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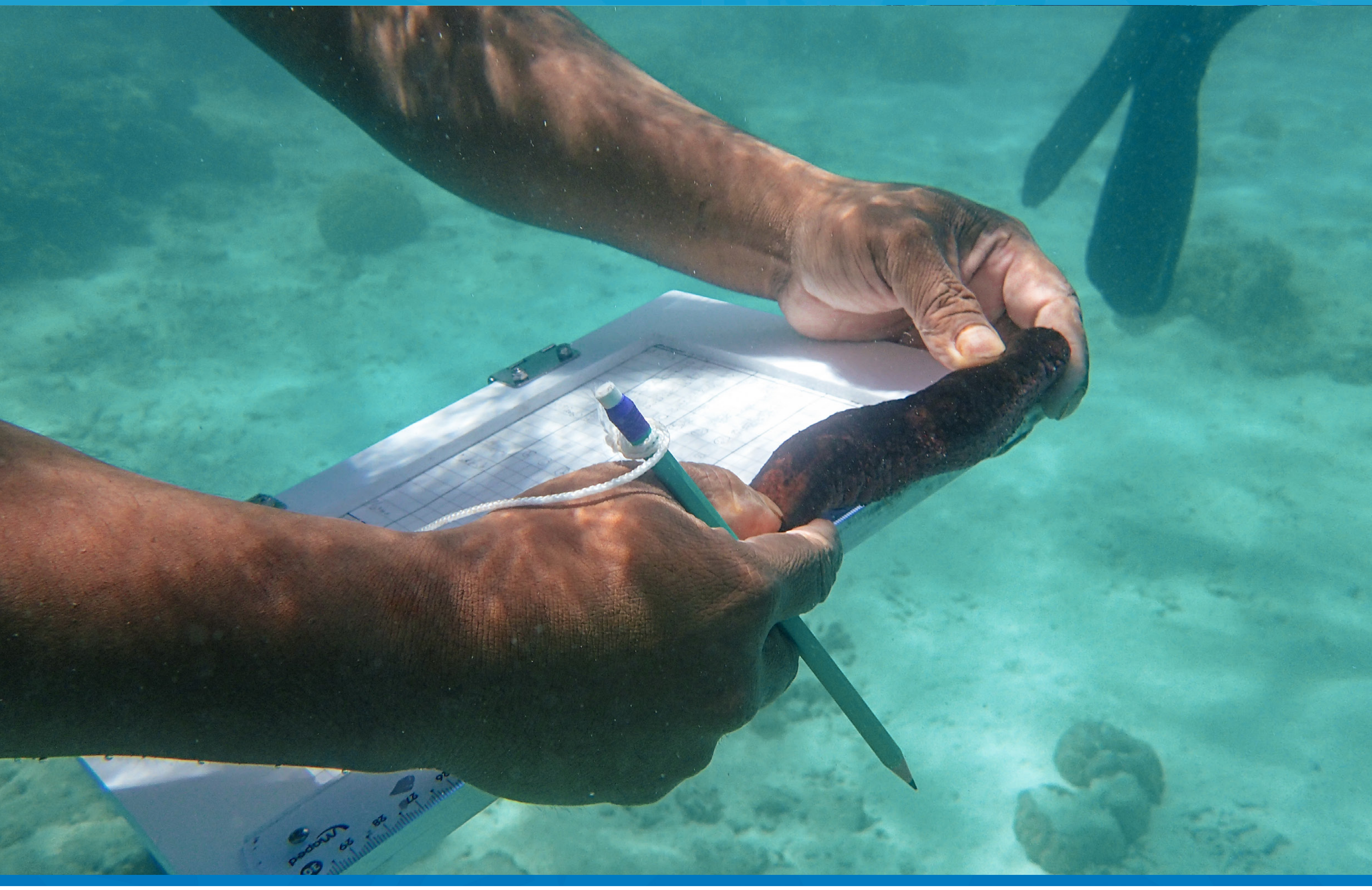

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Summary

- The results of the 2021 sea cucumber assessment indicates that densities of most sea cucumber species surveyed on reef and shallow lagoon areas of Lord Howe Atoll are depleted and not at reference densities, which includes those teatfish species listed in the Convention on International Trade in Endangered Species (CITES).

- Apart from *Holothuria atra* (lollyfish), sample sizes for all species were insufficient to allow for a meaningful analysis of their size distributions. While this strongly implies that the sea cucumber fishery at Ontong Java is overexploited, there needs to be additional targeted surveys (e.g. in deep water or from catches) completed to better assess some species.

- For the only species with sufficient sample sizes, we estimate fishing pressure was minimal on the low-value species *H. atra* (lollyfish). This was reflected in the size–frequency distribution for this species, which is centred around a mean size of 200 mm with approximately 65% of the population above length-at-maturity (160 mm).

- The species observed in fishers' catches were *Holothuria lessoni* (golden sandfish), *Stichopus herrmanni* (curryfish), *Stichopus horrens* (Peanutfish – elsewhere known as dragonfish) and *Stichopus ocellatus* (curryfish sp.). These were found in the deeper water lagoon targeted by trawl net fishing, and hence the results of shallower in-water surveys may not be entirely representative of the full suite of species and their distribution in the atoll. Additionally, these species display cryptic and nocturnal behaviours whereas our in-water surveys that were only done during daylight hours might not be well suited to assess species such as these. Accurate assessments of these species will require either night surveys in key habitats, or fishery-dependent catch per unit effort (CPUE) surveys.

- Because of logistical constraints and the remoteness of Lord Howe Atoll, this survey focussed on habitat <20 m, which left the deep-water habitat, where the fishery has mostly been focussed using trawl nets, insufficiently sampled.

- While S*tichopus ocellatus* was recorded as present in fishers' catches, this species has never previously been recorded in the Solomon Islands, so further investigation is required to confirm the identification was correct and that this species is indeed present on the atoll.

Management recommendations

The following recommendations are made based on the survey outcomes, which highlighted the unhealthy state of sea cucumber stocks across Lord Howe Atoll. The recommendations provide a framework for maintaining sea cucumber populations within sustainable harvest limits to help ensure their long-term contribution to the economic well-being of the community.

Primary management measures recommended for immediate implementation

- *Review of management plan*. It has been eight years since the Solomon Islands Sea Cucumber Management and Development Plan 2014 was introduced, so we recommend a review be conducted of the plan to ensure it remains fit for purpose and includes current management strategies suited to atoll communities that are community-based. A review can include but is not limited to:

    - adjusting the minimum legal length (MLL) of all species so that they are at least 20% above length-at-maturity. For example, using data from this survey, we recommend changing MLL for *Holothuria atra* (lollyfish) to 200 mm. Our data indicate that the MLL is set too large at 300 mm, which is at the upper 95% of the population's length structure at the atoll (and elsewhere). Also we recommend increasing the MLL for *Bohadschia argus* (tigerfish) to 360 mm wet length, so that it is 20% above length-at-maturity of 300 mm. With correctly applied and controlled size limits it is likely that the fishery will be resilient against harvesting;

    - introducing reference density thresholds like those outlined in Pakoa et al. (2014b) but developed for atolls or local conditions and used as a trigger for opening or closing the fishery for exports of beche-de-mer;

    - development of reference length thresholds where the mean length of a species is at least 20% above length-at-maturity and with a normal length distribution for the population. Used in conjunction with appropriately calculated reference densities for atolls, this can be used as a trigger for opening or closing the fishery.

- *List of permissible or banned species*. Low densities were observed of all high-value sea cucumber species, indicating that their stocks are overfished. A list should therefore be made that identifies all those species that are overfished and are hence in need of management interventions. The banned list can include those that do not meet the reference density threshold and reference length threshold. Such a list will allow community members to be aware of what species should not be caught. Support material can be developed and provided by SPC. This list can be adapted as new data on stock levels are collected and will reflect population recovery.

- *Enforcement of minimum legal sizes*. Immediately enforce the recommended minimum legal length for all species as set out in the Solomon Islands National Sea Cucumber Fishery Management and Development Plan 2014. Provide guidelines and support to the community on how to monitor catches and information on what these lengths are. Any management measures will only be effective if they are followed as closely as possible. Therefore, the focus should be on enforcing management guidelines to ensure no one is illegally harvesting sea cucumbers species that are already overfished. Support material can be developed and provided by SPC.

- *Bans and/or restrictions on unsustainable fishing gear.* High incomes generated using trawl nets were only sustained for two to three years before the fishery collapsed. The severe decline in sea cucumber catches and subsequent drop in incomes demonstrates clearly that this fishing method is highly destructive and not sustainable. A complete ban on the use of trawling nets would therefore be the most effective option to improve stock health. However, if local socio-economic conditions mean that pressure to use nets will not necessarily be removed, even with a ban, then continued use of nets would require strict conditions and oversight. If nets are to remain the fishing method of choice, then a study needs to be carried out to assess the most appropriate mesh size to be used to allow most undersized sea cucumbers to pass through the nets. It is removal of immature sea cucumbers from the population that has the greatest effect on sustainability. In addition, there must be a limit placed on the total number of nets that can be used in the fishery. The entire community must agree to the recommendations for them to work, and the fishery must be managed as a shared resource which they all look after to maximise health and returns.

- *Establishment of no-take areas*. A highly desirable management recommendation is to establish strategically placed permanent no-take zones to enable sea cucumber species to maintain stock levels large enough and old enough to contribute to the replenishment of populations elsewhere in the atoll. If sea cucumber stocks can recover to normal levels, then such high-density sea cucumber aggregations in no-take zones will increase the rates of successful fertilisation and contribute animals to other parts of the atoll. The establishment of no-take area boundaries will need to include assessments of the range of each species' key habitats, the areas that fishers use and the capacity of the community to carry out enforcement of no-take regulations within the reserve boundaries.

