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Assessment of the coconut crab (*Birgus latro*) at Palmerston Atoll, Cook Islands

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Assessment of the coconut crab (*Birgus latro*) at Palmerston Atoll, Cook Islands

Prepared for the Palmerston Island Council and Community

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Pacific Community
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Executive summary

This report presents the results of a coconut crab assessment conducted on Palmerston Atoll in October and November 2018, and provides recommendations to assist the local island government to effectively manage the coconut crab population on the island.

The primary objective of the assessment was to collect information on coconut crab population status, size structure and distribution to provide an index of relative abundance and population estimates of coconut crabs for each islet and the atoll as a whole. The secondary objective was to train and build the capacity of the Palmerston community in conducting coconut crab surveys. This is the third coconut crab assessment conducted in the Cook Islands, and findings from this assessment will be compared with past assessments on Mauke and Mangaia islands. This assessment and the findings add to the body of knowledge on the status of coconut crabs in the Cook Islands.

Three methods were utilised in this study: baited stations, transect survey and mark-and-recapture. The baited station method was used to calculate catch per unit effort (CPUE) in the form of crabs per baited station, during a six-hour time period. Transect surveys were used to calculate the number of crabs per unit of area, and mark-and-recapture was used to estimate population size.

The average CPUE for Palmerston Atoll was 0.84 (± 0.29 SE) crabs per baited station. The average transect density for Palmerston Atoll was 4.56 (± 1.18 SE) individuals per acre. Comparison with both Mauke and Mangaia, CPUE was greatest on Palmerston, and transect density was slightly lower on Palmerston than on Mauke.

In total, 301 crabs were caught and marked during the first capture (using the baited station method and opportunistic observations); 84 crabs were recorded during the second capture occasion (using transect surveys), of which 12 were recaptures of initially marked crabs. As a result of two assumption violations between capture occasions, the population estimate derived using the mark-and-recapture study is not reliable and cannot be used to assess population levels.

There was a clear difference in mean size and size distribution between female and male crabs. The average size of female coconut crabs was 38 mm (± 0.39 SE) while males were 48 mm (± 1.07 SE) thoracic length. Over 99% of female and 92% of male crabs had recorded lengths greater than 25 mm; the reported size at maturity. The sex ratio is 1:1 in the smallest size classes (20–29 mm) but increases rapidly in favour of females before switching to male crabs in size classes greater than 50 mm. From 50–59 mm, the sex ratio is 1 female to 15 males (1:15) and from 60–69, the sex ratio is 0:37.

To ensure sustainable harvests and long-term survival of coconut crabs on Palmerston Atoll, a series of recommended actions are listed for consideration. For detailed information on the reasons behind these actions, refer to section 5, the recommendations are briefly summarised below:

1. Introduce a minimum harvest size limit of 50 mm thoracic length.
2. Protect female crabs from being harvested.
3. Establish a closed season for collecting coconut crabs around their breeding season.
4. Consider banning or controlling coconut crab exports.
5. Establish a coconut crab reserve.
6. Establish a continuous monitoring programme.
7. Continue with the proposed rat eradication project.

1. Introduction

1.1. Background

Palmerston Atoll is the northernmost atoll in the Southern Group of the Cook Islands, and is situated at 18°2.975'S and 163°9.372'W (see Fig. 1)[1]. As an oceanic atoll it consists of six main islets or *motu*: Primrose, Bird, Home, Toms, North and Cooks. Each of the islets are separated by a reef flat and soft benthic habitat. The distance between each varies from 900 m to 7 km, with a total lagoon area of approximately 35 km^2 (National Environment Service 2011). Home Islet is the largest of the six islets and has the highest elevation of 5 m (National Environment Service 2011). At the last census in 2016, the total population was 58 (Cook Islands Statistics Office 2018), all of whom live on Home islet.

The governing system on Palmerston consists of an elected mayor and an Island Council, and is in accordance with the Island Government Act 2012–2013. The executive officer, who is also an Island Council member, is the primary point of contact for central government in Rarotonga, and is responsible for administrating major operations on the atoll. The elected mayor and Island Council make up the island government and are in charge of managing the atoll's resources. Moreover, the Palmerston community recently developed an island strategic plan and set the community's goals and aspirations under the vision "committed to building a better future together". The plan outlines how the Island Council and island government will improve the welfare of the island through improved and sustainable management of natural resources and the island's assets (Office of the Prime Minister 2017).

One of the key natural resources of the atoll is the coconut crab (*Birgus latro*), which is considered a delicacy by the Palmerston community as well as the rest of the Cook Islands people. The crab is harvested for special occasions such as birthdays, community celebrations and when there are special visitors to the island. To ensure the long-term sustainability of coconut crab populations on Palmerston, it is important for the Island Council to have access to up-to-date information on the status of coconut crab stocks.

Historical information on coconut crabs on Palmerston is limited. A marine resource assessment carried out by the Ministry of Marine Resources (MMR) in collaboration with the South Pacific Commission (SPC)[2]in 1988, observed coconut crabs in small numbers (Preston et al. 1995). The assessment was extensive and focused mainly on coastal and oceanic fish, squid, sharks, turtles, clams, trochus, oysters, snails, limpets and sea cucumbers, and is the first record of coconut crabs on Palmerston. In 2007, profile surveys of socioeconomic, finfish and invertebrate resource assessments (excluding coconut crabs), were conducted by SPC on four islands in the Cook Islands, including Palmerston (Pinca et al. 2009). The socioeconomic surveys revealed that the perception of the local community was that coconut crabs had moderately decreased both in size and number since the late 1990s (Pinca et al. 2009). Since these observations, no direct assessments of the status of coconut crabs have been conducted, thus prompting a specific coconut crab survey to be undertaken to assess the status and current coconut crab populations on Palmerston.

1.2. Biology

The coconut crab, locally known as *unga*, is the largest terrestrial land crab. It has a distribution range from Mauritius in the western Indian Ocean to the Tuamotus in the eastern Pacific Ocean (Fletcher 1993). They are generally more common on isolated atolls or high island habitats rather than continents such as Asia and Australia. They favour coastal habitats and will make use of any type of shelter, including caves, crevices, tree roots, hollow logs or earth burrows during the day. They are often found close to the sea because of their need for saltwater, which is ingested to maintain osmotic balance (Fletcher 1993). Their diet, other than coconut flesh, consists of other fruits such as pandanus, berries, leaves, crabs, seabirds, and other small animals such as turtle hatchlings (Wilde et al. 2004; Matamaki et al. 2016).

They are reported to reach maturity at a size of around 25 mm thoracic length (TL), which is, on average, five years of age (Helfman 1973). During mating, larger males turn the female over onto her back before depositing spermatophores at the base of the female crab's last pair of walking legs (Fletcher 1993). Fertilisation is estimated to take two to three weeks before the eggs are released into the ocean during high tide (Fletcher and Amos 1994). The larval phase typically lasts around three to four weeks in the ocean before a small percentage of these juvenile coconut crabs return to shore to find empty gastropod shells to live in (Fletcher 1993; Drew et al. 2010).

