Simutoga, M. 2008. Spatio-temporal and size-dependent variation in the success of releasing cultured sea cucumbers in the wild. *Reviews in Fisheries Science,* 16**,** 204-214. https://doi.org/10.1080/10641260701686895

Purcell, S. W. and Blockmans, B. F. 2009. Effective fluorochrome marking of juvenile sea cucumbers for sea ranching and restocking. *Aquaculture,* 296**,** 263-270. https://doi.org/10.1016/j.aquaculture.2009.08.027

Purcell, S. W. 2010b. Diel burying by the tropical sea cucumber *Holothuria scabra*: effects of environmental stimuli, handling and ontogeny. *Marine Biology,* 157**,** 663-671. https://doi.org/10.1007/s00227-009-1351-6

Purcell, S. W., Hair, C. A. and Mills, D. J. 2012b. Sea cucumber culture, farming and sea ranching in the tropics: Progress, problems and opportunities. *Aquaculture,* 368–369**,** 68-81. https://doi.org/10.1016/j.aquaculture.2012.08.053

Purcell, S. W., Mercier, A., Conand, C., Hamel, J.-F., Toral-Granda, M. V., Lovatelli, A. and Uthicke, S. 2013. Sea cucumber fisheries: Global analysis of stocks, management measures and drivers of overfishing. *Fish and Fisheries,* 14**,** 34-59. https://doi.org/10.1111/j.1467-2979.2011.00443.x

Purcell, S. W. 2014a. *Processing sea cucumbers into beche-de-mer: a manual for Pacific Island fishers*. New Zealand: Southern Cross University and the Secretariat of the Pacific Community, 44 pp.

Purcell, S. W. 2014b. Value, market preferences and trade of beche-de-mer from Pacific Island sea cucumbers. *PLoS ONE* 9(4): e95075. https://doi.org/10.1371/journal.pone.0095075

Purcell, S. W., Lovatelli, A. and Pakoa, K. 2014b. Constraints and solutions for managing Pacific Island sea cucumber fisheries with an ecosystem approach. *Marine Policy,* 45**,** 240-250. https://doi.org/10.1016/j.marpol.2013.11.005

Purcell, S. W., Conand, C., Uthicke, S. and Byrne, M. 2016b. Ecological roles of exploited sea cucumbers. *Oceanography and Marine Biology: An Annual Review,* 54**,** 367-386.

Purcell, S. W., Ngaluafe, P., Aram, K. T. and Lavavanua, W. 2016c. Variation in postharvest processing of sea cucumbers by fishers and commercial processors on three Pacific Islands. *SPC Beche-de-mer Information Bulletin,* 36**,** 58-66.

Purcell, S. W., Lalavanua, W., Cullis, B. R. and Cocks, N. 2018a. Small-scale fishing income and fuel consumption: Fiji's artisanal sea cucumber fishery. *ICES Journal of Marine Science***,** 1-10. https://doi.org/10.1093/icesjms/fsy036

Purcell, S. W., Williamson, D. H. and Ngaluafe, P. 2018b. Chinese market prices of beche-de-mer: Implications for fisheries and aquaculture. *Marine Policy,* 91**,** 58-65. https://doi.org/10.1016/j.marpol.2018.02.005

Purdy, D. H., Hadley, D. J., Kenter, J. O. and Kinch, J. 2017. Sea cucumber moratorium and livelihood diversity in Papua New Guinea. *Coastal Management,* 45**,** 161-177. https://doi.org/10.1080/08920753.2017.1278147

Purkis, S. J., Gleason, A. C. R., Purkis, C. R. and Dempsey, A. C. 2019. High-resolution habitat and bathymetry maps for 65,000 sq. km of Earth's remotest coral reefs. *Coral reefs,* 38**,** 467-488. https://doi.org/10.1007/s00338-019-01802-y

Qinzeng, X., Libin, Z., Xuelei, Z., Yi, Z. and Hongsheng, Y. 2016. Release size and stocking density for grow-out of *Apostichopus japonicus* in the sea with raft-cultured macroalgae. *Aquaculture International,* 24**,** 1141-1152. https://doi.org/10.1007/s10499-016-9976-1

Radiarta, I. N., Saitoh, S. I. and Miyazono, A. 2008. GIS-based multi-criteria evaluation models for identifying suitable sites for Japanese scallop (*Mizuhopecten yessoensis*) aquaculture in Funka Bay, southwestern Hokkaido, Japan. *Aquaculture,* 284**,** 127-135. https://doi.org/10.1016/j.aquaculture.2008.07.048

Radiarta, I. N. and Saitoh, S.-i. 2009. Biophysical models for Japanese scallop, *Mizuhopecten yessoensis*, aquaculture site selection in Funka Bay, Hokkaido, Japan, using remotely sensed data and geographic information system. *Aquaculture International,* 17**,** 403-419. https://doi.org/10.1007/s10499-008-9212-8

Radiarta, I. N., Saitoh, S. I. and Yasui, H. 2011. Aquaculture site selection for Japanese kelp *(Laminaria japonica*) in southern Hokkaido, Japan, using satellite remote sensing and GIS-based models. *ICES Journal of Marine Science,* 68**,** 773-780. https://doi.org/10.1093/icesjms/fsq163

Raison, C. M. 2008. Advances in sea cucumber aquaculture and prospects for commercial culture of *Holothuria scabra*. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources,* 3**,** 1-15. https://doi.org/10.1079/PAVSNNR20083082

Ram, R., Chand, R. V. and Southgate, P. C. 2014. Effects of processing methods on the value of bêche-de-mer from the Fiji Islands *Journal of Marine Science Research and Development* 4**,** 1-7. https://doi.org/10.4172/2155-9910.1000152

Ram, R. and Southgate, P. C. 2014. The influence of processing techniques on the quality and nutritional composition of tropical sea cucumbers. *SPC Fisheries Newsletter,* 143**,** 17-18.

Ram, R., Chand, R. V. and Southgate, P. C. 2016a. An overview of sea cucumber fishery management in the Fiji Islands. *Journal of Fisheries and Aquatic Science,* 11**,** 191-205. https://doi.org/10.3923/jfas.2016.191.205

Ram, R., Chand, R. V., Zeng, C. and Southgate, P. C. 2016b. Recovery rates for eight commercial sea cucumber species from the Fiji Islands. *Regional Studies in Marine Science,* 8**,** 59-64. https://doi.org/10.1016/j.rsma.2016.09.003

Ram, R. 2018. *Influence of processing techniques on quality and nutritional composition of the tropical sea cucumber Holothuria scabra.* PhD, James Cook University

Ramofafia, C. 2004. *The sea cucumber fisheries in Solomon Islands: benefits and importance to coastal communities*. Solomon Islands: WorldFish Center, 1-10 pp.

Rasmussen, A. E. 2015. *In the Absence of the Gift: New Forms of Value and Personhood in a Papua New Guinea Community,* New York & Oxford, Berghahn Books.