Secondary management strategies that may be used in conjunction with those described above

- *Total allowable catch*. Once independent stock assessments indicate that populations are returning to normal – which is likely to take at least five years of no harvesting (including illegal harvesting) and strong enforcement of closures – then a total allowable catch (TAC) could be estimated. This can be calculated as 30% of total adult stock, where adult stock is defined as 80% of the population estimate above MLL for each species. Detailed methods for stock assessment are described in Pakoa 2014. TAC can be refined and adapted as needed.

- *Rotational area closures*. Once stocks have recovered, rotational area management could be re-established, with demarcation of community boundaries based on traditional ownership, as previously used and insisted on by Pelau community at Lord Howe Atoll (described by Bayliss-Smith et al. 2010).

Continued monitoring of the fishery

- *Future survey methods*. It is strongly recommended that future fishery-independent surveys use the same methodologies and stations (GPS coordinates) from this and previous surveys to record spatio-temporal changes in wild sea cucumber populations in habitats shallower than 20 m in depth.

- *Increased monitoring of the fishery*. Monitoring of stock is key to all management recommendations, and this should be done with regular surveys every 2–3 years so that recovery trends can be closely tracked. During open seasons, fishery-dependent surveys should be implemented so that trends in catch per unit effort (CPUE) per species can be recorded, either by log-book collections or regular independent observers. All sea cucumbers caught must be above the minimum recommended legal sizes.

- *Surveys of deepwater stock*. Assessment/survey of the condition of deep-water sea cucumber species is required to understand what spawning stock remains.

- *Fishery dependent monitoring of beche-de-mer processors*. Mandatory monitoring as part of licencing conditions should be required for the processors and exporters to provide location-specific logs of sea cucumbers including species, wet and dry length and weight measurements. This will provide continuous indirect data on the catch of sea cucumber resources at Lord Howe Atoll. This information should be entered into a database and regularly analysed and referred to for adaptive management.

- *Improvement in the traceability of processed product.* Information on the origin of sea cucumber products within Solomon Islands is needed to improve product traceability. Mandatory submission of purchased quantities, sizes and prices must be recorded and submitted to the Ministry of Fisheries and Marine Resources (MFMR) using standardised forms as a condition of licenses. This information should be entered into a database and regularly analysed to monitor production, and this information should be made available to MFMR. The information should be regularly assessed by MFMR officers for compliance and accuracy. Having traceability and quantity information will also assist management to comply with export conditions for exporting species listed on the appendices of the Convention on International Trade in Endangered Species (CITES).

Alternative to wild harvests

- *Investigate the feasibility of sea ranching*. Upon request, SPC's aquaculture unit can assist MFMR with a feasibility assessment. If shown to be feasible, then sea ranching of high-value species such as sandfish or golden sandfish could be undertaken as an alternative to harvesting wild populations. However, to have any chance of success there would need to be access to a regular supply of juveniles from mainland hatcheries to ensure there is enough stock for grow-out to commercially viable sizes. Promising examples of aquaculture ventures for larval and juvenile rearing are in Tonga, Kiribati, New Caledonia, French Polynesia and Papua New Guinea.

Introduction

Solomon Islands is an independent archipelagic state with a population of nearly 710,000 (SINSO, 2022), located in the Western Pacific Ocean due east of Papua New Guinea. It consists of six main islands and over 900 smaller islands and atolls. The country lies within the Coral Triangle, an area of globally significant marine environments and coastal marine habitats that support high marine biodiversity (Albert et al. 2012). The coastal communities of the Solomon Islands are heavily reliant on their marine environments for food and livelihoods, and this is especially true of those communities that are based on remote atolls such as Lord Howe Atoll (also known as Ontong Java) where this report is focussed.

Harvesting, processing and selling of sea cucumbers is the second highest export fishery in the Solomon Islands (Pakoa et al. 2014a). Historically, this beche-de-mer fishery has experienced huge boom and bust cycles from poorly regulated harvesting controls. The Ministry of Fisheries and Marine Resources (MFMR) has attempted to manage the fishery through periodic closures to allow stocks to recover. The fishery was first closed by MFMR in April 2005, because of the realisation that stocks were so depleted that recovery might not be possible for some time. In May 2007, after approximately two years of recovery, the fishery was reopened for only three months before closing again. The fishery then remained closed for another two years until April 2009, when it was again opened for only three months.

Easy access to sea cucumber habitats, combined with their reproductive strategies and being the target of predominantly unregulated country-wide fisheries, has made sea cucumbers especially vulnerable to overharvesting. Most sea cucumbers can live for five to ten years, while some slow-growing species may live to 15 years (Sloan 1984; Sewell 1990). Most species attain sexual maturity at between two and six years (Charan-Dixon 2016; Charan-Dixon et al. 2019). Species that use broadcast spawning as a reproductive strategy require adequate rates of fertilisation and recruitment for them to be resilient to harvesting within a fishery. Overharvesting lowers the density of reproductively capable adults, which inhibits population growth and stock recovery (Allee 1938; Kinch et al. 2008; Friedman et al. 2011; Purcell et al. 2013). Due to Lord Howe Atoll's oceanic isolation, sea cucumbers within the atoll are unlikely to receive regular recruits from elsewhere and most likely self-recruit. This would make each species more sensitive to overharvesting and therefore would require strict adherence to best practice fisheries management.

In 2014, a Solomon Islands National Sea Cucumber Fishery Management and Development Plan was enacted to provide structure and guidelines for managing the beche-de-mer fishery in the country. After being closed for six years there was community pressure to open the fishery and so it was opened again in September 2017 for three months, with an added management measure of limiting the number of export licenses to nine across the country. In December 2018 after one year of recovery, the ban was again lifted for seven months and closed in May 2019. It remained closed until September 2021 and it currently remains open. The strategy of opening and closing the fishery at the national level has been criticised by some communities as being too coarse and not taking into consideration local differences in harvesting pressure and community management (Anon 2021).

Members of the Lord Howe Atoll community lead subsistence livelihoods through coconut and swamp taro cultivation and fishing (Bayliss-Smith et al. 2010). Their most economically lucrative source of income has come from the sea cucumber fishery, which has provided most of their revenue over the last 60 years during open seasons (Bayliss-Smith et al. 2010; Ramohia et al. 2010). However, after the introduction of net trawling, catches and revenue declined within two years so that most of the fishers returned to their original revenue sources of taro and subsistence fishing.

Governance at Lord Howe Atoll has a varied and complex history. In the 1900s, *he ku`u* (King) of Luaniua and Pelau represented a system of atoll governance that established egalitarian united customary land and resource tenure through a web of complex relationships that revolved around kinship (Bayliss-Smith 2010). In the years that followed, governance of the atoll fell to a single chief who was recognised by a District Officer from the British colonial governance system. In 1965 pressure from outside the atoll convinced the then Chief Asai to adopt a major change in atoll governance and form a "council of chiefs" that represented leaders from household lineages and slowly became known as the Area Council and the only legitimate focus of political power, especially in the 1970s and 1980s (Bayliss-Smith et al. 2010).

Prior to 1996, the beche-de-mer trade dominated the Lord Howe Atoll economy, which was a large contributor to exports of beche-de-mer that were coming from Malaita Province, Solomon Islands (Holland, 1994). Harvesting was sustainable when still regulated by an Area Council, although the distribution of generated wealth was generally less egalitarian than other revenue generating activities. The Area Council implemented management regulations on the fishery that included restrictions on technology, such as banning the use of SCUBA. Additionally, due to the local importance of the fishery and concerns of overharvesting, an additional community-based management system of alternate year bans on fishing was put in place by the Area Council in 1980 to help ensure sustainable harvesting of sea cucumber stocks (Bayliss-Smith et al. 2010). Unfortunately, due to the commercial temptation to keep the fishery open, and a lack of coordination and shared governance between villages, this system was abolished in 1996 (Bayliss-Smith et al. 2010).

The complex governance and social structure within the atoll make managing the sea cucumber fishery difficult, especially when the legitimacy of decisions by leaders to close fisheries is questioned or ignored by fishers without repercussion for non-compliance (Bayliss-Smith et al. 2010). During the 1990s, the legitimacy of the Area Council began to erode as fishers increasingly sought easier methods for fishing to increase CPUE and revenue. For example, "Following the collapse of the Area Council authority in 1996 and a lack of compliance with the former closed-season restrictions, the introduction of the trawling method led to bêche-de-mer being harvested in greater quantities" (pp. 67 Bayliss-Smith et al. 2010). The rate of exploitation using nets was unsustainable, and together with overharvesting in other parts of the country forced a country-wide government ban in 2005 resulting in the loss of their main income source.

Harvesting methods for sea cucumber at the atoll have changed over time, with more efficient gear and unregulated fishing ultimately leading to a collapse of the fishery. In the 1900s, free diving in waters less deep than 20 m was the principal method, then the "torpedo" (a barbed lead shaft at one end with line attached to the other end used for harvesting sea cucumbers) was introduced for collecting sea cucumbers in waters deeper than 20 m (Gillett and Lam, 1999). Later, in the early 2000s, trawling nets using powered boats was the preferred method used by fishers at Lord Howe Atoll (Christensen, 2011; Ramofafia, 2004). Trawling has long been recognised as a highly destructive catch method that indiscriminately damages the bottom and captures non-targeted species, all while being highly efficient at capturing target species in the short term. The use of these nets has had a destructive impact on the fishery through maximising catch-per-unit-effort in the absence of any formal fisheries management. The predictable result has been a collapse in the fishery, resulting in its closure and loss of a major income source for the community.

Study rationale

Because of the reduction in government revenue and general economic stress that communities faced during the height of the COVID-19 pandemic, the beche-de-mer fishery was re-opened by government in September 2021, and it remains open during the preparation of this report. The beche-de-mer fishery is the major contributor to the economy of the atoll both historically and currently (Holland 1994; Christensen 2011), which means it is vital that it remain sustainable (personal communication with community leaders).