1.3. Purpose of the study

The purpose of the Palmerston visit for the National Environment Service (NES) was part of a larger resource assessment in

[1] Latitude and longitude taken from Google Earth and reported in degrees, decimal minutes format.
[2] Formerly known as the South Pacific Commission here, before a name change to Pacific Community in 1997.

collaboration with other government agencies, including the Ministry of Agriculture, MMR, Marae Moana and the non-governmental agency Te Ipukarea Society. Two objectives were part of the NES visit to Palmerston:

1. **To carry out a baseline survey of the status of coconut crabs on Palmerston** by collecting information on their population status, size structure and distribution across the atoll, and providing a population estimate for each islet and the atoll as a whole. The information will assist in making sound decisions in managing Palmerston's coconut crab resource.

1. **To build capacity of the Palmerston people,** through training, to conduct coconut crab surveys using appropriate methodologies. This will enable sustained long-term monitoring of coconut crabs on the atoll, and the ability to carry out future surveys.

This is the first time a dedicated assessment specific to coconut crabs has been carried out on Palmerston Atoll. Results of this assessment will provide up-to-date baseline data on the status and distribution of coconut crab populations across the atoll. These results will assist in determining the best areas for, and best approaches to, managing the sustainable harvesting of the coconut crab population. Capacity building was an equally important outcome from the assessment, to ensure there were appropriate skills within the community to manage sustainable harvests and conduct future assessments with appropriate methodologies. The work carried out on the atoll supports the Island Council in managing species protection through recommendations from this study. It also addresses key areas in the Palmerston Island Strategic Plan 2017–2020, particularly priority number two of the strategy, which states: "to improve economic opportunity, food security and nutrition for better health and prosperity". The activities to achieve this will be through managing trips to the *motu* and minimising the overharvesting of resources, namely the coconut crab (Office of the Prime Minister 2017).

1.3.1. Participant training

Participants trained for the coconut crab survey included community members, mainly secondary school students between the ages of 14 and 17 years from Palmerston Lucky School. During training participants were introduced to the biology of the crab, its life cycle and distribution in the region, and the results from coconut crab assessments conducted on the islands of Mauke and Mangaia. This was followed by outlining appropriate survey methodologies, demonstrating the use of equipment, determining the sex of crabs, measuring their size and recording data. Further training also involved hands-on exercises in the use of callipers for measuring the thoracic length of crabs, opening coconut bait, tying coconut bait to a fixed or solid object, and pacing the 20-m distance between each bait station.

2. Methods

2.1. General

The coconut crab survey on Palmerston was carried out between 24 October and 3 November 2018, during the full moon and last quarter moon phases.

2.2. Survey design

Due to the small size of the atoll, the sampling design involved a combination of complementary methods, including baited stations, transects, and mark-and-recapture using the Lincoln-Petersen method. All six main islets (hereafter referred to as *motu*) within Palmerston Atoll were assessed: Home, Primrose, Bird, Toms, North and Cooks (Fig. 1).

For the purposes of this survey, smaller neighbouring *motu* that were also assessed were grouped with the nearest main *motu*. Hence, Lee To Us and John's Point were grouped with Bird; Calcutta grouped with Cooks; and Tara-i-Tokerau grouped with North (see Fig. 1).

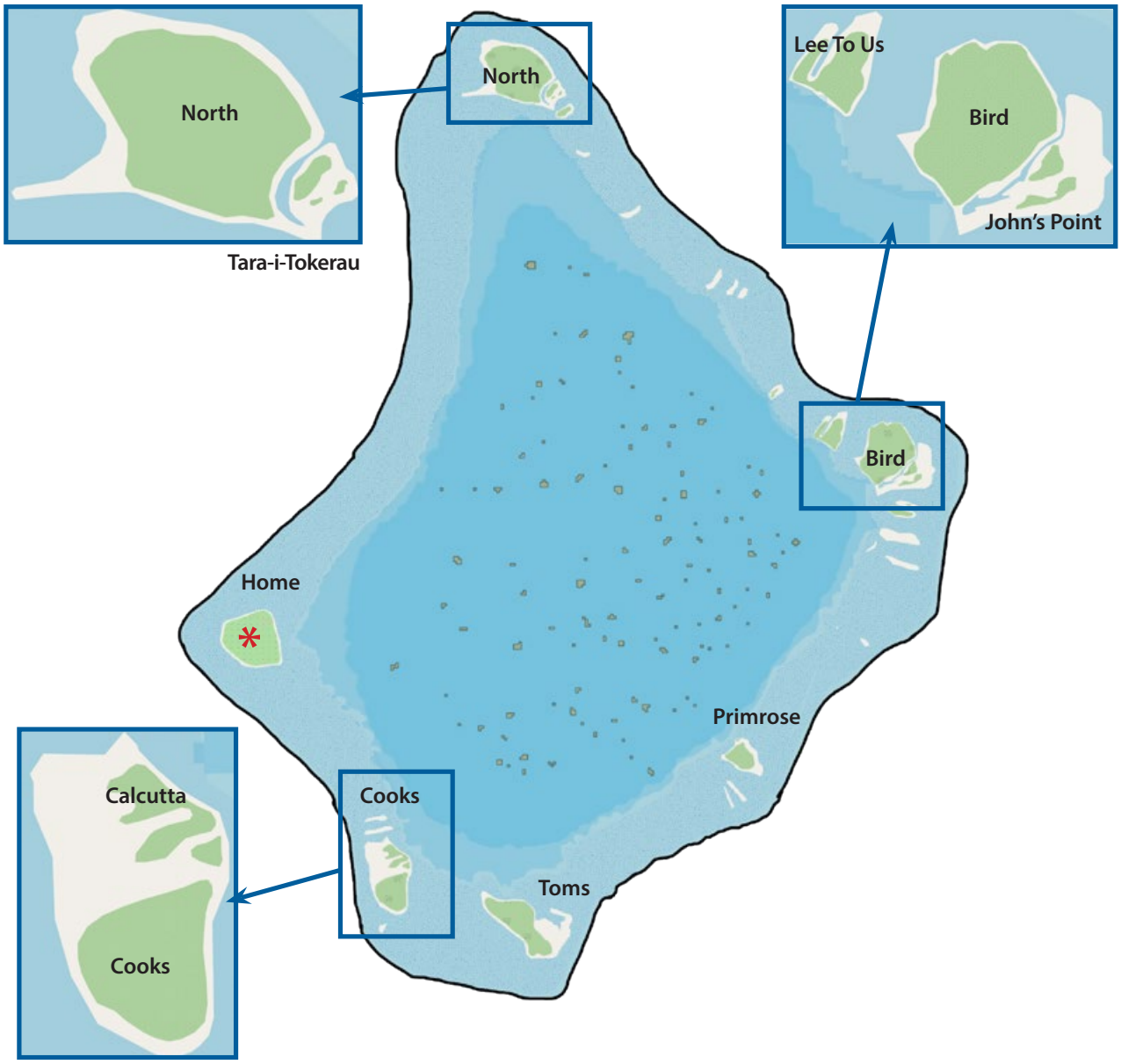

Figure 1. Map indicating the location of each of the six main *motu* assessed on Palmerston Atoll. The red star denotes the location of the village and the only *motu* that is populated. The green area indicates treeline vegetation and white areas indicate the beach for all *motu* within Palmerston Atoll.