Ren, C., Wang, Z., Zhang, B., Li, L., Chen, L., Song, K. and Jia, M. 2018. Remote monitoring of expansion of aquaculture ponds along coastal region of the Yellow River Delta from 1983 to 2015. *Chinese Geographical Science,* 28**,** 430-442. https://doi.org/10.1007/s11769-017-0926-2

Robinson, G. and Pascal, B. 2009. From hatchery to community – Madagascar's first village-based holothurian mariculture programme. *SPC Beche-de-mer Information Bulletin,* 29**,** 38-43.

Robinson, G. and Pascal, B. 2012. Sea cucumber farming experiences in south-western Madagascar. *In:* Hair, C., Pickering, T. and Mills, D. (eds.) *Asia–Pacific tropical sea cucumber aquaculture symposium. ACIAR Proceedings 136.* Canberra: Australian Centre for International Agricultural Research, pp. 142-155.

Robinson, G. 2013. A bright future for sandfish aquaculture. *World Aquaculture,* 44**,** 19-24.

Robinson, G., Slater, M. J., Jones, C. L. W. and Stead, S. M. 2013. Role of sand as substrate and dietary component for juvenile sea cucumber *Holothuria scabra*. *Aquaculture,* 392-395**,** 23-25. https://doi.org/10.1016/j.aquaculture.2013.01.036

Robinson, G., Caldwell, G. S., Jones, C. L. W., Slater, M. J. and Stead, S. M. 2015. Redox stratification drives enhanced growth in a deposit-feeding invertebrate: implications for aquaculture bioremediation. *Aquaculture Environment Interactions,* 8**,** 1-13. https://doi.org/10.3354/aei00158

Robinson, G., Caldwell, G. S., Jones, C. L. W. and Stead, S. M. 2019. The effect of resource quality on the growth of *Holothuria scabra* during aquaculture waste bioremediation. *Aquaculture,* 499**,** 101-108. https://doi.org/10.1016/j.aquaculture.2018.09.024

Rougier, A., Ateweberhan, M. and Harris, A. 2013. Strategies for improving survivorship of hatchery-reared juvenile *Holothuria scabra* in community-managed sea cucumber farms. *SPC Beche-de-mer Information Bulletin,* 33**,** 14-22.

Rouse, J. W., Haas, R. H., Schell, J. A. and Deering, D. W. 1973. Monitoring vegetation systems in the Great Plains with ERTS. *Proceedings of the Third ERTS Symposium.* Washington, pp. 309-317.

Ru, X., Zhang, L., Li, X., Liu, S. and Yang, H. 2019. Development strategies for the sea cucumber industry in China. *Journal of Oceanology and Limnology,* 37**,** 300-312. https://doi.org/10.1007/s00343-019-7344-5

Ruddle, K., Hviding, E. and Johannes, R. 1992. Marine resources management in the context of customary tenure. *Marine Resource Economics,* 7**,** 249-273. https://doi.org/10.1086/mre.7.4.42629038

Ruddle, K. 1993. External forces and change in traditional community-based fishery management systems in the Asia-Pacific region. *Maritime Anthropological Studies,* 6**,** 1-37.

Saito, M., Kunisaki, N., Urano, N. and Kimura, S. 2002. Collagen as the major edible component of sea cucumber (*Stichopus japonicus*). *Journal of Food Science,* 67**,** 1319-1322. https://doi.org/10.1111/j.1365-2621.2002.tb10281.x

Salam, M. A., Ross, L. G. and Beveridge, C. M. M. 2003. A comparison of development opportunities for crab and shrimp aquaculture in southwestern Bangladesh, using GIS modelling. *Aquaculture,* 220**,** 477-494. https://doi.org/10.1016/S0044-8486(02)00619-1

Salayo, N. D., Perez, M. L., Garces, L. R. and Pido, M. D. 2012. Mariculture development and livelihood diversification in the Philippines. *Marine Policy,* 36**,** 867-881. https://doi.org/10.1016/j.marpol.2011.12.003

Saweri, W. 2001. The rocky road from roots to rice: a review of the changing food and nutrition situation in Papua New Guinea. *PNG Medical Journal,* 44**,** 151-163.

Schneider, K., Silverman, J., Woolsey, E., Eriksson, H., Byrne, M. and Caldeira, K. 2011. Potential influence of sea cucumbers on coral reef $CaCO_3$ budget: A case study at One Tree Reef. *Journal of Geophysical Research,* 116**,** 1-6. https://doi.org/10.1029/2011jg001755

Schoeffel, P. 1997. Myths of community management: sustainability, the state and rural development in Papua New Guinea, Solomon Islands and Vanuatu. *State, Society and Governance in Melanesia Discussion Paper,* 97**,** 1-10.

Schwerdtner Máñez, K. and Ferse, S. C. A. 2010. The history of Makassan trepang fishing and trade. *PLoS ONE,* 5**,** e11346. https://doi.org/10.1371/journal.pone.0011346

Sewell, M. A. 1991. Measurement of size in live sea cucumbers. *SPC Beche-de-mer Information Bulletin,* 3**,** 4-5.

Shelley, C. C. 1981. *Aspects of the distribution, growth and 'fishery' potential of holothurians (beche-de-mer) in the Papuan Coastal Lagoon.* MSc, University of Papua New Guinea.

Shelley, C. C. 1985. Growth of *Actinopyga echinites* and *Holothuria scabra* (Holothurioidea: Echinodermata) and their fisheries potential (as beche-de-mer) in Papua New Guinea. Tahiti, French Polynesia. 297-302 pp.

Shiell, G. 2004. Field observations of juvenile sea cucumbers. *SPC Beche-de-mer Information Bulletin,* 20**,** 6-11.

Sievanen, L., Crawford, B., Pollnac, R. and Lowe, C. 2005. Weeding through assumptions of livelihood approaches in ICM: Seaweed farming in the Philippines and Indonesia. *Ocean and Coastal Management,* 48**,** 297-313. https://doi.org/10.1016/j.ocecoaman.2005.04.015

Silva, C., Ferreira, J. G., Bricker, S. B., DelValls, T. A., Martín-Díaz, M. L. and Yáñez, E. 2011. Site selection for shellfish aquaculture by means of GIS and farm-scale models, with an emphasis on data-poor environments. *Aquaculture,* 318**,** 444-457. https://doi.org/10.1016/j.aquaculture.2011.05.033

Simms, A. 2002. GIS and aquaculture: Assessment of soft-shell clam sites. *Journal of Coastal Conservation,* 8**,** 35-47.

Skewes, T., Dennis, D. and Burridge, C. 2000. *Survey of Holothuria scabra (sandfish) on Warrior Reef, Torres Strait, in January 2000*. Brisbane: CSIRO Division of Marine Research, 28 pp.

Skewes, T., Kinch, J., Polon, P., Dennis, D., Seeto, P., Taranto, T., Lokani, P., Wassenberg, T., Koutsoukos, A. and Sarke, J. 2002. *Research for the sustainable use of beche-de-mer resources in the Milne Bay Province, Papua New Guinea.* Cleveland: CSIRO Division of Marine Research, 40 pp.