Community leaders and Honiara-based Lord Howe people have expressed growing community concerns about external coarse-scale decisions, such as nationwide bans on the harvest of sea cucumbers. Several successful consultations in 2021 were done with communities both in Honiara and Lord Howe Atoll to assist MFMR and Solomon Islands government develop a way forward, which includes developing a community-based fisheries management (CBFM) plan. This led MFMR to initiate this assessment of the status of sea cucumber populations at Lord Howe Atoll, the results of which will be used to inform the development of management recommendations in the CBFM plan.

The report outlines the results and recommendations of a fishery-independent sea cucumber survey conducted in August 2021 at reefs traditionally belonging to Pelau and Luaniua communities at Lord Howe Atoll, and includes:

- a general description of the sea cucumber population of the atoll,
- comparisons with the 2010 baseline densities to assess trends in the fishery,
- a description of the population size structure for species encountered during the survey and comparisons with length at maturity for each species and
- prioritised management recommendations to guide the development of the CBFM plan.

Methods

Survey methods

In-water sea cucumber surveys were conducted at Pelau and Luaniua in September 2021 (Figure 1) using the reef benthos transect (RBT) survey method (Pakoa et al. 2014a). Station selection was carried out in the field after assessing for suitable sea cucumber habitat and their GPS coordinates were recorded. Each station survey consisted of six 40 m × 2 m RBTs laid end-to-end in series rather than in parallel (Pakoa et al. 2014b, Ramohia 2010), leaving a 10-m gap between each transect (Figure 2). This minor change to the transect alignment at each station allows for more of the same habitat to be surveyed. This was often not the case with the previous design where transects could be laid in different habitats because they were placed across, rather than along, the reef flats.

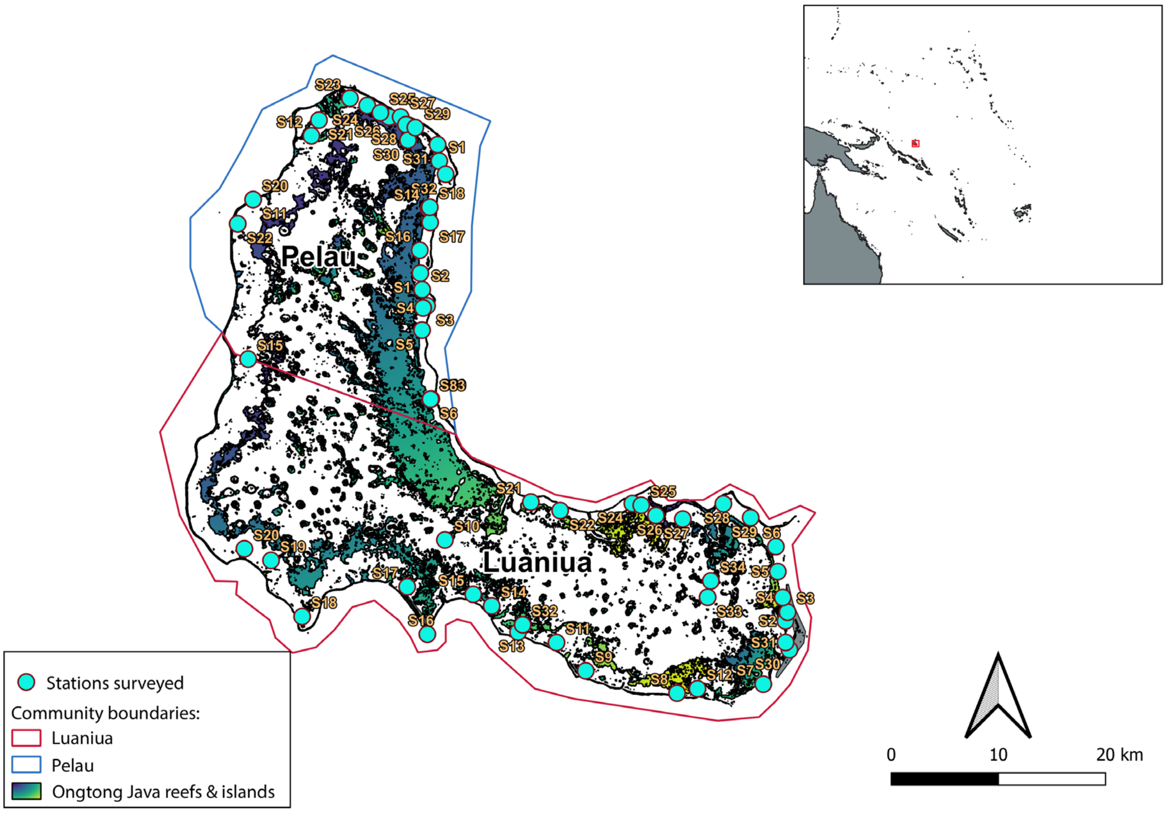

Figure 1. Map of Lord Howe Atoll (Ontong Java), Solomon Islands, indicating all survey locations. Bounding box shows the position of Lord Howe Atoll relative to the mainland and the greater Western Pacific region. Community boundaries are not officially recorded and are used here solely for the purposes of separating the two community fishing regions to guide management.

The surveyed habitat within each station was kept consistent; for example, all transects were completed in either sand or coral reef habitat, and at a consistent depth. While stations were placed within as many sea cucumber habitats as possible, habitats in the reef front and deepwater zones were limited due to wind and wave exposure and SCUBA-related logistical constraints at this remote atoll (Figure 4 shows the locations of stations in the two communities). Stations were surveyed by three snorkelers for shallow stations (0.5–5 m), two setting the transect line, a third recording the data, and by two SCUBA divers for stations deeper than 10 m. All sea cucumbers encountered within the 2 m × 40 m transect belt were identified to species, tallied, and lengths measured to the nearest centimetre (cm) using a rigid plastic ruler. Length was measured as the distance from mouth to anus along the ventral side of the body wall when the animal was in an undisturbed state.

Stations were always positioned within a single, defined, geomorphic reef zone within each location (community) (Figure 3). In total, 66 stations were surveyed at Lord Howe Atoll: Pelau – 28 stations in the backreef, and shallow lagoon zones, two stations in the deep lagoon and two in the outer reef zones; Luaniua – 30 stations in the backreef and shallow lagoon zones, and four stations in the deep lagoon.

Sea cucumber aggregating behaviour and survey errors

Sea cucumbers often clump together in aggregations, which can cause significant errors in survey counts if not properly addressed. Aggregations can occur due to multiple factors, such as responding to chemical cues for spawning or preference for a particularly favourable patch of habitat (Hamel and Mercier 2005; Marquet et al. 2018). However, these aggregations are isolated and do not represent the overall distribution patterns of sea cucumbers across the reef. Relying on estimates of sea cucumber densities within aggregations to calculate total stock sizes results in severe overestimations. To reduce the likelihood of this occurring, stations were chosen to ensure balance within and between the various geomorphic zones, thereby ensuring sufficient coverage across the various sea cucumber habitats. Geomorphic zones across Lord Howe Atoll were assigned using categories in the Allen Coral Atlas.[3] Total area in hectares (ha) for each category was calculated using the open-source spatial data management and analysis program, QGIS (Table 1). A polygon was generated outlining each geomorphic zone within each community boundary to enable total area to be derived.

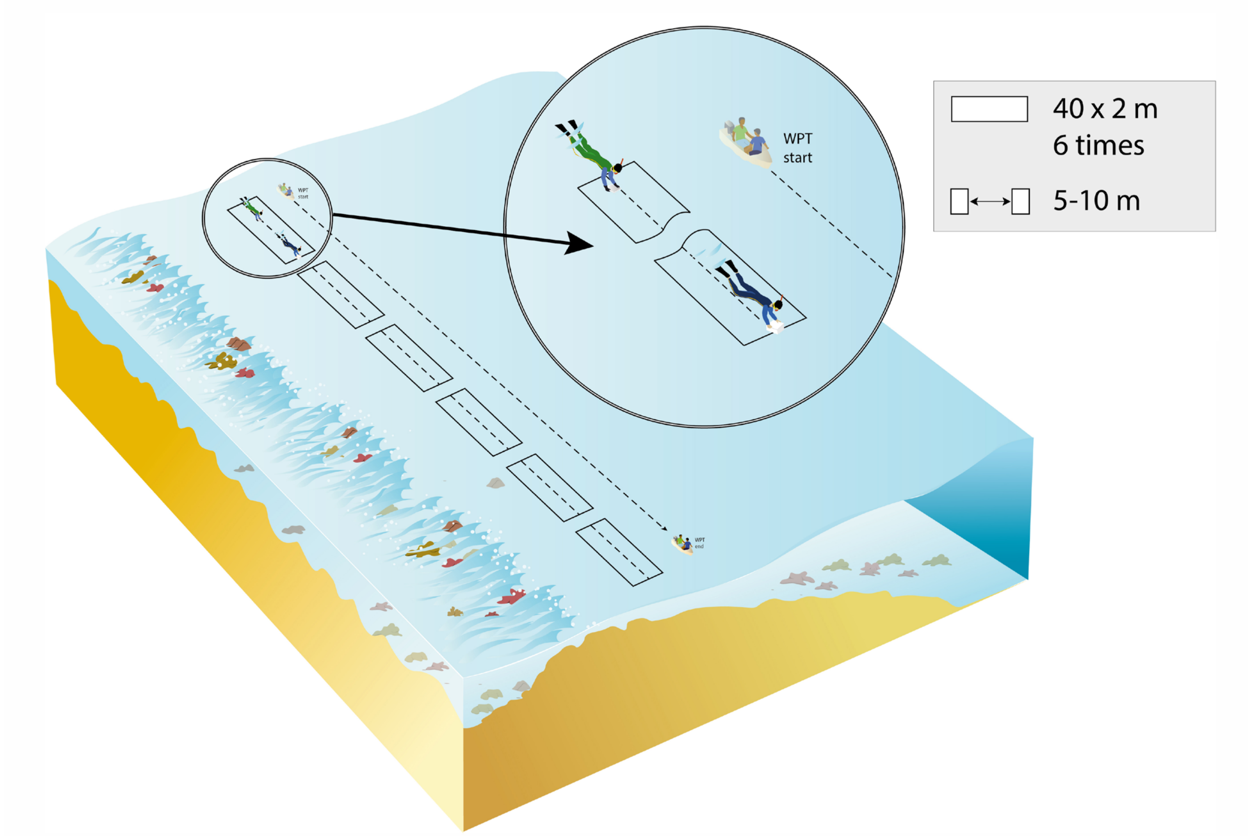

Figure 2. The six 40 m × 2 m reef benthos transect lines aligned in series to ensure they are within the same habitat type. WPT stands for GPS waypoint position at the start of the transect or station.