2.3. Survey methods

2.3.1. Bait station

One of the six *motu* was assessed each day. Unhusked coconuts were collected, split in half for baiting, and attached to tree roots, or other solid structures along a baited trail. One bait was set for each station, and all bait stations were separated by a minimum distance of 20 m and no greater than 30 m. All bait stations contained a fixed bright ribbon that was easily identifiable. A global positioning system (GPS) was also used to mark bait, measure distance between stations and relocate bait at night.

During the day, all bait stations were set in the afternoon before 14:00. Any crab encountered during the setting of bait was noted, measured and marked for the mark-and-recapture study. To ensure a six-hour time period was allowed for crabs to detect the bait, at approximately one hour after sunset (generally around 20:00), a team of two surveyors visited each bait station. At the end of each bait station survey, the bait was removed, although ribbons were left in place for the other surveys.

2.3.2. Transect surveys

Transect surveys were conducted four to six days after the bait station surveys, again assessing one *motu* per day. The baited station trails were used. Although all bait had been removed prior to the transect surveys, ribbons were left to mark the location and guide surveyors along the transect. A team of three (two surveyors and one recorder) visited the first *motu* surveyed during the baited stations one hour after sunset, and then continued to the next *motu*, the following day. Each surveyor walked along the trail recording crabs in a 10-m-wide swath (5 m each side of the transect). Due to the different sizes of each *motu*, transect lengths varied from 171 m to 1004 m.

2.3.3. Mark-and-recapture

All crabs that were seen during the baited stations survey were marked and released with a second capture and release occasion done during the transect surveys. The first capture and release occasion also included crabs encountered opportunistically (either when setting bait, at the camp site, or along the beach). The first captured crabs were marked with a number using a permanent marker on the carapace (see Fig. 2), with the number and location (*motu*) of each crab recorded on datasheets before their release.

Figure 2. A coconut crab marked with a permanent white marker during a thoracic length measurement. © Elizabeth Munro

2.3.4. Records of size, sex and other observations

The thoracic length (TL) of each crab encountered during a survey was measured to the nearest millimetre using callipers (see Fig. 3) in order to calculate the population size structure. The sex of each crab was also recorded (see Fig. 4) for calculating the sex ratio, while females were also recorded as having eggs or not.

During baited station surveys, several other animals were observed at the bait, including rats, other crabs (hermit crabs and the brown land crab or *tupa*), and ants. At one stage, a juvenile chicken was observed, although this was on Home *motu* and chickens

were not observed at bait on the other *motu*. Rats were observed frequently at bait stations on two of the six *motu*, Home and Cooks. Rats were not observed at bait stations on other *motu*. All crabs (both hermit and *tupa*) were observed frequently at bait stations except for Toms *motu*. Ants were observed at the majority of all bait sites on Toms.

Figure 3. Measuring the thoracic length of a coconut crab. © Ian Bertram (SPC)

Figure 4. Identifying the sex of a crab; a female crab with three pleopods (appendages), indicated by three red arrows (left), and male crab with no pleopods present (right). © Elizabeth Munro

2.3.5. Hunter interviews

NES conducted one-on-one interviews with local coconut crab hunters on Home *motu*. Interviews on coconut crab hunting practices were conducted and it was evident that the hunting practices on Palmerston differed from those used on Mauke and Mangaia.

2.4. Data analysis

All data, including site name, transect length, sex and date, were recorded by multiple surveyors, including community members and students from Palmerston Lucky School with direct supervision of NES Project Officers Elizabeth Munro and Moana Tetauru. All data were entered into the SPC Coastal Fisheries Applications web database.[3]

Data were extracted and analysed using Microsoft Excel. All coconut crab length measurements correspond to TL in millimetres. All averages include the standard error of the measurement per transect.

2.4.1. Relative density (bait stations)

We followed the methodology used by Fletcher and Amos (1994) to estimate catch per unit effort (CPUE) values. CPUE was calculated using the equation:

CPUE = number of crabs caught ÷ number of bait set

To represent the average density for each *motu*, the aggregated total number of crabs and the total number of set bait per *motu* were used. CPUE provides an indication of the status of the population and how it responds to fishing pressure through time (Appendix 1). This analysis excluded crabs encountered while setting bait stations and walking to and from bait stations along the beach (i.e. opportunistic observations and records).

2.4.2. Transect density (transect surveys)

Densities were calculated from the transect surveys using the equation:

Transect density = number of crabs found on transect ÷ (transect area x 4047[4])

The transect area was calculated by multiplying the total transect length surveyed (Appendix 2) by a transect width of 10 m. Where no GPS coordinates were available for transects, a value of a nearby transect was used as a reference or the mean of several transects.

Estimates of density are expressed as individuals per acre.[5] All individuals encountered (including recaptured individuals marked during the bait station surveys) were included in the analysis. The transect density was calculated for both *motu* and atoll populations.

2.4.3. Recaptured individuals (Mark – Recapture)

We again followed the methodology used by Fletcher and Amos (1994) to estimate coconut crab populations from our mark and recapture surveys. The Lincoln-Petersen method equation follows:

Total number = (total number of marked crabs at first capture + 1) x (total number of crabs caught at second capture + 1) ÷ (total number of recaptured crabs +1) – 1)

Population estimates were calculated for all six *motu* and for Palmerston as a whole.

2.4.4. Population size structure

Size structure was analysed by 2-mm size classes and separated by sex. Frequency is expressed as the percentage of crabs of the corresponding sex. Size structure results from other islands in the Cook Islands (Matamaki et al. 2016; Munro et al. 2017) are also provided for comparison. All recaptured individuals were excluded[6] from this analysis while all opportunistic observations were included. The minimum legal size from Mauke in 2016 and Mangaia in 2017 were compared with data from Palmerston.

2.4.5. Sex ratio

The sex ratio was analysed for the entire population of coconut crabs by size class of 10 mm, by *motu* and for the entire atoll, and compared with two previous surveys of Mauke and Mangaia in the Cook Islands. The mean, minimum and maximum sizes by sex are presented. All crabs encountered during the survey, excluding individuals from recapture, were included in the analysis. All recaptured individuals were excluded from this analysis while all opportunistic observations were included.

2.4.6. Coconut crab stock estimates

Coconut crab population estimates were calculated using transect density estimates, and extrapolating these to the total area of each *motu* and the entire atoll. All calculations for area were conducted using the open source Quantum Geographic Information System (QGIS) software. Population estimates were calculated using the following equation:

population estimate = transect density x area size[7]

[3] https://www.spc.int/CoastalFisheries
[4] The number used to convert square metres to acres; 10,000 should be used to convert to hectares.
[5] Land in the Cook Islands is measured in acres and, therefore, an acre is used here as it is understood by local communities.
[6] Recaptured crabs were already measured during first capture in the bait station survey.
[7] Area was calculated in QGIS and refers to the vegetation on each *motu* up to the treeline and excludes the beach (see Fig. 1).