Skewes, T., Smith, L., Dennis, D., Rawlinson, N., Donovan, A. and Ellis, N. 2004. *Conversion ratios for commercial beche-de-mer species in Torres Strait*. CSIRO Marine Research, Australian Maritime College, 32 pp.

Slater, M. J. and Jeffs, A. G. 2010. Do benthic sediment characteristics explain the distribution of juveniles of the deposit-feeding sea cucumber *Australostichopus mollis*? *Journal of Sea Research,* 64**,** 241-249. https://doi.org/10.1016/j.seares.2010.03.005

Slater, M. J., Mgaya, Y. D., Mill, A. C., Rushton, S. P. and Stead, S. M. 2013. Effect of social and economic drivers on choosing aquaculture as a coastal livelihood. *Ocean and Coastal Management,* 73**,** 22-30. https://doi.org/10.1016/j.ocecoaman.2012.12.002

Sloan, N. A. and von Bodungen, B. 1980. Distribution and feeding of the sea cucumber *Isostichopus badionotus* in relation to shelter and sediment criteria of the Bermuda Platform. *Marine Ecology Progress Series,* 2**,** 257-264. https://doi.org/10.3354/meps002257

Smith, R. E. 2018. Changing Standards of Living: The Paradoxes of Building a Good Life in Rural Vanuatu. *In:* Gregory, C. and Altman, J. (eds.) *The Quest for the Good Life in Precarious Times: Informal, Ethnographic Perspectives on the Domestic Moral Economy,*. Canberra: ANU Press, pp. 33-55.

Snyder, J., Boss, E., Weatherbee, R., Thomas, A. C., Brady, D. and Newell, C. 2017. Oyster aquaculture site selection using Landsat 8-derived sea surface temperature, turbidity, and chlorophyll a. *Frontiers in Marine Science,* 4. https://doi.org/10.3389/fmars.2017.00190

Southgate, P. C., Wani, J. A. and Garcia Gomez, R. 2012. Promoting sustainable mariculture in Papua New Guinea. *SPC Fisheries Newsletter,* 139**,** 20-21.

Southgate, P. C. and Lucas, J. S. 2019. Principles of Aquaculture. *In:* Lucas, J.S., Southgate, P.C. and Tucker, C. (eds.) *Aquaculture: Farming Aquatic Animals and Plants.* Third Edition ed. Chichester: John Wiley & Sons Ltd, pp. 19-39.

Steenbergen, D., Marlessy, C. and Holle, E. 2017a. Effects of rapid livelihood transitions: Examining local co-developed change following a seaweed farming boom. *Marine Policy,* 82**,** 216-223. https://doi.org/10.1016/j.marpol.2017.03.026

Steenbergen, D. J., Clifton, J., Visser, L. E., Stacey, N. and McWilliam, A. 2017b. Understanding influences in policy landscapes for sustainable coastal livelihoods. *Marine Policy,* 82**,** 181-188. https://doi.org/10.1016/j.marpol.2017.04.012

Stelzenmüller, V., Gimpel, A., Gopnik, M. and Gee, K. 2017. Aquaculture Site-Selection and Marine Spatial Planning: The Roles of GIS-Based Tools and Models. *In:* Buck, B.H. and Langan, R. (eds.) *Aquaculture Perspective of Multi-Use Sites in the Open Ocean: The Untapped Potential for Marine Resources in the Anthropocene.* Cham: Springer International Publishing, pp. 131-148.

Stevenson, J. R. and Irz, X. 2009. Is aquaculture development an effective tool for poverty alleviation? A review of theory and evidence. *Cahiers Agricultures,* 18**,** 292-299. https://doi.org/10.1684/agr.2009.0286

Stuart, V., Platt, T. and Sathyendranath, S. 2011. The future of fisheries science in management: A remote-sensing perspective. *ICES Journal of Marine Science,* 68**,** 644-650. https://doi.org/10.1093/icesjms/fsq200

Stumpf, R. P., Holderied, K. and Sinclair, M. 2003. Determination of water depth with high-resolution satellite imagery over variable bottom types. *Limnology and Oceanography,* 48**,** 547-556. https://doi.org/10.4319/lo.2003.48.1_part_2.0547

Sulistyo, B., Purnama, D., Anggraini, M., Hartono, D., Wilopo, M. D., Wulandari, U. and Listyaningrum, N. 2018. Refining suitability modelling for sea cucumber (*Holothuria scabra*) using fully raster-based data. *Forum Geografi,* 32**,** 119-130. https://doi.org/10.23917/forgeo.v32i2.6662

Sulu, R. J., Eriksson, B. H., Schwarz, A.-M., Andrew, N. L., Orirana, G., Sukulu, M., Oeta, J., Harohau, D., Sibiti, S., Toritela, A. and Beare, D. 2015. Livelihoods and fisheries governance in a contemporary Pacific Island setting. *PLoS ONE,* 10**,** 1-23. https://doi.org/10.1371/journal.pone.0143516

Tamori, M., Takemae, C. and Motokawa, T. 2010. Evidence that water exudes when holothurian connective tissue stiffens. *The Journal of Experimental Biology,* 213**,** 1960-1966. https://doi.org/10.1242/jeb.038505

Tan, J., Sun, X., Gao, F., Sun, H., Chen, A., Gai, C. and Yan, J. 2016. Immune responses of the sea cucumber *Apostichopus japonicus* to stress in two different transport systems. *Aquaculture Research,* 47**,** 2114-2122. https://doi.org/10.1111/are.12665

Tanaka, M. 2000. Diminution of sea cucumber *Stichopus japonicus* juveniles released on artificial reefs. *Bulletin of Ishikawa Prefecture Fisheries Research Center,* 2**,** 19-29.

Taylor, A. 2016. A modified method for processing fluorescently marked sea cucumber ossicles. *SPC Beche-de-mer Information Bulletin,* 36**,** 54-57.

Taylor, A. L., Nowland, S. J., Hearnden, M. N., Hair, C. A. and Fleming, A. E. 2016. Sea ranching release techniques for cultured sea cucumber *Holothuria scabra* (Echinodermata: Holothuroidea) juveniles within the high-energy marine environments of northern Australia. *Aquaculture,* 465**,** 109-116. https://doi.org/10.1016/j.aquaculture.2016.08.031

Taylor, M. D., Chick, R. C., Lorenzen, K., Agnalt, A. L., Leber, K. M., Blankenship, H. L., Haegen, G. V. and Loneragan, N. R. 2017. Fisheries enhancement and restoration in a changing world. *Fisheries Research,* 186**,** 407-412. https://doi.org/10.1016/j.fishres.2016.10.004

Teixeira, J. B., Martins, A. S., Pinheiro, H. T., Secchin, N. A., Leão de Moura, R. and Bastos, A. C. 2013. Traditional ecological knowledge and the mapping of benthic marine habitats. *Journal of Environmental Management,* 115**,** 241-250. https://doi.org/10.1016/j.jenvman.2012.11.020

Torell, E., Crawford, B., Kotowicz, D., Herrera, M. D. and Tobey, J. 2010. Moderating our expectations on livelihoods in ICM: Experiences from Thailand, Nicaragua, and Tanzania. *Coastal Management,* 38**,** 216-237. https://doi.org/10.1080/08920753.2010.483166

Tsiresy, G., Pascal, B. and Plotieau, T. 2011. An assessment of *Holothuria scabra* growth in marine micro-farms in southwestern Madagascar. *SPC Beche-de-mer Information Bulletin,* 31**,** 17-22.