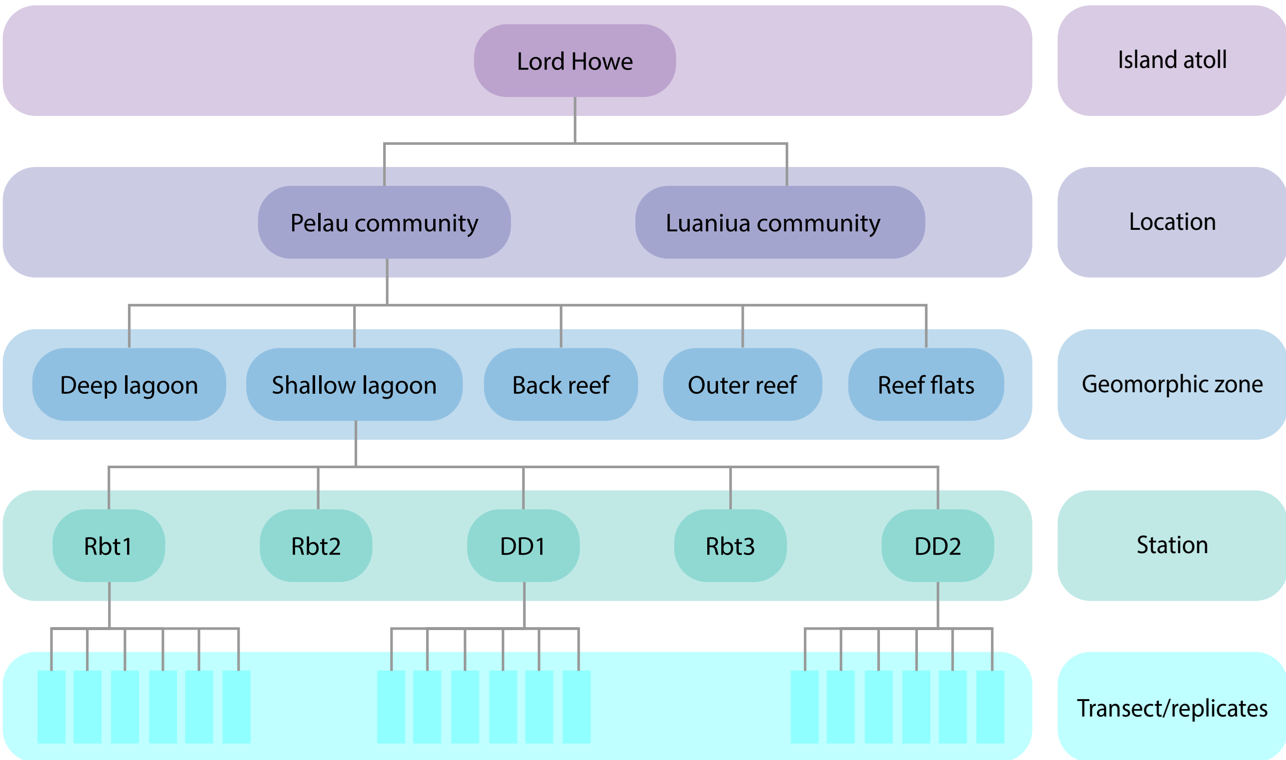

Figure 3. Survey sampling design across each location (community), and geomorphic zones at Lord Howe Atoll. Stations were chosen to survey a representative sample across each of the geomorphic zones.

Surveying deepwater sea cucumber stocks

Satellite-derived data are usually used to determine the area of available habitat for sea cucumbers. While the advantage is large-scale coverage of reefs at high spatial resolution, satellites cannot penetrate effectively any deeper than ~20 m due to light absorbance through the water column. This means that features beyond this depth are not reliably classified using automated classification from the Allen Coral Atlas. In most cases they are absent from habitat classification, for example, deep-water reefs and platforms where species such as *Holothuria fuscogilva* (white teatfish) will often be found. Because the amount of appropriate deep-water habitat for associated sea cucumber species is not well estimated, it is particularly challenging to accurately estimate their population size. A more intensive survey effort is usually required to overcome the increased habitat uncertainty at depth.

Analyses

Data collected at a representative number of stations in various habitats across Lord Howe Atoll in 2021 were compared with historical 2010 data from an MFMR-led assessment (see Ramohia et al. 2010), to ascertain if each species' population had changed. Unfortunately, the raw data were not available, so the means and standard errors were taken directly from Table 3 in the report.

Mean density ($\bar{x}$) at each of the two communities for the 2021 survey data was extracted from the SPC Field Surveys Online Tool. The mean density per hectare and the standard error of the mean is an automated output from the online tool.

Standard error (SE) was calculated by dividing the standard deviation of the mean station density by the square root of the number of stations (n) at each community within each habitat (Table A3 – Appendices).

The steps used to calculate density per hectare at the station, the standard error of the mean (SE) and the mean density per hectare ($\bar{x}$) for each species surveyed within each community boundary were as follows:

- Station density (individuals per 480 m^2) (y) is given by

  $y = \sum_{t=1}^{t} count\ per\ transect$ …eq.1

  where t is the transect which has a surveyed area of 80 m^2

  (e.g. six transects: $y = 2 + 2 + 0 + 0 + 0 + 0$

  $y = 4$) individuals per 480 m^2.

- Density per hectare at each station is given by

  $D.st = \left(\frac{y}{y = \sum_{t=1}^{t} surface\ area\ of\ the\ transect} \right) \times 10{,}000$ …eq.2

  where y is the station density and t is the transect surface area (SA)

  e.g. 80 m^2 SA per transect × 6 transects, with a total of four individuals of a species observed;

  $$D.st = \left(\frac{4}{80 + 80 + 80 + 80 + 80 + 80} \right) \times 10{,}000$$

  $$D.st = \left(\frac{4}{480} \right) \times 10{,}000$$

  $D.st = 83.33$ individuals per hectare (ind.ha^{-1}).

- Mean density (per hectare at each community habitat group inside each of the geomorphic zones is given by

  $x = \left(\frac{y = \sum_{n=1}^{n} D.st}{n} \right)$ …eq.3

  where n is the number of stations surveyed inside each of the geomorphic zones within each community boundary,

  e.g. with only three stations in a shallow lagoon geomorphic zone:

  $$\bar{x} = \left(\frac{80.33 + 20.83 + 41.67}{3} \right)$$

  $\bar{x} = 41.61$ ind. ha^{-1} on average in shallow lagoon area.

Note: The calculation of the density per transect (i.e. per 80 m^2) could also be used instead of the total count for the station (i.e. per 480 m^2). If count per transect is used for y rather than the sum of all transects, then the surface area of the transect (e.g. 80 m^2) in equation 2 above is used without summing.

- Standard error (SE) of a mean is given by:

$$SE = \left(\frac{\sigma}{\sqrt{n}}\right) \quad \ldots eq.4$$

where σ is the standard deviation (SD) of a mean $\bar{x}$. The SD can be calculated by the Microsoft Excel function "*stdev(80.33 + 20.83 + 41.67)"* or in R function *sd(x)*, and *n* is the number of stations surveyed within each group.

e.g. with only three stations and a SD of 30.19:

$$SE = \left(\frac{30.19}{\sqrt{3}}\right) = 17.43$$

$$SE = 17.43$$

Size/length structure

Length data from the surveys were grouped into 20 mm size categories and plotted as histograms. Onto these plots we added the MLL as designated in the Solomon Islands National Sea Cucumber Fishery Management and Development Plan 2014 and also length-at-maturity estimates taken from the science literature (Table A1 - Appendices) (Figure 6). Calculating the proportion of individuals greater than length-at-maturity (1) provides a visual assessment of the proportion of the population that can reproduce and therefore contribute to recruitment and stock recovery, and (2) tracks the relative abundance of length cohorts through time to assess whether adults have reproduced sufficiently to supply recruits, which is especially important in heavily fished populations where fertilisation and recruitment potential is dependent on the density of breeding adults (Shepherd and Partington 1995).

Results

Habitat

Deepwater geomorphic zones that were less than 15–20 m deep were classified visually in QGIS using satellite imagery. Visual classifications were completed manually in QGIS by drawing polygons on those deepwater zones that could not be auto-classified with Alan Coral Atlas. Total area was calculated for 10 geomorphic reef zones representing the range of sea cucumber habitat across the atoll (Table 1). Total area of targeted habitat within the Luaniua community boundaries was twice that for Pelau. The zone we classified as Deep Lagoon had by far the largest area represented inside both community boundaries at 57% for Luaniua and 62% for Pelau. This was followed by the Shallow Lagoon at 32% and 27% for Luaniua and Pelau, respectively. The inner and outer reef flats encompassed a much smaller, though still significant, amount of habitat. These four geomorphic zones represent most of the preferred habitats that sea cucumbers use.