3. Results

3.1. Relative density (CPUE)

In total, 284 crabs were recorded at 18 out of 23 bait stations (Appendix 1). The number of set bait per station ranged from 7 to 32. No crabs were recorded on Home *motu* and only four crabs were recorded for Cooks. The average CPUE ranged from 0.79 (± 0.32) at Bird to 1.54 (± 0.28) crabs per bait at North. The average CPUE for Palmerston Atoll was 0.84 (± 0.29) crabs per bait (Fig. 5).

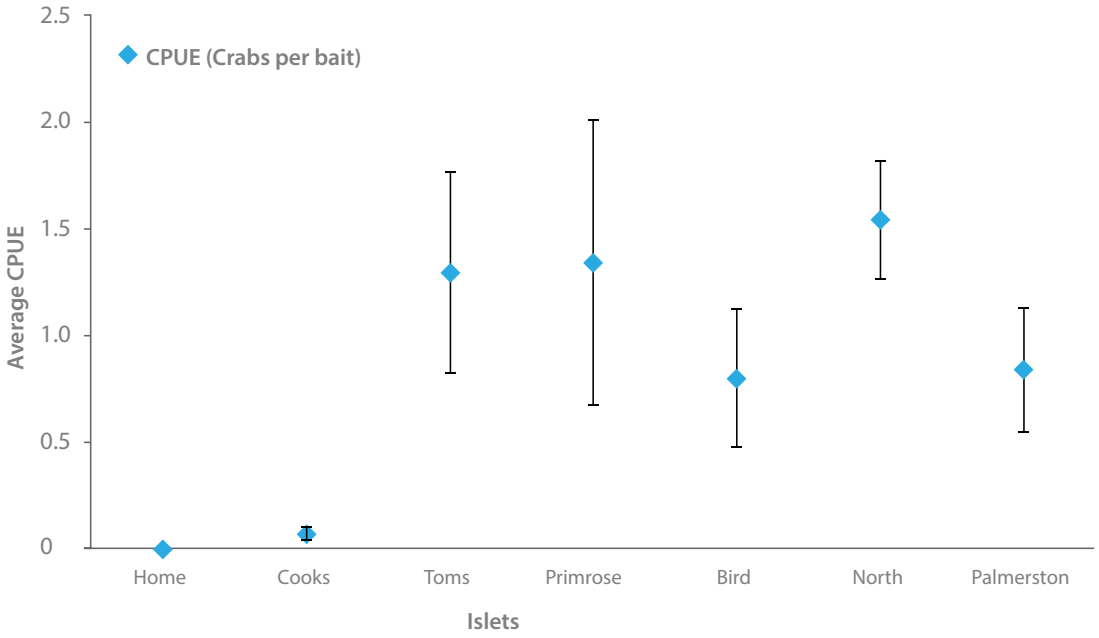

Figure 5. Aggregated average catch per unit effort (CPUE) for each *motu* and the average CPUE for Palmerston Atoll.

3.2. Transect density

A combined total of 84 crabs (72 including 12 recaptured crabs), were recorded for 13 out of 23 transects (Appendix 2). No crabs were recorded from Home and Cooks. Densities ranged from 1.15 (± 0.51) individuals per acre at Bird to 11.26 (± 2.41) at Toms. The average density for Palmerston Atoll was 4.56 (± 1.18) individuals per acre (Fig. 6).

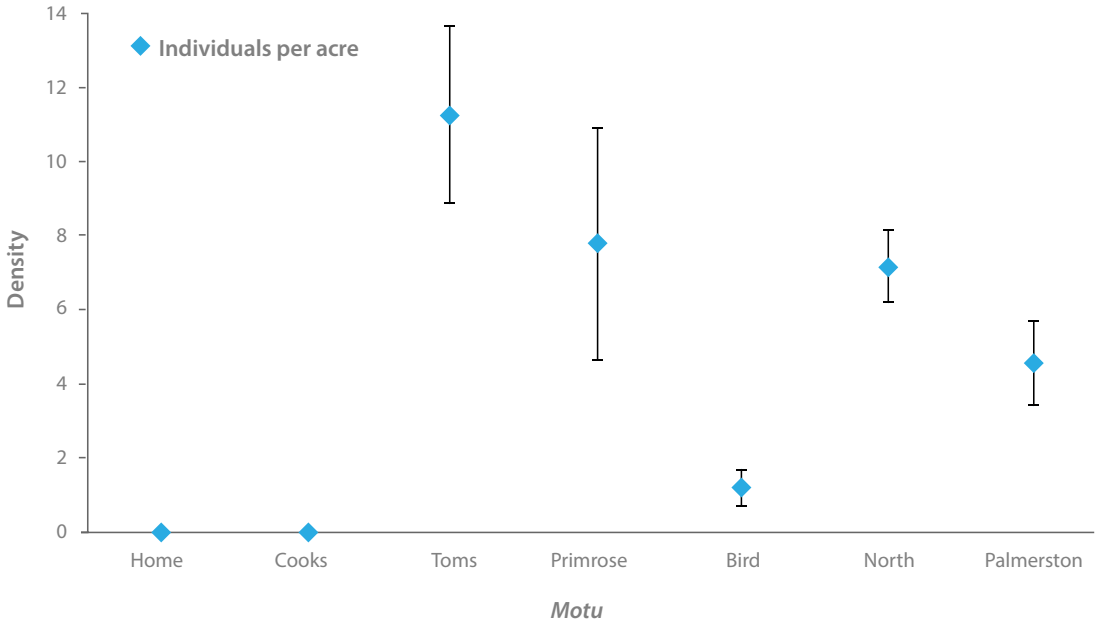

Figure 6. Aggregated average densities for each *motu* and the average density for Palmerston Atoll.

3.3. Mark-and-recapture

A combined total of 301 crabs were caught and marked during the first sampling occasion at baited stations as well as during opportunistic encounters. The second sampling occasion was taken from non-baited transect surveys. In total, 84 coconut crabs, including 12 marked ones, were recaptured during the second sampling occasion. About 4% of marked crabs were recaptured, although the population estimates derived from this method are not reliable because two survey assumptions were violated.

1. The Lincoln-Petersen method assumes that a population is closed. This means that there is no mortality, recruitment or migration of crabs between the sampling occasions (i.e. at marking and recapture occasions). An unknown number of marked and un-marked crabs were harvested between sampling occasion one (i.e. the time of marking crabs) and at sampling occasion two (i.e. recapture).
2. The probability of crab capture on sampling occasion one (i.e. at marking) and on sampling occasion two (i.e. at recapture) were not the same for all crabs. At sampling occasion one, the bait used to attract the crabs to an area increased the probability of capture. On sampling occasion two, bait was not used to lure crabs to an area. The two sampling occasions had different probabilities of capturing crabs. This method and the equation for estimating population size requires the detection probability on both sampling occasions to be the same.

3.4. Population size structure

In total, 375 coconut crabs were measured at Palmerston Atoll (Appendix 3). Length-frequency data from Palmerston were compared with proposed size limits from Mauke and Mangaia. The total number of coconut crabs ranged from 0 on Home *motu* to 169 on North *motu* (Table 1). Sizes ranged from 14 mm to 76 mm TL, with the average size of female crabs being 38 mm (± 0.39), and males 48 mm (± 1.07) (Table 2). Over 99% of female crabs and 92% of male crabs were greater than 25 mm, the reported size at maturity (Fig. 7). Approximately, 1% of female crabs and 48% of male crabs were greater than the proposed 50 mm minimum size limit. Male crabs over 60 mm were only found at Birds, North and Primrose (Fig. 8). Female crabs less than the 25 mm size at maturity were common at Toms *motu*, and less so at North. Females less than 25 mm were not found at Bird or Primrose (Fig. 8).