Tuwo, A., Yasir, I., Tresnati, J., Aprianto, R., Yanti, A., Bestari, A. D., Syafiuddin, M. and Nakajima, M. 2019. Evisceration rate of sandfish *Holothuria scabra* during transportation. *IOP Conf. Series: Earth and Environmental Science,* 370**,** 1-10. https://doi.org/10.1088/1755-1315/370/1/012039

Uekusa, R., Yoshida, N., Kashio, S., Tokaji, H., Asami, A., Nakahara, K. and Goshima, S. 2012. Low discovery rate of sea cucumber *Apostichopus japonicus* juveniles after seed release in the field *Bulletin of Fisheries Sciences Hokkaido University,* 62**,** 43-49.

Uthicke, S. 1999. Sediment bioturbation and impact of feeding activity of *Holothuria* (*Halodeima*) *atra* and *Stichopus chloronotus*, two sediment feeding holothurians, at Lizard Island, Great Barrier Reef. *Bulletin of Marine Science,* 64**,** 129-141.

Uthicke, S. and Purcell, S. 2004. Preservation of genetic diversity in restocking of the sea cucumber *Holothuria scabra* investigated by allozyme electrophoresis. *Canadian Journal of Fisheries and Aquatic Sciences,* 61**,** 519-528. https://doi.org/10.1139/f04-013

Uthicke, S., Schaffelke, B. and Byrne, M. 2009. A boom–bust phylum? Ecological and evolutionary consequences of density variations in echinoderms. *Ecological Monographs,* 79**,** 3-24. https://doi.org/10.1890/07-2136.1

van der Meeren, G. I. 1991. Out-of-water transportation effects on behaviour in newly released juvenile Atlantic lobsters *Homarus gammarus*. *Aquacultural Engineering,* 10**,** 55-64. https://doi.org/10.1016/0144-8609(91)90010-H

van Eys, S. 1986. *The market for sea cucumber from the Pacific Islands*. 14 pp.

Verfaillie, E., Degraer, S., Schelfaut, K., Willems, W. and Van Lancker, V. 2009. A protocol for classifying ecologically relevant marine zones, a statistical approach. *Estuarine, Coastal and Shelf Science,* 83**,** 175-185. https://doi.org/10.1016/j.ecss.2009.03.003

Vieira, S., Kinch, J., White, W. and Yaman, L. 2017. Artisanal shark fishing in the Louisiade Archipelago, Papua New Guinea: Socio-economic characteristics and management options. *Ocean and Coastal Management,* 137**,** 43-56. https://doi.org/10.1016/j.ocecoaman.2016.12.009

Vincenzi, S., Caramori, G., Rossi, R. and Leo, G. A. D. 2006. A GIS-based habitat suitability model for commercial yield estimation of *Tapes philippinarum* in a Mediterranean coastal lagoon (Sacca di Goro, Italy). *Ecological Modelling,* 193**,** 90-104. https://doi.org/10.1016/j.ecolmodel.2005.07.039

von Essen, L.-M., Ferse, S. C. A., Glaser, M. and Kunzmann, A. 2013. Attitudes and perceptions of villagers toward community-based mariculture in Minahasa, North Sulawesi, Indonesia. *Ocean and Coastal Management,* 73**,** 101-112. https://doi.org/10.1016/j.ocecoaman.2012.12.012

Wagner, J. 2007. Conservation as development in Papua New Guinea: The view from Blue Mountain. *Human Organization,* 66**,** 28-37. https://doi.org/10.17730/humo.66.1.q21q23v06t374204

Wang, J. Q., Jin, X. M. and Zhang, J. C. 2007. Effect of density and water temperature on survival and evisceration of juvenile sea cucumber (A*postichopus japonicus*) in the process of transportation. *Journal of Modern Fisheries Information,* 22**,** 3-5.

Wang, Z., Liu, Q., Cao, R. and Yin, B. 2012. Comparative analysis of nutritive composition between wild and cultured sea cucumber *Apostichopus japonicas*. *South China Fisheries Science,* 8**,** 64-70.

Ward, R. G. 1972. The Pacific beche-de-mer trade with special reference to Fiji. *In:* Ward, R.G. (ed.) *Man in the Pacific Islands : Essays on Geographical Change in the Pacific Islands.* Oxford: Oxford University Press, pp. 91-123.

WCS 2016a. *Limanak Fisheries Management Plan: An Agreement by the Community Members of Limanak*. Kavieng: Wildlife Conservation Society, 25 pp.

WCS 2016b. *Ungakum Marine Resources Management Plan: An Agreement by the Community Members of Ungakum*. Kavieng: Wildlife Conservation Society, 23 pp.

Wiedemeyer, W. L. 1992. Feeding behavior of two tropical holothurians *Holothuria* (*Metriatyla*) *scabra* (Jager 1833) and *H.* (*Halodeima*) *atra* (Jager 1833), from Okinawa, Japan. *Proceedings of the 7th International Coral Reef Symposium, Guam,* 2**,** 853-860.

Wilkie, I. C. 2002. Is muscle involved in the mechanical adaptability of echinoderm mutable collagenous tissue? *The Journal of Experimental Biology,* 205**,** 159-165.

Wolkenhauer, S.-M. 2008. Burying and feeding activity of adult *Holothuria scabra* (Echinodermata: Holothuroidea) in a controlled environment. *SPC Beche-de-mer Information Bulletin,* 27**,** 25-28.

Wolkenhauer, S.-M., Uthicke, S., Burridge, C., Skewes, T. and Pitcher, R. 2010. The ecological role of *Holothuria scabra* (Echinodermata: Holothuroidea) within subtropical seagrass beds. *Journal of the Marine Biological Association of the United Kingdom,* 90**,** 215-223. https://doi.org/10.1017/S0025315409990518

Wright, A., Chapau, M. R., Dalzell, P. J. and Richards, A. H. 1983. *The Marine Resources of the New Ireland Province. A Report on Present Utilisation and Potential for Development*. Port Moresby, PNG: Fisheries Research and Surveys Branch, 54 pp.

Wulandari, U., Sulistyo, B. and Hartono, D. 2016. The application of GIS in determining the suitability of sea cucumber (*Holothuria scabra*) in Kiowa Bay, Kahyapu Village, District of Enggano. *Journal of Enggano,* 1**,** 57-73.