Species composition, distribution, and density

Species composition of the sea cucumber community was similar between surveys carried out in 2010 and 2021 (Table 2). There were 13 species recorded in 2021 and 12 in 2010 and of those *Thelenota anax* (amberfish)*, Actinopyga miliaris* (hairy blackfish), *Bohadshia marmorata* (chalkfish) (formerly known and recorded as *Bohadschia similis;* Purcell et al. 2012) and *Holothuria coluber* (snakefish) were recorded in 2010 but not 2021, whereas *Bohadschia vitiensis* (brown sandfish)*, Actinopyga mauritiana* (surf redfish)*, Actinopyga palauensis* (deepwater blackfish) *and Holothuria leucospilota* (white threadfish) were recorded in 2021 but not in 2010. The top five encountered species in 2021 were *Holothuria atra* (lollyfish), *Bohadschia argus* (tigerfish), *Pearsonothuria graeffei* (flowerfish), *Holothuria whitmaei* (black teatfish) *and Holothuria edulis* (pinkfish) (Table 2).

In 2021, the frequency of occurrence (i.e. number of stations where each species was encountered out of the total number of stations surveyed) across the stations was lower than in 2010 (Table 2), yet in contrast the mean densities of all recorded species were higher in 2021 than in 2010 (Table 3), but still below regional reference densities (Table 4). The high value species *Holothuria whitmaei* and *Holothuria fuscogilva* (white teatfish) had ten- and five-times-higher densities in 2021, respectively. The density of medium value species including *Bohadschia argus* (tigerfish) and *Bohadschia vitiensis* (brown sandfish) were also approximately five times higher in 2021 than in 2010. The relative densities of other low value species were variable but, excluding those three species not observed during this survey, all were higher in 2021 than in 2010 (Table 3). Data collected in 2021 at stations within 1 km of those surveyed in 2010 also showed that most species are now at higher densities. The densities of the high value species *H. whitmaei,* and *H. fuscogilva* were also higher, although the differences were not as large (Table 3).

Table 1. Total area in hectares of geomorphic reef zones across the two major communities of Lord Howe Atoll.

Community	Geomorphic reef zone*	Area (ha)
Luaniua	Back reef slope	144
	Deep lagoon	4890
	Inner reef flat	303
	Outer reef flat	216
	Plateau	3
	Reef crest	76
	Reef slope	42
	Shallow lagoon	2751
	Sheltered reef slope	9
Total		8433

Community	Geomorphic reef zone*	Area (ha)
Pelau	Back reef slope	78
	Deep lagoon	2562
	Inner reef flat	152
	Outer reef flat	101
	Plateau	6
	Reef crest	34
	Reef slope	23
	Shallow lagoon	1109
	Sheltered reef slope	4
	Terrestrial reef flat	2
Total		4071

*Habitat maps sourced from Allen Coral Atlas[3] (https://www.allencoralatlas.org accessed 01-10-2021) were used to calculate total area of each habitat category.

Table 2. Percentage occurrence of species across surveyed stations during 2010 and 2021 surveys

Common name	Scientific name	Occurrence (%) 2021 (66 stations)	Occurrence (%) 2010 (12 Stations)
Lollyfish	*Holothuria atra*	48	70
Tigerfish	*Bohadschia argus*	29	85
Flowerfish	*Pearsonothuria graeffei*	15	40
Black teatfish	*Holothuria whitmaei*	14	5
Pinkfish	*Holothuria edulis*	12	40
Brown sandfish	*Bohadschia vitiensis*	8	25
White teatfish	*Holothuria fuscogilva*	6	15
Greenfish	*Stichopus chloronotus*	3	5
Prickly redfish	*Thelenota ananas*	3	5
Surf redfish	*Actinopyga mauritiana*	2	0
White threadfish	*Holothuria leucospilota*	2	0
Amberfish	*Thelenota anax*	0	10
Hairy blackfish	*Actinopyga miliaris*	0	1
Snakefish	*Holothuria coluber*	0	5

Table 3. Comparisons between mean densities from the 2021 survey with the 2010 survey by Ramohia et al. 2010.

	2021 (All survey stations)		2021 (Stations within 1 km of the 2010 survey)		2010	
Species	Average density (ind. ha^{-1})	SE	Average density (ind. ha^{-1})	SE	Average density (ind. ha^{-1})	Range
Bohadschia argus	24.10	6.21	23.96	11.64	5	2–17
Bohadschia vitiensis	3.27	1.47	7.29	3.13	1.4	2–8
Holothuria atra	203.84	54.94	322.92	81.62	37	2–279
Actinopyga palauensis	1.23	0.69	1.04	1.04	0	0
Holothuria edulis	27.78	19.45	10.42	7.17	0.2	2
Holothuria fuscogilva	2.45	1.39	3.12	1.71	0.4	2
Holothuria fuscopunctata	0.41	0.41	0	0	0	0
Holothuria leucospilota	0.41	0.41	0	0	0	0
Holothuria whitmaei	4.90	1.71	1.04	1.04	0.3	4
Pearsonothuria graeffei	24.92	11.13	0	0	5	4–33
Stichopus chloronotus	1.63	1.28	3.13	3.13	1	10
Thelenota ananas	0.82	0.57	0	0	0	0
Thelenota anax	0	0	0	0	0.5*	1–3

*Found in deepwater stations only

Site-specific differences in species composition across the atoll were correlated with geomorphic zones (Figure 4); for example the high value species *Actinopyga mauritiana* (surf redfish) and *Holothuria fuscogilva* (white teatfish) were found at a reef flat station exposed to waves and in the shallow lagoon that was exposed reef passage. The high value species *Holothuria whitmaei* (black teatfish), was found across the atoll but was also highly habitat specific and found only on the inner reef flat and in the shallow lagoon (Figure 4), while *Holothuria atra* (lollyfish) was observed across all the habitats surveyed, except the outer reef slope. *Bohadschia argus* (tigerfish) was common across the atoll and observed at stations located in all but the outer reef slope.

No differences in the densities of some commonly observed species were found between community boundaries (Figure 5). However, the usually quite common species such as surf redfish, elephant trunkfish and greenfish were absent at stations located within the Pelau community boundary (Figure 5), whereas pinkfish, another usually common species, was at very low densities inside the Pelau community boundary.

Table 4. Regional reference densities derived from Pacific datasets of 1,493 reef benthos stations and 476 soft benthos stations (Pakoa et al. 2014b).

Species	Regional reference density (ind. ha^{-1})
Bohadschia vitiensis	100
Pearsonothuria graeffei	100
Holothuria atra	5600
Holothuria edulis	260
Holothuria fuscogilva	20
Holothuria fuscopunctata	10
Stichopus chloronotus	3500
Holothuria whitmaei	12.5
Bohadschia argus	120
Actinopyga mauritiana	200
Thelenota ananas	30

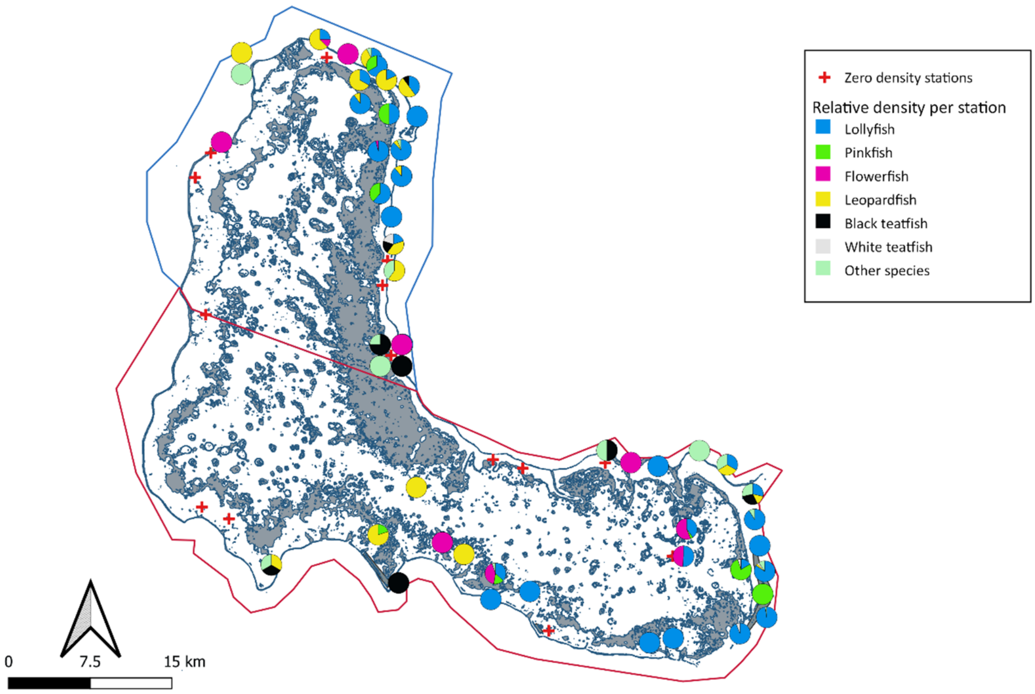

Figure 4. Relative density of the six most abundant species. Relative density is the proportional density of each species out of the total density at each station. The densities of all other species were summed as a group at each station. Stations where sea cucumbers were absent are indicated with a (+) symbol.

Length–frequency patterns

Densities of most species were too low to analyse for length–frequency patterns. The numbers of length measurements were only sufficient for *Holothuria atra* (n = 349)*, Bohadschia argus* (n = 59) and *Holothuria edulis* (n = 48) (Figure 6).

The length distributions of *H. atra* had 65%, *B. argus 76%* and *H. edulis* 44% of individuals above length-at-first maturity (L_{50}) (Figure 6). The percentage of the population above mean length was 47%, 54% and 43% for *H. atra, B. argus* and *H. edulis*, respectively. The ratio between mean length and L_{50} was 1.20, 1.12 and 1.03 for *B. argus, H. atra* and *H. edulis*, respectively; values greater than 1 reflect a population mean larger than L_{50}, so there are proportionally more mature adults within the population.