Table 1. Summary of the number of female and male coconut crabs.

Motu	Females	Males	Total
Home	0	0	0
Cooks	1	4	5
Toms[8]	42	38	80
Primrose	33	22	55
Bird	38	28	66
North	93	76	169

Table 2. Summary of size information – thoracic length (mm) – for female and male coconut crabs recorded in the Cook Islands.

Statistics	Palmerston (2018)		Mauke (2016)		Mangaia (2017)	
	Females	Males	Females	Males	Females	Males
Sample size	207	168	59	79	62	137
Smallest measured (mm)	19	14	16	19	13	12
Largest measured (mm)	58	76	49	61	42	35
Average size (mm)	37.93	48.33	32	36	30	0.9
Standard error	0.39	1.07	0.83	1.16	0.6	88%
Proportion > 25 mm*	99%	92%	85%	91%	92%	15%
Proportion > 50 mm**	1%	48%	0%	13%	0%	15%

* Reported size at maturity.
** Proposed minimum size limit for Mauke and Mangaia assessments.

[8] Two extra crabs were included in the size structure and sex ratio analyses for Toms; these crabs were not observed on any of the three methods (for more information refer to Appendix 3).

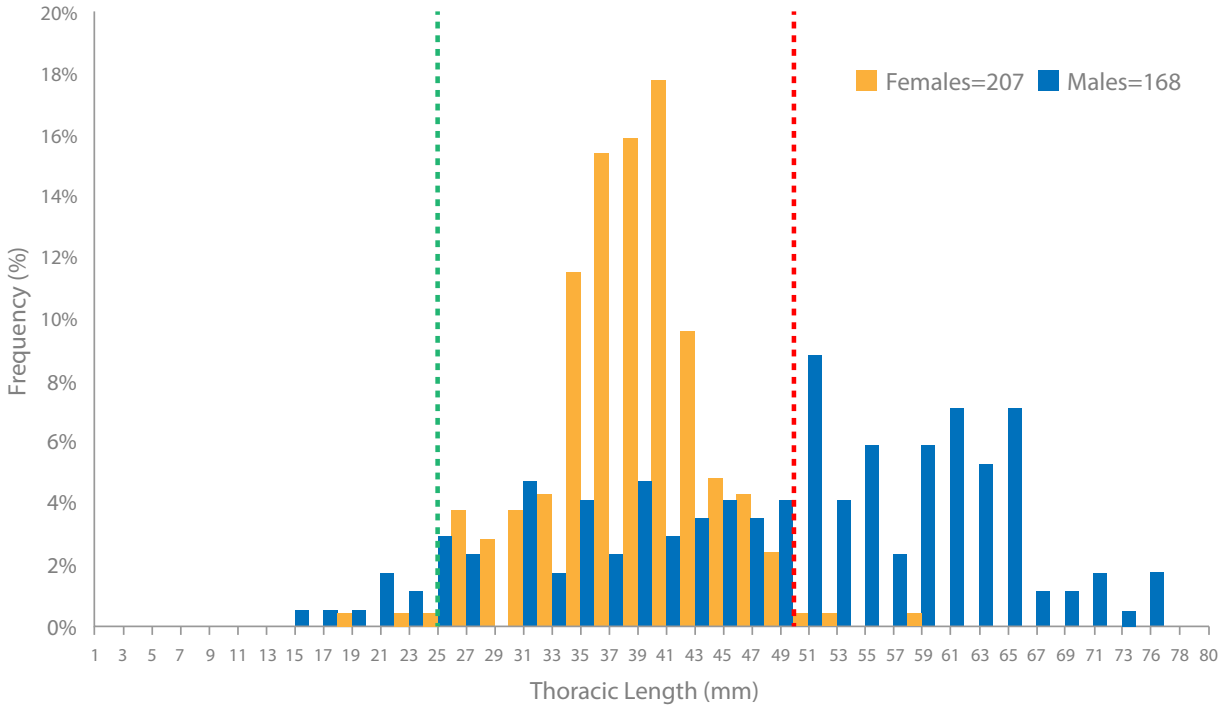

Figure 7. Size frequency distribution of female (orange) and male (blue) coconut crabs recorded at Palmerston Atoll. The size at maturity (25 mm TL) is indicated by the dotted green line; the proposed minimum size limit (50 mm TL) for Mauke and Mangaia is indicated by the dotted red line.


Female coconut crab with spermatophores present © Ian Bertram (SPC)