Xia, S. and Wang, X. 2015. Nutritional and Medicinal Value. *In:* Yang, H., Hamel, J.-F. and Mercier, A. (eds.) *The Sea Cucumber Apostichopus japonicus History, Biology and Aquaculture.* london: Academic Press, pp. 353-365.

Yamanouchi, T. 1956. The daily activity rhythms of the holothurians in the coral reef of Palao Island. *Publications of the Seto Marine Biological Laboratory,* 5**,** 45-60.

Yang, C., Yang, D., Cao, W., Zhao, J., Wang, G., Sun, Z., Xu, Z. and Ravi Kumar, M. S. 2010. Analysis of seagrass reflectivity by using a water column correction algorithm. *International Journal of Remote Sensing,* 31**,** 4595-4608. https://doi.org/10.1080/01431161.2010.485138

Yingst, J. Y. 1982. Factors influencing rates of sediment ingestion by *Parastichopus parvimensis* (Clark), an epibenthic deposit-feeding holothurian. *Estuarine, Coastal and Shelf Science,* 14**,** 119-134. https://doi.org/10.1016/s0302-3524(82)80040-6

Young, A. C., Johnson, E. G., Davis, J. L. D., Hines, A. H., Zmora, O. and Zohar, Y. 2008. Do hatchery-reared blue crabs differ from wild crabs, and does it matter? *Reviews in Fisheries Science,* 16**,** 254-261. 10.1080/10641260701684122

Yu, Z., Yang, H., Hamel, J.-F. and Mercier, A. 2015. Larval, Juvenile, and Adult Predators. *In:* Yang, H., Hamel, J.-F. and Mercier, A. (eds.) *The Sea Cucumber Apostichopus japonicus: History, Biology and Aquaculture.* Academic Press, pp. 243-256.

Zamora, L. N. and Jeffs, A. G. 2013. A review of the research on the Australasian sea Ccucumber, *Australostichopus mollis* (Echinodermata: Holothuroidea) (Hutton 1872), with emphasis on aquaculture. *Journal of Shellfish Research,* 32**,** 613-627. https://doi.org/10.2983/035.032.0301

Zamora, L. N. and Jeffs, A. G. 2015. Evaluation of transportation methods of juveniles of the Australasian sea cucumber, *Australostichopus mollis*. *Aquaculture Research,* 46**,** 2431-2442. https://doi.org/10.1111/are.12400

Zhang, L., Song, X., Hamel, J.-F. and Mercier, A. 2015. Aquaculture, Stock Enhancement and Restocking. *In:* Yang, H., Hamel, J.-F. and Mercier, A. (eds.) *The Sea Cucumber Apostichopus japonicus: History, Biology and Aquaculture.* London: Academic Press, pp. 289-322.

Zhang, Z., Zhou, J., Song, J., Wang, Q., Liu, H. and Tang, X. 2017. Habitat suitability index model of the sea cucumber *Apostichopus japonicus* (Selenka): A case study of Shandong Peninsula, China. *Marine Pollution Bulletin,* 122**,** 65-76. https://doi.org/10.1016/j.marpolbul.2017.06.001

Appendices

APPENDIX 1. Summary of responses to selected Chapter 1 interview questions from Limanak community members. NA denotes that the question was not applicable. Number of responses totals more than 13 if multiple responses were given by the respondent.

Interview questions	Most common answer (*n*)	2nd common answer (*n*)	3rd common answer (*n*)	4th common answer (*n*)
Marine Tenure				
Who "owns" area in front of your house	Community (9)	Clan (4)		
Any disputes over fishing	No (13)			
Who can fish there	Three island communities (13)			
Who can't fish there	Outsiders (12)	No-one (1)		
What can be fished	All resources (12)	Not resources for money (1)		
Can outsiders get permission to fish	Yes (11)	Not for sea cucumber (1)	No (1)	
Who owned the sea cucumber harvested	Fisher (9)	Clan (2)	Fisher, if not an outsider (2)	
Were there rules related to fishing	No answer (5)	Outsiders banned (4)	Tambu, area closures (3)	NFA laws (2)
Where are your fishing ground boundaries	See map, Figure 1.5 (13)			
Decision making				
Who makes community decisions	Village Planning Committee (13)			
How is this person/group nominated	Elected (10)	No answer (3)		
How are rules decided	Joint VPC/community (8)	No answer (4)	Unsure (1)	
Who enforces the rules	Village police/court/VPC (6)	No answer (3)	Community (1)	Unsure (1)
Examples of rules that are broken	CBFM rules (9)	No specific example (4)	Gambling, home brew, drugs (2)	Outsiders fishing (1)
Disciplinary action taken	No action taken (9)	Reported, but no action (2)	No answer (3)	
CBFM examples	Tambu area close to shore (7)	NFA laws (4)	Nil CBFM (4)	Outsider fishing (3)
Pre-moratorium sea cucumber fishery and BDM trade				
Were you involved in this fishery in the past	Yes (12)	No (1)		
What species	All commercial sea cucumber (12)	NA (1)		
How far to where you fished for sea cucumber	Community fishing grounds (11)	Other islands/areas (1)	NA (1)	
How often did you fish for sea cucumber	Intense, i.e., 6-7 days (8)	Moderate i.e., 3-4 days (3)	No answer (2)	
What was your preferred sea cucumber species	Sandfish (11)	Yellowfish (1)	NA (1)	
Why	High price (10)	Abundant species (3)	Accessible in shallow, nearshore waters (2)	
How did you process sandfish BDM	Standard method (10)	Used pawpaw sometimes (2)	No answer (2)	
Where did you sell your BDM	Buyers in Kavieng (12)	NA (1)		
Effect of NFA moratorium	Loss of big income (9)	Not affected (3)	Loss of related livelihood (1)	NA (1)
Alternative income in moratorium	Fishing (11)	Sago harvest (4)	Other, e.g., paid, store, timber, pension (6)	
Attitude to moratorium	Happy (7)	Unhappy (2)	Unhappy, now happy (2)	NA (1)
Aquaculture				
Previous knowledge of aquaculture	None (11)	Heard of tilapia farming (1)	LRFFT cage culture (1)	
Are you interested in sea cucumber mariculture	Yes, very keen (11)	Yes, uncertain (2)		
Why	Money, income (6)	Learn about sandfish/mariculture (6)	Have them close by (2)	Unsure (1)

APPENDIX 2. Household survey forms used in Chapter 2 socio-economic data collection.