The MLL for *H. atra* is set at 300 mm, so only 7% of measured individuals were above MLL. That 65% of *H. atra* were above L_{50} but only 7% were above MLL indicates that the MLL for *H. atra* has been set too large and is not consistent with the known L_{50} for this species. The MLL for *B. argus* is 300 mm and is set at the same length as L_{50} so retains the same proportion, that is, percentage of the population above MLL and L_{50}. The MLL for *H. edulis* is set at 200 mm, so 29% of measured individuals were above MLL.

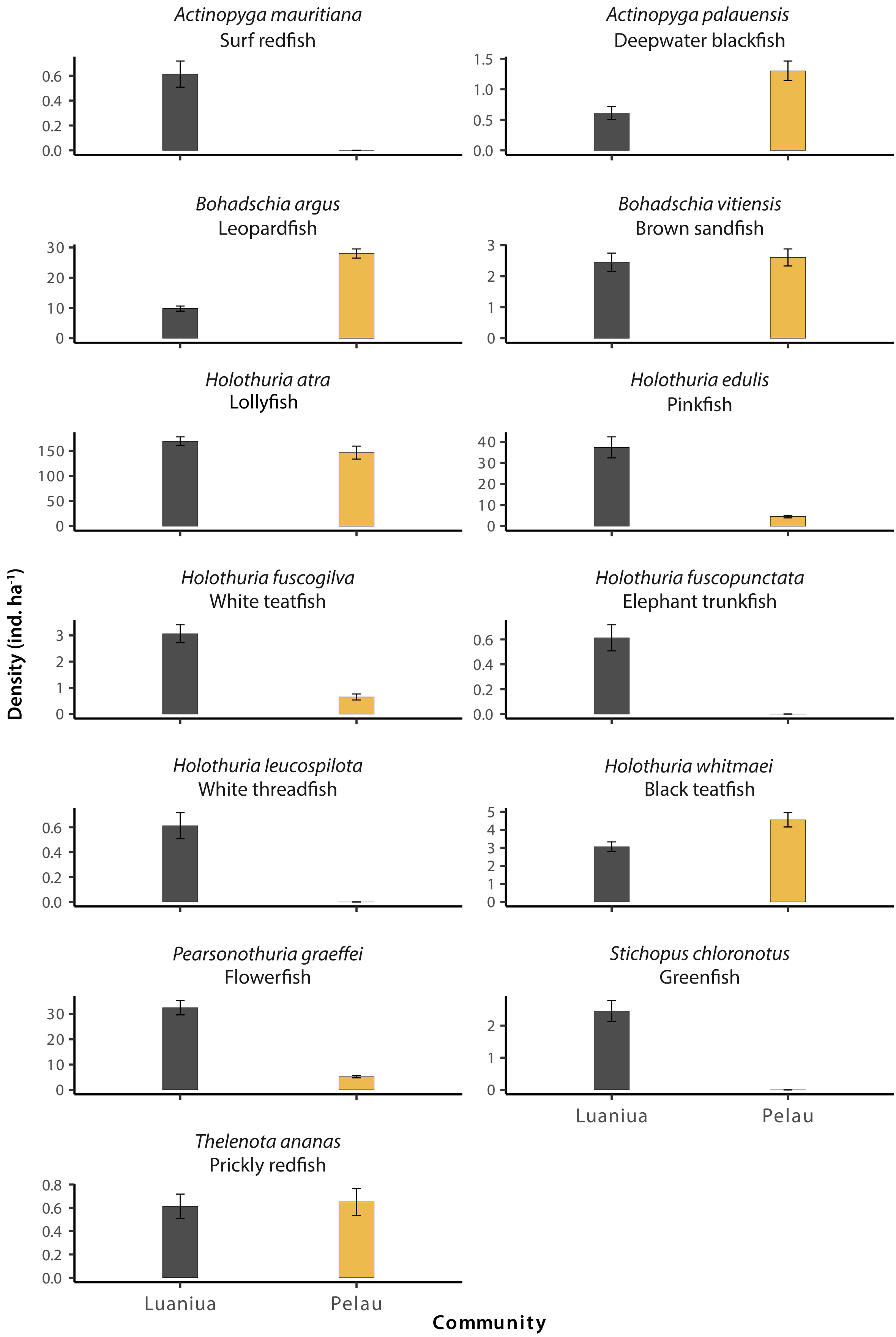

Figure 5. Mean density (ind. $ha^{-1} \pm$ SE) for 13 sea cucumber species from surveys carried in 2021 at two communities, Pelau and Luaniua, at Lord Howe Atoll. Plot titles are scientific and local common names.

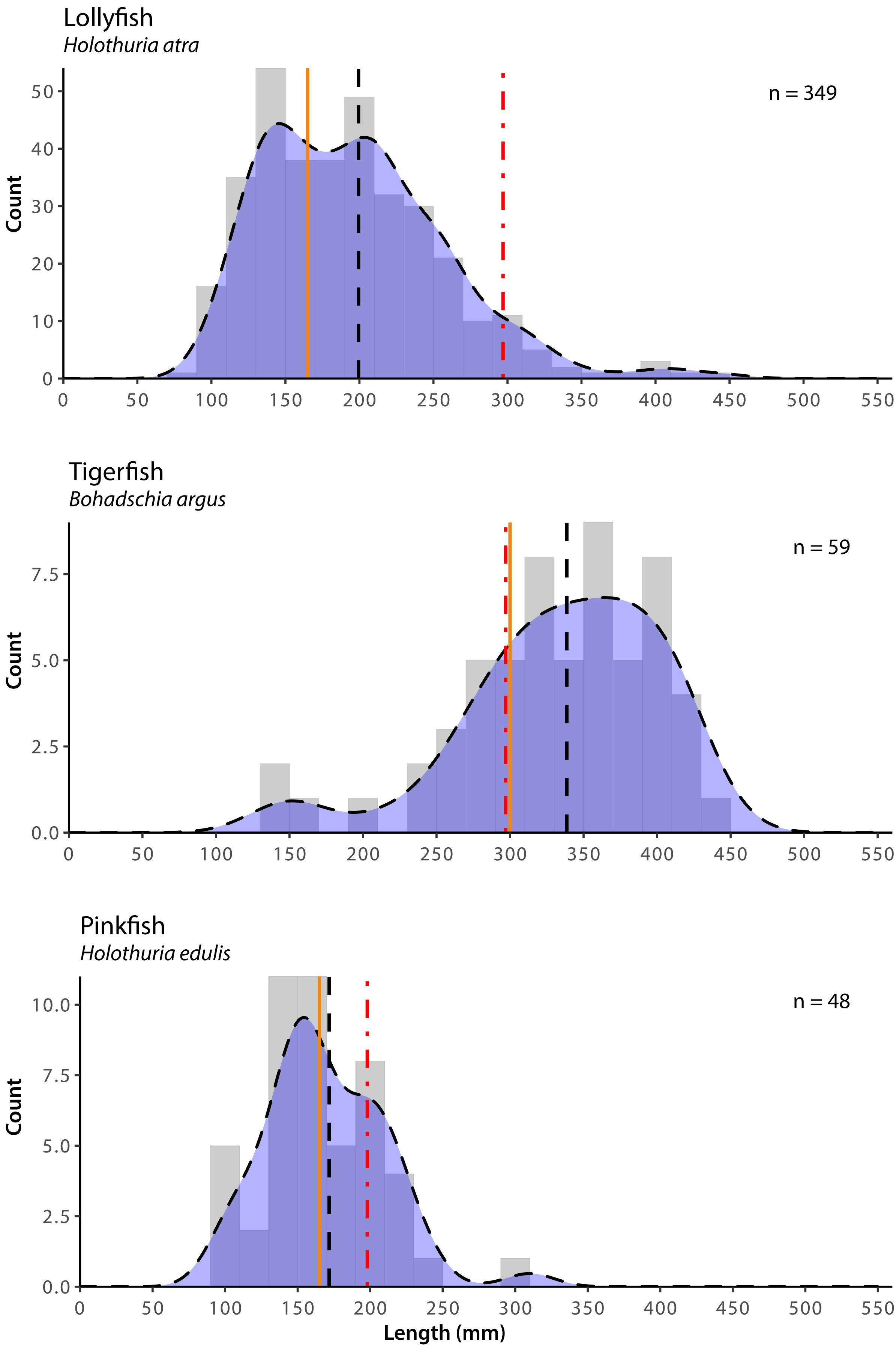

Figure 6. Length frequency (i.e. count of the number of individuals within each length category) and density curves for three sea cucumber species from 2021 survey. Data were pooled from both community boundaries. Black and red dashed lines indicate mean length for this survey and MLL respectively, and the orange solid line indicates length-at-first maturity (L_{50}) (Conand 1989; Conand and Byrne 1993; Purcell et al. 2012). Plot titles are common name and scientific name and n represents the total number of length measurements for each species.

Discussion

Results of the 2021 survey show that sea cucumber population densities remain extremely low at Lord Howe Atoll (herein called the atoll) and are well below relevant regional reference densities for stocks considered healthy. This is despite periodic, and sometimes years-long, nationwide bans on harvesting and exports to try and manage stocks. These low numbers are closely correlated with heavy exploitation levels over the last four decades, including the likelihood of illegal harvesting during national bans. It is difficult to quantify the effects beyond general conclusions, given the absence of regular harvest data from the atoll, which could have provided some detail around CPUE, species composition and size structure of catches and would have allowed for a more precise assessment. Nevertheless, there are some obvious outcomes that can be discussed when considering the recent survey results.