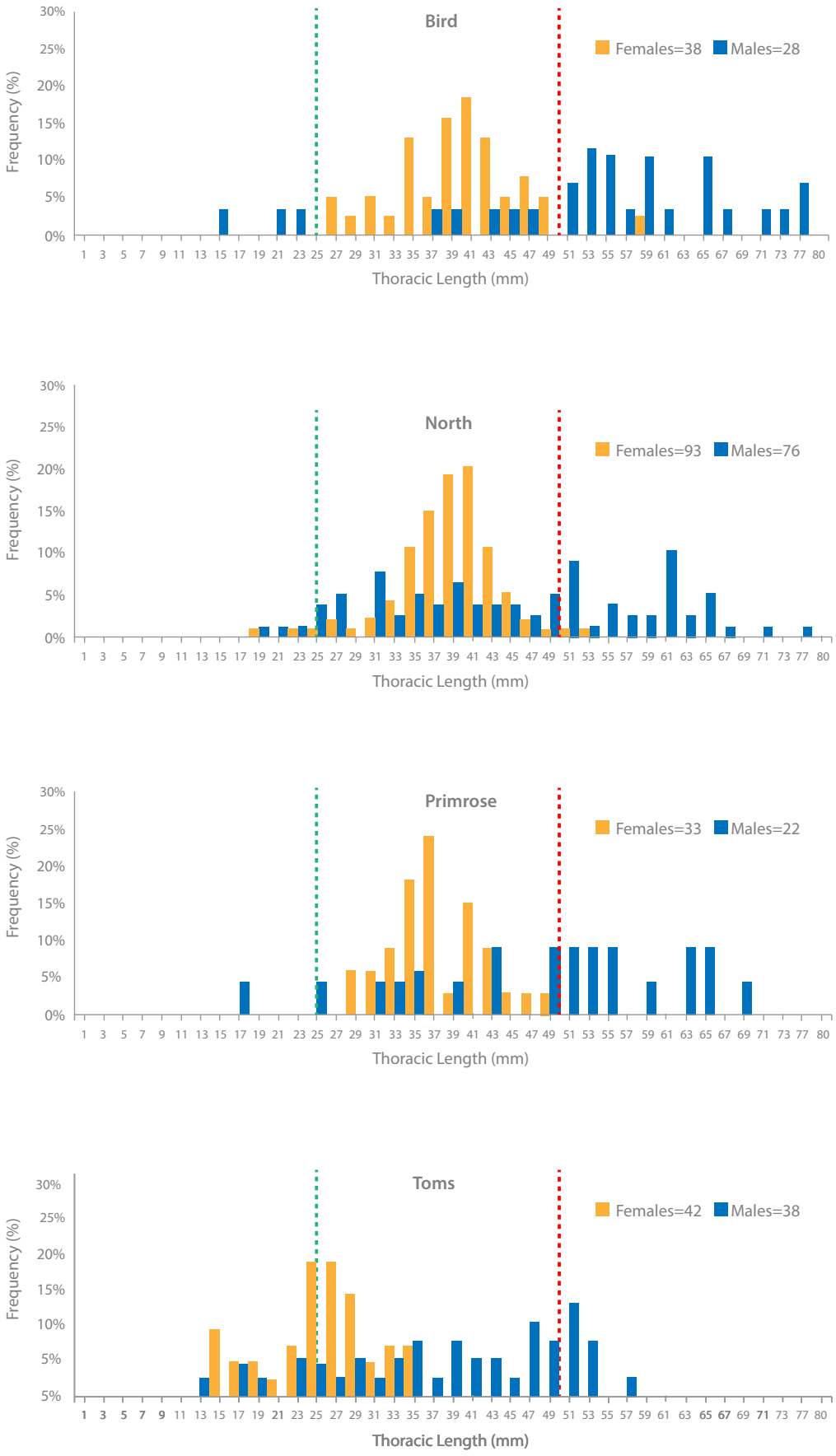

Figure 8. Size frequency distribution of coconut crabs recorded on four *motu* in Palmerston. Cooks *motu* was excluded due to the low numbers recorded (n=5). The size at maturity (25 mm TL) is indicated by the dotted green line; the proposed minimum size limit (50 mm TL) for Mauke and Mangaia is indicated by the dotted red line.

3.5. Sex ratio

Out of the 375 coconut crabs measured across Palmerston Atoll, 207 (55%) were females and 168 (45%) were males. The sex ratio at 20–29 mm is one female to one male (1:1), and increases rapidly until 50 mm (Table 3), then reverses in favour of males. The sex ratio at 50–59 mm is one female to 15 males (1:15), and the sex ratio at 60–69 mm is 0 females to 37 males (0:37) (Table 3).

Two females were observed carrying eggs and two more females were observed with spermatophores present. The mean size for these crabs (n=4) was 41.5 mm (± 0.7).

Table 3. Sex ratio (females to males) by size of coconut crabs at Palmerston Atoll.

Size class	Females	Males
10–19	1	3
20–29	1	1
30–3	4	1
40–49	3	1
50–59	1	15
60–69	0	37
70–80	0	7

3.6. Coconut crab stock estimates

Coconut crab population estimates from the transect survey ranged from 318 crabs at Bird to 2300 crabs at Toms. No population estimates were made for Home and Cooks (Table 4). Overall, the population estimate for Palmerston Atoll was 5367 crabs. The 95% confidence intervals that were calculated for the population estimates indicate that the true crab population lies somewhere between 3086 and 7644 individuals for Palmerston Atoll (Table 4).

Table 4. Population estimates calculated by transect density and area size for each *motu* and Palmerston Atoll as a whole.

Motu	Transect density (ind/acre)	SE	Habitat area (acre)	Population Estimate		
				Numbers	Lower 95% CI	Upper 95% CI
Home	0	0	274.94	0	0	0
Cooks	0	0	167.77	0	0	0
Toms	11.26	2.41	204.29	2300	1334	3265
Primrose	7.76	3.16	70.03	543	110	977
Bird	1.15	0.51	275.88	318	41	595
North	7.18	1	307.38	2206	1601	2811
Palmerston	4.56	1.18	1300.30	5367	3086	7644

3.7. Hunter interview summary by Moana Tetauru

In comparison, Palmerston crab hunting practices differed from Mauke and Mangaia. Palmerston hunters do not use moon phase, tides or other traditional methods and practices. Hunting takes place at any time of the day or night and at any given time without the use of bait.

Some hunters were concerned about the size of crabs being caught by other hunters, while some thought that size was not a concern. Hunters began to understand the importance of not harvesting female crabs with eggs and the reason for a minimum size for harvest. It was also noted that the harvesting of coconut crabs was for home consumption and for special occasions. Crabs are also sometimes sent to Rarotonga for special occasions.

4. Discussion

Using past assessments as a guide, the CPUE of coconut crabs on Palmerston Atoll is higher than for other islands in the Cook Islands. For example, the average CPUE of Palmerston Atoll (0.84 ± 0.29) was approximately twice that of the coastal regions of Mauke and Mangaia at 0.43 (± 0.09), and 0.33 (± 0.08), respectively (Matamaki et al. 2016; Munro et al. 2017). This result correlates with levels of harvesting pressure that are lower on Palmerston than on Mauke where it is regarded as heavy (Matamaki et al. 2016). Based on hunters' experiences and perceptions from assessments conducted in the region (Fletcher et al. 1991; Kessler 2006; Munro et al. 2017) the history of moderate to heavy levels of exploitation in an area is often reflected in low CPUE. CPUE values less than 1 are indicative of crabs barely being seen during the day and night without the use of bait (Fletcher and Amos 1994). Interestingly, the local harvesting areas for coconut crabs are predominantly Cooks *motu* and occasionally North *motu* (Elizabeth Munro, Cook Islands National Environment Service, pers. obs.). The average CPUE for Palmerston is heavily influenced by the very low number of crabs observed on Home and Cooks. For example, the average CPUE for Palmerston Atoll is 1.24 (± 0.43), excluding Home and Cooks. Thus, the average CPUE is much greater across the *motu* where harvesting pressure is much lower.

In contrast to the CPUE results, the average density of coconut crabs on Palmerston appeared similar (4.6 ± 1.18) to that in the coastal region of Mauke (6.4 ± 1.36). Average *motu* densities correlate with CPUE, with the four *motu* with high densities also having high CPUE, excluding Home and Cooks. This result suggests harvesting intensity is greater close to the resident population and would help explain the lack of coconut crabs on Home. Considering Cooks is the next closest *motu* 700 m away, a short boat ride during the night is more convenient for local hunters as opposed to travelling 7 km to North. We suspect that populations in Home and Cooks were significantly reduced through overharvesting to support celebratory events. Exploitation levels do, however, appear low on the unpopulated *motu* within Palmerston Atoll.

There was a clear difference in size distribution between female and male coconut crabs within the population. The maximum size recorded for males was greater than the maximum size recorded for females, which is consistent with other assessments in the Pacific region (Helagi et al. 2015; Matamaki et al. 2016; Munro et al. 2017; Pasilio et al. 2013). In this study, the average size of female coconut crabs was 38 mm, which was 21% smaller than for males at 48 mm. In comparison, there was a 15% and 10% difference between average sizes on Mauke and Mangaia, respectively (Matamaki et al. 2016; Munro et al. 2017). Average sizes for male crabs were 35 mm for Mauke and 36 mm for Mangaia, which is smaller than the average female size within Palmerston Atoll, and indicates much higher levels of harvesting in these locations. As females preferentially mate with males equal to or larger than themselves (Suzuki and Sato 2010), maintaining large male crabs in the population will ensure that successful rates of reproduction are maintained.