Part 1: Pre-fishery Socio-economic Household Survey Form for M/F Head of Household

Date: ________________________________ HH ID No: ____________

Community/village: ________________ WCS interviewer: ________________

Head of household name: ____________________ (male/female)

1. Could you please provide the following details for each person currently residing in your household:

Age
Clan
Marital status
Current student
Highest level of education
Religion
Origin (inside/outside village)
Primary source of individual income
Secondary source of individual income

2. In the house you reside, please indicate the type of materials used for your roof, windows & floors:

Roof: Iron; Wood; Thatch; Other (list): ________________________________
Windows: Glass; Flywire; Wooden; Open; Other (list): _______________
Floor: Wooden; Concrete; Thatch/bamboo; Dirt/sand; Other (list): ____________

3. Please indicate whether a member of your household owns any of the following assets, how many and whether primary user is male, female or equal use:

Out board motor engine
Fibreglass boat/ dingy
Dugout canoe
Fishing net
Fishing line
Snorkelling gear
Fishing spear
Generator
Chain saw

4. Does your household run a canteen? What items does it sell?

5. In the past week, how many people in your household went fishing or seafood collecting for the following:

Finfish: No. of males; No. of times; No. of females; No. of times
Shellfish (e.g. trochus, kina shell etc.): No. of males; No. of times; No. of females; No. of times
Crustaceans (e.g. crabs, lobster): No. of males; No. of times; No. of females; No. of times

6. Of your household's catch this week, how much was for selling?

Finfish: None / Some / All
Shellfish: None / Some / All
Crustaceans: None / Some / All

7. Did you or someone from your household sell any seafood in the past week?

8. Of your household's catch this week, how much was for selling?

Finfish: None / Some / All
Shellfish: None / Some / All
Crustaceans: None / Some / All

9. In the past week, how much of your household's income came from selling seafood?

10. Where do you or someone in your household sell most of your seafood?

Inside the village; To other villages; Kavieng market; Other (please specify)11. In the past week, what was your household's total weekly income from all sources?

12. In the past week, did you or someone in your household buy seafood from other sources (e.g. other fishermen/women, other villages, market)? (if no, go to Q13)

13. In the past week, how much did your household spend on seafood?

14. In the past week, how many times did your household consume the following?

Canned fish
Finfish
Shellfish
Crustaceans
Canned meat
Poultry (chicken, pigeon etc.)
Pig
Eggs
Mud crab
Kina shell
Ark shell
Mangrove snail
Mangrove bean

15. Please indicate which of the following activities males, females or both do?

Preparing gear for fishing
Repairing and maintaining fishing gear
Cooking fish
Preparing fish for sale
Selling/marketing fish

Diving
Spearfishing
Gleaning
Bait collection
Make decisions about household fishing activities
Make decisions about how income from fishing within the household is spent

Is there anything else you'd like to share related to fisheries in your community?

Thank you.

Part 2: Fishery Socio-economic Household Survey – Head of Household

Date: ________________________ HH ID No: ________ Consent given: _________

Community/village: ____

Interviewer: _____________ ____

Interviewee Name: (Male)___________ or (Female) ___________

1. How many people reside in your household, including their age and gender:

2. In the past week, how many people in your household went fishing or seafood collecting for the following:

Finfish: No. of males; No. of times; No. of females; No. of times
Shellfish (e.g. trochus, kina shell etc.): No. of males; No. of times; No. of females; No. of times
Crustaceans (e.g. crabs, lobster): No. of males; No. of times; No. of females; No. of times
Pislama (sea cucumber): No. of males; No. of times; No. of females; No. of times

3. Of your household's catch this week, how much was for selling?

Finfish: None / Some / All
Shellfish: None / Some / All
Crustaceans: None / Some / All
Pislama (sea cucumber): None / Some / All

4. How was the sea cucumber processed? Provide closest estimates.

Fresh (gutted only): None / Some / All
Partly processed (describe how): None / Some / All; How processed?
Fully dried: None / Some / All

5. In the past week, how much of your household's income came from (exact value, choose from range):

a. selling seafood: None; K1-50; K51-150: K151-250; K251-400; >K400.
b. selling sea cucumber: None; K1-50; K51-150; K151-250; K251-400; >K400.
c. other sources: None; K1-50; K51-150; K151-250; K251-400;>K400.

6. If you think extra income was earned from pislama, what was it mostly spent on? Provide explanatory details where required.

Food (store food)
Food (market food)
Clothing
Personal accessories (watch, headphones, etc)
Betelnut
Alcohol
Fuel
Fishing gear
School expenses
Building materials (house improvements)
Saved (bank or at home)
Given to wantoks
Other cultural obligations
Church tithes
Other

7. In the past week, did you or someone in your household buy seafood (e.g. from other fishermen/women, other villages, market)? How much did you spend

8. In the past 24 hours, what did you eat? (tick any items and provide more detail on the type of fresh fish, shellfish or crustacean: Tokples names are acceptable)

Tinned fish
Fresh finfish (what kind?)
Other seafood (fresh)
Crustaceans (fresh)
Tinned meat
Frozen store meat (kakaruk, pig)
Rice
Biscuits
Kumu
Garden food (e.g. taro, kau kau, banana)
Island meat (kakaruk, pig)
Turtle
Eggs
Other (describe)

9. Please indicate which of the following activities males, females or both do?

Diving for pislama (sea cucumber)
Gleaning for pislama
Processing pislama: Boiling; Scraping (sandfish only); Drying
Selling pislama
Make decisions about how income from pislama is spent within the household

Additional Comments

Is there anything else you'd like to tell me about pislama fishing in your community?

Do you have any questions about this survey or about the research being carried out?

Additional interviewer's comments.

Thank you – Tenk yu – Giro – Kalaro

Part 3: Post-fishery Socio-economic Household Survey – Head of Household

Date: _________________ HH ID No: ____________ Tok Orait: ____________

Community/village: ____

Interviewer: ____________________ ____

Interviewee Name: (Male)_____________ or (Female)_____________

1. Did you use any extra money earned during the pislama season for home improvements, for example, any of the following:

Roof: Iron; Wood; Thatch; Other (list): ______________________________
Windows: Glass; Flywire; Wooden; Other (list): ______________
Floor: Wooden; Concrete; Thatch/bamboo; Other (list): ____________
Other: New house; Extension (extra room); Other (list): ____________

2. Did you use any extra money earned during the pislama season for purchasing assets (provide details on type, number, etc):

Out board motor engine
Fibreglass boat/ dingy
Dugout canoe
Fishing gear (specify, e.g. torch, net)
Generator
Chain saw

Other power tools (specify, e.g. grinder)
TV/video screen
Phone
Other electronic gear (specify, e.g. computer)
Freezer
Solar (specify light/panel)
Pressure lamp
Other

3. Does your household run a canteen: Yes /No/ during sea cucumber season only

4. Do you have any savings left from beche-de-mer sales? Yes / No

5. Do you feel you benefitted overall from the recent open pislama fishery? Yes / No

6. In the past week, how many people in your household went fishing for the following:

Finfish: No. of males; No. of times; No. of females; No. of times
Shellfish (e.g. trochus, kina shell etc.): No. of males; No. of times; No. of females; No. of times
Crustaceans (e.g. crabs, lobster): No. of males; No. of times; No. of females; No. of times

7. Of your household's catch this week, how much was for selling?

Finfish: None / Some / All
Shellfish: None / Some / All
Crustaceans: None / Some / All

8. In the past week, how much of your household's income came from:

a. selling seafood? Kina value_____________________
b. other sources (list)? Kina value_____________________