A major factor in the overharvesting of sea cucumbers at the atoll is the method used for catching them. Trawling has long been recognised as a highly efficient but destructive fishing method for sea-bed communities (Jones 1992; Kaiser 2019). Sea cucumbers are particularly vulnerable as they form aggregations and have no "escape response" that more mobile organisms can use to avoid the net. Therefore, all sea cucumbers within the trawl paths are likely to be caught and where aggregations exist very high catches can occur, removing many animals with minimal effort. Removing trawling as a fishing method would be the quickest way to release significant pressure off stocks. Continued use of nets for catching sea cucumbers would need significant regulation and strong oversight to avoid the continual wholesale depletion and commercial extinction of sea cucumbers in the atoll. Increasing net mesh sizes, returning undersize individuals to the water, and a cap on total nets allowed in the fishery are all necessary management requirements if this method remains.

Ongoing illegal activity may also have played a role in impeding stock recovery. There have been multiple reports of illegal harvesting out of Lord Howe Atoll, with anecdotal evidence of attempted illegal exporting in shipping containers (Christensen, 2011). In July 2017, Solomon Star news reported that local people in Lau lagoon had requested that MFMR investigate illegal harvesting of sea cucumbers from the area (Wilson 2017). The newspaper article indicated that their sources (members of the public) observed locals from Lord Howe Atoll selling illegally acquired sea cucumber to a Chinese businessman in Auki Malaita provincial town during the national ban on harvest and export. The concerned citizens also claimed that the local buyer was purchasing sea cucumbers for as little as SBD 70 per kg; which is severely undervalued at half the 1999 value of SBD 130 per kg for those species (Gillet and Lam, 1999). The people reporting illegal activities to the newspaper also claimed that, despite the government ban, some locals continued to harvest sea cucumbers. More recently, on 18 June 2021, MFMR confiscated and destroyed a large illegal beche-de-mer shipment and it was understood that the products were mostly from Lord Howe Atoll individuals selling to a few Chinese buyers.

Previous studies have all confirmed high fishing pressure at the atoll (Crean 1977, Holland 1994, Gillett and Lam 1999, Ramohia et al. 2010). Initially fishers in the 1970s were highly selective, targeting only the high value species such as the black teatfish, *Holothuria whitmaei* (Crean 1977). However, when these species became depleted, prices rose for the remaining medium-to-low-value species, which the fishery subsequently targeted (Ramohia et al. 2010) to maintain an income. This is a common pattern in poorly managed commercial fisheries known as "fishing down the value food chain" (Pauly et al. 1998; Hutchings and Reynolds 2004; Essington et al. 2006).

The 2021 survey found very low numbers of all sea cucumber species except for *H. atra* which has low commercial value and hence would not be expected to be heavily harvested. Comparison with regional reference densities (see Table 3) confirms the densities of all commercially valuable species at the atoll are far below healthy levels. Moreover, numbers were so low that population size structures could not be examined for 10 out of the 13 species targeted in the surveys. During the 1970s, for example, the CPUE of black teatfish was 11.1 individuals per man hour (Crean 1977), while in 2021 only 11 individuals in total were seen across the 66 stations surveyed. If each station requires 1.5 hours to complete, the CPUE for those 11 individuals found across 66 stations would be approximately 0.11 individuals per hour of search effort, which is 100 times lower in 2021 than it was in the 1970s. Additionally, these 11 individuals in total calculates to approximately 3 ind. ha^{-1}, which compares poorly with the regional reference density for this species of 12.5 ind. ha^{-1}.

While densities of *H. atra* were also lower than expected, the length–frequency distribution shows the population is still structurally healthy and it increased substantially in density from 2010 to 2021. The length–frequency plot (Fig. 6a) shows that approximately 65% of individuals surveyed were above length-at-maturity, with mean size of measured individuals approximately 20% above length-at-maturity (L_{50}). This is what a size distribution should look like if a stock is structurally healthy and not being overfished. The presence of individuals across all size classes with a mean size at least 20% above maturity indicates there remains regular recruitment to the stock and enough mature and larger more fecund adults that continue to contribute disproportionately more to reproduction.

Of the other two species that had just enough numbers to investigate their size structure, both *Bohadschia argus* (tigerfish) and *Holothuria edulis* (pinkfish) showed an increase in density from 2010 to 2021, which does indicate growing/recovering populations, although their densities remain well below the regional reference densities. While the overall densities for *B. argus* are low, the mean size of the population remains 11% above length-at-maturity, which indicates there are proportionately more adults above L_{50} and the potential for some recruitment. The situation looks less favourable with *H. edulis*, with mean length of the surveyed animals only 3% above the length-at-maturity. This indicates a lack of mature animals in the population that will impede reproduction and recruitment levels. The numbers counted for both species are, however, too low to be confident with interpretations other than to suggest more time for recovery is clearly needed. While there were insufficient numbers of other species to make a clear assessment, there is still evidence that some of them increased in density between 2010 and 2021 (Table 4). However, the increases were small and the only conclusion to be made is that more time is needed for recovery.

Lord Howe Atoll is remote from other reef systems so there will be limited sea cucumber larvae arriving from outside sources. Therefore, sea cucumber stocks within the atoll are more than likely to be providing most of the new recruits back into the system. So low numbers of mature animals due to overharvesting will mean reduced levels of both recruitment and stock recovery. In addition, as an atoll ecosystem, productivity is lower than that found around high islands in the Solomons, such as Santa Isabel or Choiseul, where there is greater transfer of nutrients/energy from land to the sea (Eriksson et al. 2018). This translates to slower rates of recovery from overharvesting in atolls. A critical mass of mature sea cucumbers must be retained in the atoll to sustain populations, and the only way to achieve this, given the state of the stocks at this time, is to allow recovery to continue without fishing. Subsequent re-surveys would need to show sufficient recovery before harvesting could resume.

While the visual surveys done in 2021 provided a robust assessment of sea cucumber densities around the atoll, they were confined to depths less than 20 metres. This would be satisfactory if fishing were limited to these depths and to those species and populations whose habitat is largely defined within this depth range. This survey, however, does not provide any information on the state of deep-water sea cucumber stocks. A single observation of a fisher's trawl from deep water made by the survey team showed that catch composition includes *B. argus* (tigerfish), *Holothuria lessoni* (golden sandfish), *Stichopus herrmanni* (curryfish), *Stichopus horrens* (Peanutfish, elsewhere known as dragonfish) and *Stichopus ocellatus* (curryfish sp.) a previously unrecorded species in the atoll. The presence of these species from the trawl and their absence (excluding *B. argus*) from the 2021 survey data, highlight the need for increased monitoring of deepwater stocks. Without this information it is not possible to assess the health of these species in deepwater habitats; however, because trawling targeted the deeper lagoon areas and continued until catches were minimal it is highly likely that stock levels of the deepwater species are also depleted, just like the shallow water stocks. Surveying deepwater sea cucumber stocks is difficult and will require either a towed video camera approach or sampling of the population via trawling to calculate relative population density through assessment of CPUE.

Sea cucumbers display a range of behaviours such as burrowing or nocturnal versus daylight activity, all of which can affect the ability of surveys to accurately reflect population densities (Friedman et al. 2006). There is no one survey method that will capture all species information equally well and the best approach is to combine multiple methods. In-water visual surveys remain the most powerful method for assessing shallow water densities, while trawls would be the most logistically appropriate method to assess deep water densities. Recovery of the sea cucumber populations should be regularly monitored with these methods to map when the fishery becomes viable again. When the fisheries open, then close monitoring and enforcement of catches to ensure minimum size limits are being adhered to should be enough to control CPUE.

Calculation of regional reference densities has been one approach to try and obtain baseline estimates of healthy sea cucumber population densities (e.g. Pakoa et al. 2014b) against which to compare individual surveys. The use of multiple surveys from multiple areas to generate a reference density is a valid approach as it will incorporate the range of natural densities that different habitats, countries and regions can sustain. However, currently available estimates have not distinguished between atoll environments and high-island environments which have been shown to have substantially different carrying capacities (Eriksson et al. 2018). This has meant that comparison of Lord Howe Atoll estimates with regional reference densities can exaggerate the poor state of the atoll sea cucumber fishery. Subsequent reporting of regional reference densities will provide an atoll versus high island estimation to provide for more realistic interpretation. We have used the reference density comparisons more generally here just to illustrate the types of densities that can be found elsewhere.

Management interventions

Until stocks recover to sustainable levels the focus must be on preventing illegal fishing from occurring, and undertaking surveys every two to three years to measure the rate and extent of any recovery. It is extremely difficult, however, to gauge healthy stock levels in a mixed species fishery given the variable growth rates, preferred habitat and natural population densities among species. Moreover, the time and costs involved in continuously conducting fishery-independent stock assessment surveys to calculate stock size creates situations where monitoring occurs less often than what is optimal, leading to data deficiencies and poor management (Prince et al. 2015). A relatively simple and effective method, however, that can be used to gauge healthy stock levels would be to use length-based indicators calculated from population size distributions (Hordyk et al. 2015). For example, healthy stock densities could be assumed when the mean length of the measured species population is approximately 30% above L_{50} and the length distribution of a species population is near normal. These data can be easily constructed from data collected during fishery-dependent and/or independent surveys (Hordyk et al. 2016; Chong et al. 2020; Kell et al. 2022). For this management measure to work, however, the MLL must be set at least 20% above L_{50} so that mature adults remain within the population and can contribute to stock recovery. If size limits are strictly followed, then sea cucumber populations could deal with sustainable levels of extraction, avoiding the boom–bust cycles that so often characterise sea cucumber fisheries across the Pacific. During this period of recovery, investment should be made in training of community members to work with MFMR staff to undertake monitoring and surveillance of their sea cucumber resources. This is necessary to ensure compliance with fishing bans and should be implemented not only in the atoll but across the Solomon Islands.

Once recovery of sea cucumber stocks has reached acceptable levels as measured through surveys, then to achieve sustainable fishing targets, the sea cucumber fishery should establish stringent management and compliance strategies around harvesting. Foremost in plan development should be recognition that it is the proportion of reproductively mature stock within the atoll that will decide the health and resilience of the fishery. A minimum percentage of the reproductively active stock for each species must therefore be maintained to allow for sustainability in the fishery: usually set at 30%–40% of the total reproductively active stock (e.g. Prince et al. 2015). Surveys of size and density will provide the necessary information to calculate this and set a minimum allowable size for each species to ensure population sizes remain viable.