Average sizes for coconut crabs on Palmerston can be considered relatively healthy, as they are among the largest sizes when compared to unexploited crab populations in the Pacific Islands region. In Vanuatu, the average sizes of male crab sizes were reported to be 54.7 mm (Tegua Island, Vanuatu) and 53.3 mm (Hiu Islands, Vanuatu), while in the Minni Minni Conservation Area of the Chagos Archipelago in the Indian Ocean, the average male size was 48.0 mm, which is similar to males at Palmerston (Fletcher et al. 1991; Vogt 2004). Largest female mean sizes were 42.0 mm at the Minni Minni Conservation Area in the Chagos Archipelago, 40.2 mm at Taiaro, French Polynesia, 39.0 mm on the Kole Coast in Vanuatu, 38.9 mm on Tegua Island, Vanuatu and 38 mm

A berried female coconut crab © Ian Bertram (SPC)

on Diego Garcia in the Chagos Archipelago (Fletcher et al. 1991; Chauvet and Kadiri-Jan 1999; Vogt 2004), which was also observed for females at Palmerston in this study.

Sexual size differences are found in many different animal populations, including coconut crabs (Bauer et al. 2014). Females spend much more energy on reproduction than males, with egg masses weighing up to 30% of their body weight (Helfman 1973). Males instead can redirect their energy towards increasing their size for defence and mate selection (Drew et al. 2013; Fletcher 1993). There have not been any direct studies of energy expenditure for female coconut crabs during reproduction, so this is an area for further research (Drew et al. 2013).

Across all size classes combined there was a higher proportion of female to male (55:45) crabs on Palmerston. This was in direct contrast to other locations in the Cook Islands, which had a greater proportion of males (Mauke 31:69 and Mangaia 43:57) (Matamaki et al. 2016; Munro et al. 2017). The results from this study, however, are similar to findings of a study conducted in French Polynesia on an unexploited population of coconut crabs where there was a higher proportion of females to males (Chauvet and Kadiri-Jan 1999). The current health of the coconut crab population on Palmerston Atoll can be measured against the prevalence of mature females in this study, which shows that 99% of the female crabs measured were above the reported size at maturity of 25 mm. It is important to note that coconut crabs are a cryptic species where juveniles are generally much harder to find. However, the greater number of females of reproductive age in the population suggests sustained contributions to reproductive output and stable levels of recruitment.

Although limited, our observations of berried and fertilised females indicate that the onset of the mating season had begun around early October. The timing of the survey coincided with the full moon and last quarter moon phases, and because reproduction is known to occur around the new moon phase, the mating season had most likely begun during the new moon phase of October 2018. This is also consistent with other islands nearby. No crabs were recorded carrying eggs during the month of October at either Mauke and Mangaia, indicating that mating had not yet occurred. The mating season on Niue also occurs around October–November (Helagi et al. 2015; Matamaki et al. 2016; Munro et al. 2017). Therefore, mating season on Palmerston likely begins around the new moon phase of October, with peak mating occurring during late November.

The average size of the two female crabs that had eggs and the two that had spermatophores were 41.5 mm (± 0.7), indicating they were mature, long-lived females. Larger females have been found to have a significant impact on larval size, larval weight and longer survival periods under non-fed conditions (Suzuki and Sato 2010). Hence, the presence of larger females in the Palmerston stock should ensure that recruitment and survival rates remain relatively high. However, this information should be considered with caution as the sample size for egg-bearing females was small (n=4). Further assessments during peak mating season are needed to determine the relative proportion of large egg-bearing females within the population.

Community consultations during the 2018 expedition also resulted in the Island Council requesting a rat eradication project from Te Ipukarea Society (Smith 2019). The proposed project to eradicate the Polynesian rat (*Rattus exulans*) from Home and Cooks, was in response to the large number of rats observed by residents and hunters on these two *motu* (Smith 2019). During our baited stations survey, rats were observed at bait on both Home and Cooks, consistent with community observations. Eradication programmes are generally the result of the detrimental impact that rats have on other animals – most notably population decline – following their arrival into an area (Harper and Bunbury 2015). Future studies should be considered following the completion of the proposed project, as information on rats influencing coconut crab populations is scarce and eradication may significantly increase coconut crab populations on these two *motu*.

Estimating overall populations of wild animals is often a difficult process because it relies on subsampling and extrapolation to come up with total population numbers. Two critical assumptions were violated for the mark-and-recapture study, which makes any estimates from this part of the study unrealistic. Mark-and-recapture programmes can be very powerful methods for calculating population sizes but only if a strict methodology is followed. If this method is used in future coconut crab studies, it is important that the same crab detection probability is present during all sampling occasions. In this study, baited traps were used initially and then on the second sampling occasion (recapture) unbaited searches were used and these were done four to six days after the crabs were marked, which may still be too soon for crab behaviour to have returned to normal. Different methods and migration of crabs, due to harvests between sampling events, will influence the behaviour and detectability of crabs and, therefore, dilute the useability of data. We suggest a month between first and second sampling occasions using the same method and controlling for the migration of crabs (i.e. no harvesting during sampling events) to satisfy the two assumptions violated in this study.

It was nevertheless possible to calculate population estimates through the extrapolation of transect densities to estimated total area of liveable habitat. Overall, we estimated a coconut crab population of 5367 (± 1536) for Palmerston Atoll. However, it is important to recognise that when the variability of the data collected are taken into account, the actual population size could be anywhere between 3086 and 7644 crabs. This uncertainty highlights the difficulties of getting total population estimates and why management measures need to take into account the inherent variability in natural populations. For comparison, on Mauke, the estimated coastal coconut crab population in October 2015 was 22,785 (± 4830) (Matamaki et al. 2016). The difference is because there is much less available habitat at Palmerston, with a cumulative area of 1300 acres, compared with 3559 acres in the coastal region of Mauke. A lack of available habitat at Palmerston will always restrict coconut crab numbers. Smaller populations are generally less resilient to major disturbances, such as overharvesting or disease; therefore, careful management of harvesting levels is recommended.

5. Management recommendations

Multiple approaches can be taken towards managing a resource within a community, with each combination of approaches having outcomes that are more acceptable to some members of the community than others. Community consultations are key to obtaining good management outcomes as is including community members in the decision-making process. The unpredictable recruitment and slow growth rate of coconut crabs on Palmerston, coupled with harvesting pressure, suggests a fragile population that may benefit from management measures. From the results of this assessment, it seems the coconut crab stock is in a relatively healthy state and several recommended actions are listed here for management consideration. These are provided here to support the Island Council in managing the coconut crab resource for long-term sustainability as well as satisfying "priority two" of the Palmerston Island Strategic Plan.