(Please specify: paid work (e.g. resort), copra, timber, canteen, transport, etc)

9. In the past 24 hours, what did you eat? (tick any items and provide more detail on the type of fresh fish, shellfish or crustacean: Tokples names are acceptable)

Tinned fish
Fresh finfish (what kind?)
Other seafood (fresh)
Crustaceans (fresh)
Tinned meat
Frozen store meat (kakaruk, pig)
Rice
Biscuits
Kumu
Garden food (e.g. taro, kau kau, banana)
Island meat (kakaruk, pig)

Turtle
Eggs
Other (describe)

10a. Did you have any beche-de-mer rejected during the fishing season? Yes / No

10b. How much?   Full bag; Half Bag; Small amount

10c. What reason for the rejection: Wet; Undersized; Damaged/broken; Too dry; No reason; Other reason (list)

11. Were you happy with the sea cucumber fishery season in your village? Yes / No

Why or why not? [e.g. fishing practices (self, others), buyers, management, etc)

12. If the fishery opens again next year, what would you do differently?

13. Did outsiders fish for sea cucumber in your waters?   Yes / No

Comments?

Additional Comments

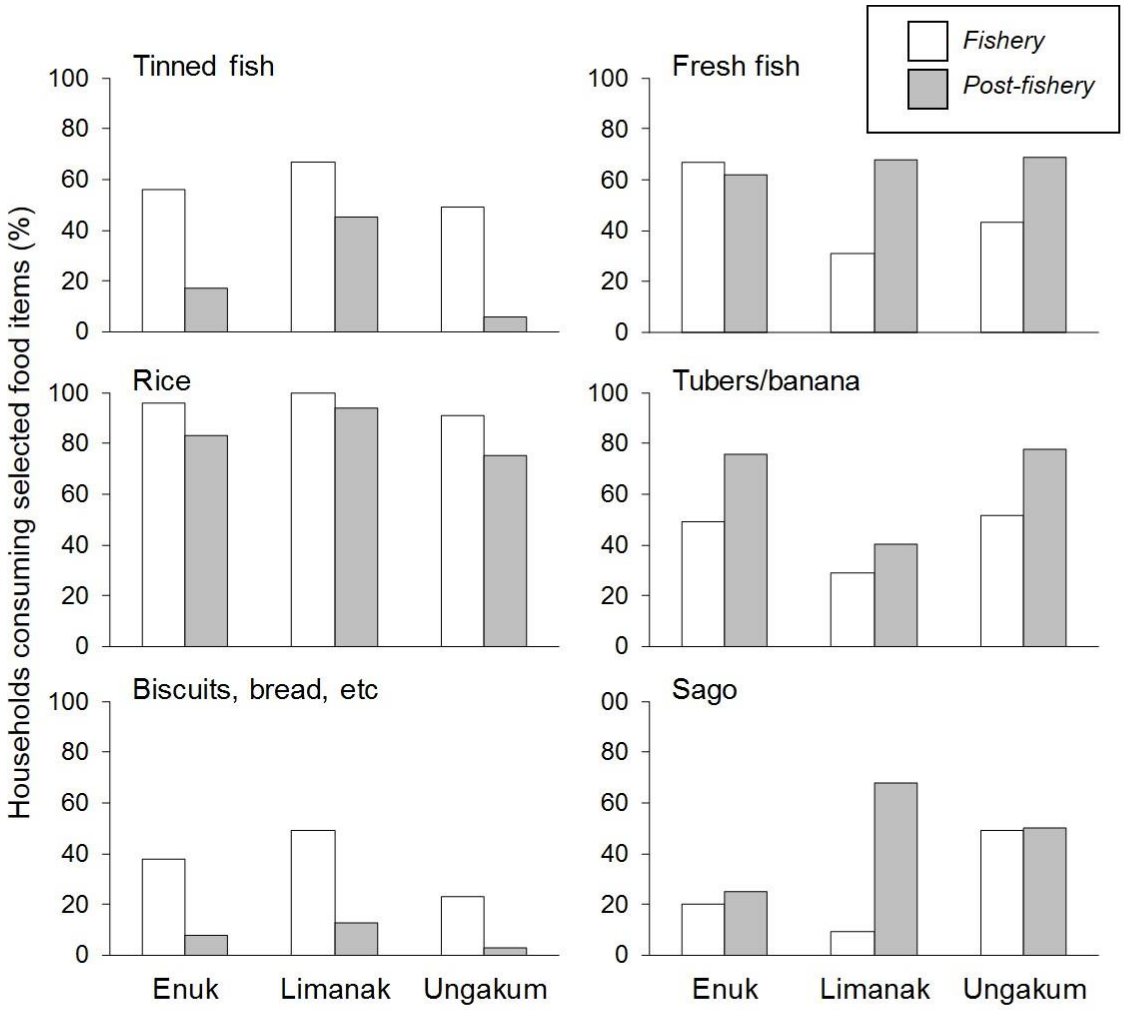
Is there anything else you'd like to tell me about pislama fishing in your community?

Do you have any questions about this survey or about the research being carried out?

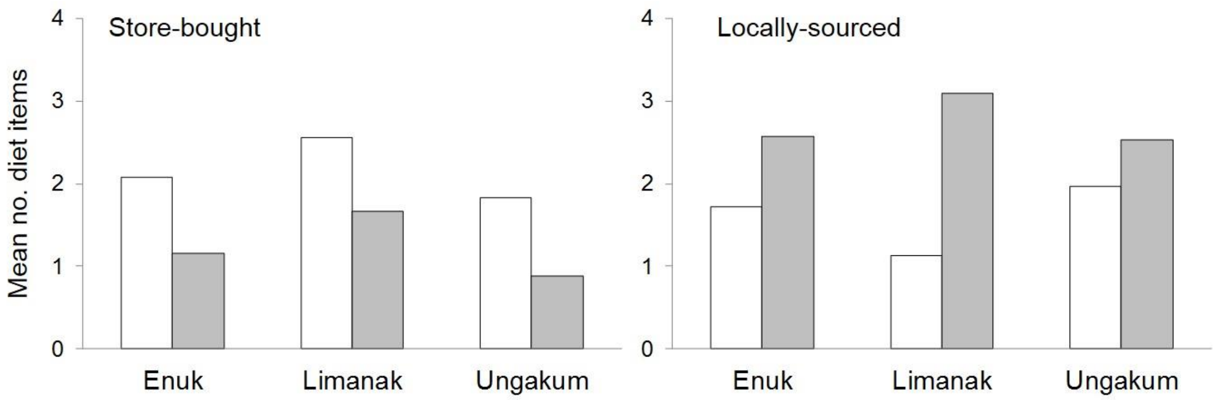
Additional interviewer's comments.