To provide more security around maintaining sufficient breeding stocks in the atoll, especially if trawl nets continue to be used, we recommend that community managed, permanent no-take zones should be established, to work alongside size limits. These zones will help to maintain a population of reproductively mature adult sea cucumbers by providing animals with time to grow without being taken (Purcell and Kirby 2006; Cariglia et al. 2013). Populations within permanent no-take zones will provide benefits to the fishery by enhancing levels of spawning and subsequent rates of fertilisation, leading to higher levels of recruitment back into the fishery (Purcell et al. 2010). Site selection of the protected areas and the amount of area to be protected are key considerations in order for this approach to work.

In some traditional management systems rotational no-take zones have been a preferred method for managing fisheries. Rotational harvest management has been defined as the “spatial shifting of fishing effort, in a systematic way among demarcated fishing grounds, over set periods of time” (Purcell et al. 2010). This system is supposed to allow stocks to recover in one area by shifting fishing effort to another area before too much fishing has occurred (Purcell et al. 2010). Rotational closures have been used historically by Lord Howe Atoll fishers (Crean, 1977); however, its eventual demise was symptomatic of the many reasons why management of sea cucumber stocks is difficult to uphold. There needs to be capacity to enforce the regulations, to measure catch effort in opened areas, to measure the recovery of populations in closed areas, navigate complex access rights to fishing grounds and remove the influence of unscrupulous buyers (Purcell et al. 2016).

Management recommendations seek to provide a system that will allow for continual access to a fishery without permanently damaging the viability of the stocks underlying the fishery. The key drivers of this are an understanding of the biology and ecology of the animals being caught. With this information we can design fishing protocols that will ensure not too many individuals are taken from the population and it will remain viable and healthy. Unfortunately, this means there will always be a limit on how many individuals can be taken from a fishery. This part of fisheries management is actually the easiest to achieve; it is managing the human interactions within the fishery that is most difficult. The total benefit that can be extracted from the fishery each year is set by the biological and ecological parameters; it is then up to the communities to allocate this total benefit equitably. Going back to the resource to top up the annual benefit only succeeds in reducing the benefit for subsequent years until there is nothing of commercial value left.

Capacity building

Training for MFMR inshore science staff (one woman and three men) took place before and after the survey. The major objectives of the training were to build capacity in fishery independent survey methods and data analysis.

Before the survey, remote training with MFMR and SPC staff took place. Training in historical data review and subsequent utilisation for planning surveys was completed. Survey design – including habitat selection, survey methods, and logistics were discussed, as well as training in the use of handheld global positioning systems (GPS). Upon completion of the pre-survey training, MFMR inshore science staff completed the survey over a period of four weeks in August and September 2021.

After the survey, further training in data management, quality control and entry into SPC web application was carried out. MFMR inshore science staff retrieved data from the SPC web portal in Excel sheets and were trained on data analysis through Excel and the open-source spatial data management software QGIS.

Due to travel restrictions to combat the COVID-19 pandemic, training – which is usually done at SPC headquarters in Noumea, New Caledonia – was completed remotely. Nevertheless, the success of the training provided in-country has enabled these data to be collected and reported on by MFMR staff and SPC. MFMR staff who underwent training successfully carried out the survey and played key roles in data analysis and reporting. With the training provided, MFMR staff will continue to collect data on key invertebrate populations and on the health of reef habitats. These data will highlight shifting trends in populations as well as changes in key habitats.

Conclusions

Recovery of sea cucumber stocks in Lord Howe Atoll is limited, having only marginally improved since 2010. We have indicated that there are multiple possible reasons for the slow recovery and persistent low densities; excessive historical harvests and historical illegal poaching would seem to be the most likely causes. Increasing demand for sea cucumbers and stock depletions at regional scales drive increasing demand for products from more remote regions, which will only exacerbate overharvesting at Lord Howe Atoll unless robust management strategies are implemented. These strategies should include the use of appropriately located marine protected areas to provide a space for sea cucumber populations to grow and reproduce normally while free from harvesting pressure. There should also be a reduction in local harvesting levels via appropriate mechanisms such as shortened open seasons, no-takes zones, appropriately researched and established rotational closures, size limits and increased monitoring, control, surveillance and enforcement to ensure that such measures are implemented effectively.

The Luaniua Community field survey team: left to right: Mr Dauwane, Assaneth Buarafi, Ronnie Posala, Paul J Tua, Mathew Vasi and David Aram. (image: ©Ronnie Posala)

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Appendix

Table A1. FAO Code, MLL live and dry (Solomon Islands Beche-de-mer Sea Cucumber Management and Development Plan), and length-at-maturity (Conand 1981, 1993a, 1993b, 2003, 2006) of all species encountered across Lord Howe Atoll during the 2021 survey. Bold indicates length is too large. Italics and underlined indicates the MLL can be increased to at least 20% larger than length-at-maturity.

Scientific name	Common name	FAO code	Minimum legal length live (mm)	Minimum legal length dry (mm)	Length-at-maturity live (mm)
Actinopyga mauritiana	Surf redfish	KUY	*<u>250</u>*	100	220
Bohadschia argus	Leopardfish/tigerfish	KUW	*<u>300</u>*	150	300
Bohadschia vitiensis	Brown sandfish	BDV	*<u>350</u>*	150	300
Holothuria atra	Lollyfish	HFA	**300**	150	165
Holothuria edulis	Pinkfish	HFE	*<u>200</u>*	150	200
Holothuria fuscogilva	White teatfish	HFF	*<u>350</u>*	150	320
Holothuria fuscopunctata	Elephant trunkfish	HOZ	450	200	350
Holothuria whitmaei	Black teatfish	JDG	*<u>300</u>*	150	260
Pearsonothuria graeffei	Flowerfish	EHV	300	150	300
Stichopus chloronotus	Greenfish	JCC	*<u>200</u>*	100	200
Thelenota ananas	Prickly redfish	TFQ	*<u>350</u>*	200	300

Table A2. Stock level estimates within each community boundary expressed as number of individuals rounded to the nearest 100. These values were calculated from the bootstrapped lower confidence interval for species that were observed during the survey.

Scientific name	Common name	Community	Stock level estimate
Actinopyga mauritiana	Surf redfish	Luaniua	0
		Pelau	0
Bohadschia argus	Tigerfish	Luaniua	34,000
		Pelau	11,500
Holothuria atra	Lollyfish	Luaniua	44,900
		Pelau	14,500
Holothuria edulis	Pinkfish	Luaniua	48,700
		Pelau	2,000
Holothuria fuscogilva	White teatfish	Luaniua	0
		Pelau	0
Holothuria fuscopunctata	Elephant trunkfish	Luaniua	300
		Pelau	0
Holothuria lessoni	Brown sandfish	Luaniua	400
		Pelau	1,100
Holothuria whitmaei	Black teatfish	Luaniua	1,000
		Pelau	500
Pearsonothuria graeffei	Flowerfish	Luaniua	438,900
		Pelau	2,300
Stichopus chloronotus	Greenfish	Luaniua	3,300
		Pelau	0
Thelenota ananas	Prickly redfish	Luaniua	300
		Pelau	0

Table A3. The mean density (ind. ha-1) and standard error (SE) at each community within each geomorphic reef zone during the 2021 survey.

Scientific name	Community	Inner reef flat	Outer reef flat	Back reef slope	Deep lagoon	Shallow lagoon	Reef slope
Actinopyga mauritiana	Pelau	0	0	0		0	0
	Luaniua	2.08 ± 0.81	0	0	0	0	
Bohadschia argus	Luaniua	6.25 ± 1.24	33.33 ± 7.82	0	10.42 ± 1.81	8.33 ± 3.24	
	Pelau	24.31 ± 6.16	52.08 ± 9.07	34.72 ± 7.36		13.89 ± 2.87	0
Bohadschia vitiensis	Luaniua	4.17 ± 1.62	0	5.95 ± 1.94	0	0	
	Pelau	3.47 ± 1.05	0	1.74 ± 0.74		4.63 ± 1.71	0
Holothuria atra	Luaniua	64.58 ± 21.61	179.17 ± 47.89	321.43 ± 53.13	104.17 ± 18.13	175 ± 31.32	
	Pelau	24.31 ± 6.16	62.5 ± 3.63	38.19 ± 10.36		337.96 ± 86.74	0
Holothuria edulis	Luaniua	0	0	23.81 ± 7.75	10.42 ± 1.81	108.33 ± 37.74	
	Pelau	0	20.83 ± 3.63	0		11.57 ± 4.27	0
Holothuria fuscogilva	Pelau	0	0	0		2.31 ± 0.85	0
	Luaniua	2.08 ± 0.81	0	0	0	8.33 ± 2.48	
Holothuria fuscopunctata	Luaniua	2.08 ± 0.81	0	0	0	0	
	Pelau	0	0	0		0	0
Holothuria whitmaei	Luaniua	8.33 ± 1.79	0	0	0	2.08 ± 0.81	
	Pelau	3.47 ± 1.05	0	8.68 ± 2.31		2.31 ± 0.85	0
Pearsonothuria graeffei	Luaniua	8.33 ± 3.24	0	80.36 ± 21.07	145.83 ± 25.39	16.67 ± 6.49	
	Pelau	0	10.42 ± 1.81	6.94 ± 2.28		2.31 ± 0.85	20.83 ± 3.63
Stichopus chloronotus	Luaniua	6.25 ± 2.43	0	0	0	2.08 ± 0.81	
	Pelau	0	0	0		0	0
Thelenota ananas	Luaniua	2.08 ± 0.81	0	0	0	0	
	Pelau	0	0	1.74 ± 0.74		0	0

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