1. **Introduce a minimum harvest size limit.** Minimum size limits allow animals to reach reproductive maturity before being exposed to capture. This enables all individuals to contribute to the next generation and maintain the population. We recommend a minimum size limit of 50 mm thoracic length (TL).
    a. The limit of 50 mm effectively protects 75% of all mature coconut crabs (all individuals above 25 mm) in the population observed on Palmerston. This size also effectively protects 99% of the female population (including 98% of females above 25 mm). The larger the female crab, the greater the number of eggs.
    b. The 50 mm size limit means that during hunting, significantly large crabs would be caught for household consumption. The resident population of 58 during the last census in 2016 will benefit from this as this size limit will ensure sustainable harvests.
2. **Protect female crabs from being harvested**. Larger females make a greater contribution to reproductive output and improved rates of survival and recruitment. With a small coconut crab population, the supply of new recruits each season must be maximised to ensure that stocks remain viable. Protection of female crabs from harvest will ensure the supply of new recruits of coconut crabs is maximised, each season.
3. **Establish a closed season for collecting crabs around breeding season**. This will ensure that crabs are protected during reproductive activities. This also allows coconut crabs to mate undisturbed, thus ensuring a higher chance of fertilisation, larger number of released eggs, and higher recruitment. As with proposed closing areas, consultations are needed with the community. For a closed season, we recommend seasonal months from November to February.
4. **Consider banning or controlling coconut crab exports**. The Manihiki Island Council banned the export of coconut crabs to remove harvest pressure from people frequently exporting crabs to families overseas in large quantities. This control allows for more crabs on the island to contribute to reproductive output and therefore replenish stocks. Similarly, to the size limits suggested above, this ensures coconut crab populations are for the consumption of resident Palmerston people and visitors. Exports are driven by markets much larger than the Palmerston crab population could support, and this demand could cause rapid depletion of stocks quicker than they can replenish.
5. **Establish a coconut crab reserve on one *motu*.** Reserves allow for coconut crabs to exist in a near natural state (i.e. harvesting is prohibited) and can be used for educational purposes. Reserves can also benefit the community as a source population where harvesting has no impact on reducing coconut crab populations. As with recommendation 2, public consultations are required.
   Reserves should be placed where:
    - crab densities are high;
    - there is enough suitable coconut crab habitat (dense forest cover and high availability of food); and
    - it is relatively easy to monitor and enforce.

   Taking these into account, we recommend North *motu* because high densities were found there, and it is the largest uninhabited *motu*. It is also the farthest away from Home, which may make enforcement easier and other *motu* are closer to residents.
6. **Establishing an ongoing monitoring programme**. The training provided by NES to school participants has equipped some members of the community with survey skills to conduct surveys independent of NES staff. A school programme of active monitoring for coconut crab populations can provide good information of the population status over time. Analysis of the information gathered can measure the success or otherwise of management actions on Palmerston. These could also compare against natural state populations in a reserve area mentioned in recommendation 5.
7. **Continue with proposed rat eradication project**. In support of the request from the Island Council in 2018 to eradicate rats from Home and Cooks for agricultural and environmental reasons, significant benefits may also exist for coconut crab populations. The low number of crabs observed on Cooks (in part due to suspected harvesting pressure) and the presence of rats indicate a low population and inter-species competition for food and space. If crab recruitment is currently inhibited, then there may be other factors involved, and coconut crab habitat may already be at carrying capacity on Palmerston. This means Home and Cooks may have significant benefits in restoring coconut crab populations due to habitat availability. Rat eradication would enable a greater chance for successful recruitment, resulting in restoring crab populations on these two *motu*.

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Appendices

Appendix 1. Coconut crab baited stations: summary information and results.

Station #	Station name	*Motu*	No. crabs observed	No. set bait	CPUE
1	BrA	Bird	13	22	0.59
2	BrB	Bird	19	23	0.83
3	BrC	Bird	5	14	0.36
4	BrD	Bird (John Point)	3	15	0.20
5	BrE	Bird (Lee To Us)	16	8	2.00
6	NhA	North	25	26	0.96
7	NhB	North	45	32	1.41
8	NhC	North	46	20	2.30
9	NhD	North (Tara-i-Tokerau)	15	10	1.50
10	PrA	Primrose	6	11	0.55
11	PrB	Primrose	9	11	0.82
12	PrC	Primrose	23	9	2.56
13	TmA	Toms	15	12	1.25
14	TmB	Toms	32	15	2.13
15	TmC	Toms	8	16	0.50
16	PnA	Palmerston	0	15	0.00
17	PnB	Palmerston	0	12	0.00
18	PnC	Palmerston	0	18	0.00
19	CkA	Cooks	1	10	0.10
20	CkB	Cooks	0	7	0.00
21	CkC	Cooks	0	15	0.00
22	CkD	Cooks (Calcutta)	1	10	0.10
23	CkE	Cooks (Calcutta)	2	13	0.15

CPUE = catch per unit effort

Appendix 2. Coconut crab transect survey: summary information and results.

Station #	Station name	*Motu*	No. crabs observed	Transect length (m)	Transect area (acre)	Density (ind/acre)
1	BrA	Bird	3	632	1.56	1.92
2	BrB	Bird	2	632	1.56	1.28
3	BrC	Bird	4	632	1.56	2.56
4	BrD	Bird (John Point)	0	192	0.47	0.00
5	BrE	Bird (Lee To Us)	0	192	0.47	0.00
6	NhA	North	5	436	1.08	4.64
7	NhB	North	17	1004	2.48	6.85
8	NhC	North	8	418	1.03	7.75
9	NhD	North (Tara-i-Tokerau)	4	171	0.42	9.47
10	PrA	Primrose	5	226	0.56	8.95
11	PrB	Primrose	7	226	0.56	12.53
12	PrC	Primrose	1	226	0.56	1.79
13	TmA	Toms	11	332	0.82	13.41
14	TmB	Toms	12	349	0.86	13.92
15	TmC	Toms	5	314	0.78	6.44
16	PnA	Palmerston	0	340	0.84	0.00
17	PnB	Palmerston	0	350	0.86	0.00
18	PnC	Palmerston	0	330	0.82	0.00
19	CkA	Cooks	0	229	0.57	0.00
20	CkB	Cooks	0	241	0.60	0.00
21	CkC	Cooks	0	442	1.09	0.00
22	CkD	Cooks (Calcutta)	0	226	0.56	0.00
23	CkE	Cooks (Calcutta)	0	289	0.72	0.00

ind = individuals

Appendix 3. Summary of all coconut crabs observed for all survey methods in Palmerston.

Motu	Bait stations	Opportunistic crabs observed		Transect	Crabs recaptured	Opportunistic and off transect
		day bait	*beach*			
Bird	56	2	0	8	1	0
North	131	1	7	30	4	0
Primrose	38	5	0	12	1	0
Toms	55	1	0	22	6	2
Home	0	0	0	0	0	0
Cooks	4	1	0	0	0	0
Total	**284**	**10**	**7**	**72**	**12**	**2**

Appendix 4. List of surveyors for Palmerston Atoll.

Agency	Name
Palmerston Island volunteers	Edward Marsters
	David Marsters
	John Marsters
	Nauma Marsters
	Mehau Marsters
	Dion Marsters
	Caroline Marsters
Other volunteers	Taokia (Sone) Taokia - Mangaia
	Davis Tetauru - Rarotonga
Ministry of Agriculture	Victor Mataora
	Joshua Jim
National Environment Service	Elizabeth Munro
	Moana Tetauru

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