Thank you – Tenk yu – Giro – Kalaro

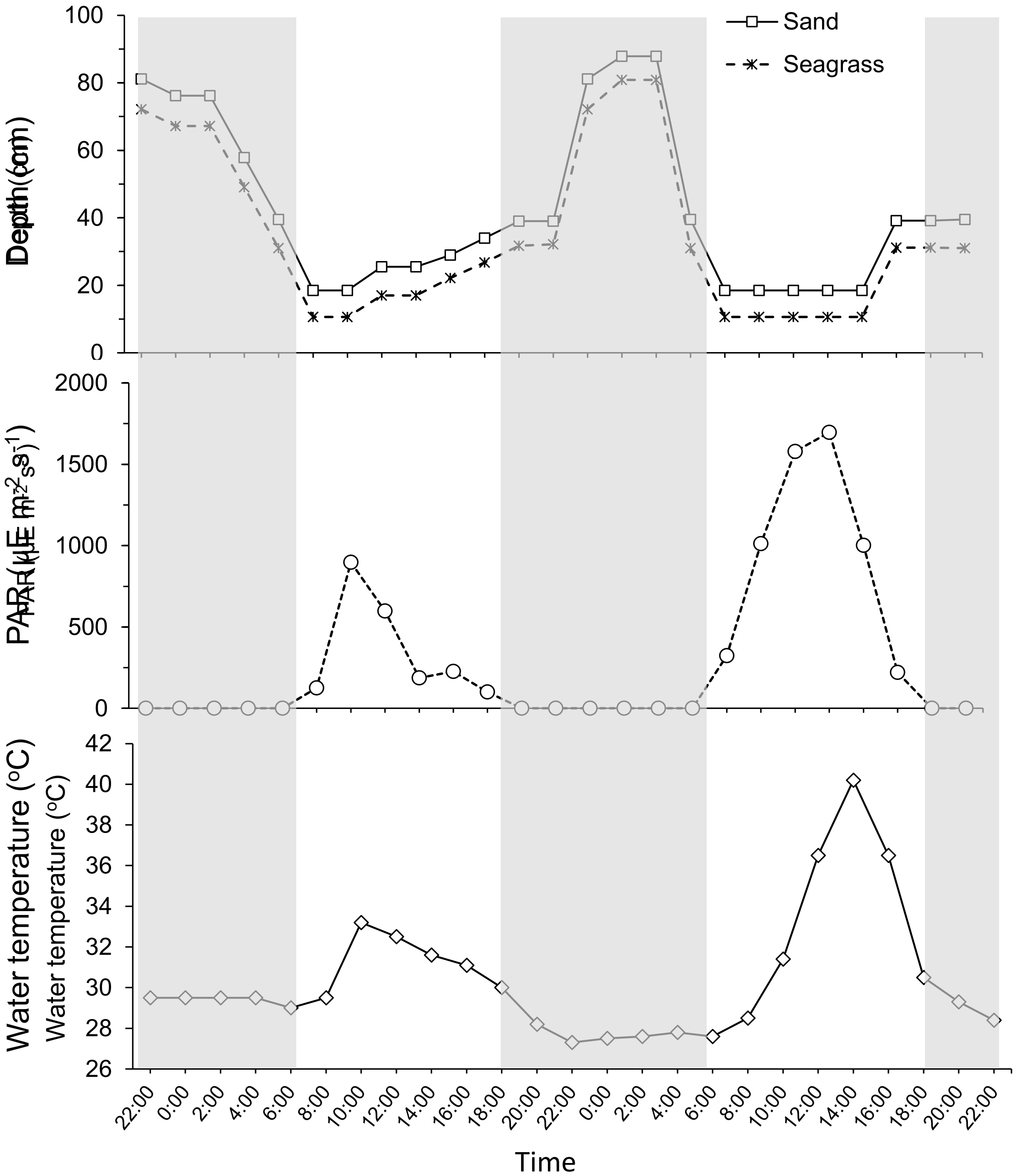
APPENDIX 3a. Households (%) in Enuk, Limanak and Ungakum that reported consuming common store-bought (left) and locally-sourced foods (right) During the *Fishery* (open bars) and *Post-fishery* (shaded bars) periods.



APPENDIX 3b. Mean number of store-bought and locally-sourced foods consumed per household during the *Fishery* (open bars) and *Post-fishery* (shaded bars) periods.



APPENDIX 4. Graphs of co-linear environmental variables from the burying experiment in Chapter 5. Water temperature (°C), light (calibrated photosynthetically active radiation 2-h mean: PAR, µE m^{-2} s^{-1}) and water depth (cm) of experimental pens in bare sand and seagrass habitat at 2-h intervals (observation times) for the duration of the burying behaviour experiment. Shaded area indicates night-time.



APPENDIX 5. Interview questions used in Chapter 7 socio-economic data collection.

<u>Sea ranch questionnaire</u>

Date: **Location:** **Gender:** **Interviewer:** **Permission:**

---

1. Did you know that there was a tambu on pula collection from the sea ranch and channel? ____

2. How did you learn that the tambu on the channel and sea ranch was lifted? (*How nau yu bin save dispela tambu long basis na ranch i op, na ol man na meri ikan kisim pislama long hap*?)

____

3. Why do you think the tambu was lifted? (*long wanem ol i opim bek ranch na basis*?)

____

4a. Did you fish in the ranch or channel? (*yu iet yu kisim pislama long ranch o basis*?)__

4b. What pula did you collect? (*yu kisim hamas na wanem kain pula*?)______________

4c. Were you happy with this catch? (*yu hamamas*?)______________________________

5a. Were there more pula in the ranch area? (*igat plenti moa pula insait long ranch winim sidsid*?)______________

5b. More sandfish in the ranch (*moa pula sok*)? _______ Bigger size? ___________

6. Were you happy that these areas opened up to collect pula? Why? (*Yu hamamas taim ol i rausim tambu*? *Olsem wanem*?)

____

7a. Did outsiders fish in the tambu areas? (*Ol narapela lain long outsait i bin kam kisim pula long hia*?)____¬¬¬_

7b. What do you think about outsiders (non-community) coming in to fish the channel and ranch? Why?

____

8a. Do you think the ranch / basis channel should have stayed closed to pula? ______

8b. If yes, why? (*sapos yes, long wanem*?)

____

9. Was the sea ranch a good thing, overall? (*Pula farm i gudpela samting or nogat*? *Long wanem*?)

____

10a. Was the 2018 season different to 2017? How? (e.g. *pula i no plenti, plenti buyer tru*, etc)

____

11a. Are there still plenty of pula around? ____ 11b. Where? (lo we?) __________

12. What does development mean to you? (*Developmen i minim wanem long yu*?)

____

13. Does loss of the sea ranch affect you? How? (*Pundaun long ranch i affectim yu iet*?)(How?)

____

14a. How do you think *mipela* (NIMRF) could have done the project better?

____

14b. How do you think fisheries (NFA, province) could have done the project better?

____

14c. How do you think you (*komuniti*) should have done the project better?

____

Any comments on the ranch, sea cucumber fishing or anything else?

____

Thank-you for your time in doing this survey!

Tenk yu tru!

Kalaro Lui