ECOLOGICAL AND ECONOMIC ASSESMENT OF THE MUD CRAB FISHERY IN NORTHERN NEW IRELAND PROVINCE, PAPUA NEW GUINEA

RESULTS OF A SURVEY UNDERTAKEN AT THE KAVIENG MARKET, NEW IRELAND PROVINCE. TO PROVIDE A BASELINE UNDERSTANDING OF THE MUD CRAB FISHERY AND INFORM FUTURE MANAGEMENT

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EXECUTIVE SUMMARY

The majority of mud crabs (*Scylla* spp.) harvested in the northern New Ireland region are sold through the Kavieng market. The Wildlife Conservation Society undertook a market survey over 2014/15 to collect data on the social, economic and biological dimensions of the fishery spanning the Tigak and Tsoi islands plus mainland New Ireland. Comparing fishery health indicators across harvesting grounds was a key objective. During the survey, 359 vendors were interviewed on 38 separate days and biological data were collected from 3,195 crabs. A similar survey conducted by WCS in 2012/13 enabled temporal comparisons for some variables.

Results suggest that around 28,000 crabs (approximately 20 tonnes in mass) are sold through the Kavieng market annually. At an average selling price of PGK 11.55, this equates to around PGK 323,000 per year. Comparative estimates between both surveys suggest that mud crab sales by numbers and weight have increased by around 35% and 21% respectively since 2012/13. In financial terms, sales have increased by 57% due to a combination of increased volumes and higher prices. In only two years, prices per kilogram have increased by 30%, despite an increase in production.

While crabs were reportedly harvested from 17 separate sites, 87% were derived from just five - Tugalob, Tome, Kavulik , Kaplaman and Salapiu. In the two years between surveys, relative catches (and fishing intensity) increased considerably at Sivasat, Tome and Tugalob while relative decreases were recorded from Nonovaul, Kaplaman, Salipiu, Kavulik and Liminack. At a sub-regional scale, relative catch and effort increased by around 8% on mainland New Ireland but decreased by around 9% from the Tsoi Islands.

Scylla serrata and *S. paramamosain* accounted for 93% and 7% of crabs sampled. In 2014/15 male crabs dominated catches for both *S. serrata* (66%) and *S. paramamosain* (91%): in 2012/13 male crabs accounted for 73% and 89% of crabs sampled, respectively. The predominance of males is likely due to extensive offshore spawning migrations of female crabs which makes them unavailable for capture in mangroves. Monthly male: female ratios suggest that spawning and recruitment occur year-round, though heightened spawning activity may occur from January to April. Evidence of year-round spawning and recruitment was also provided by monthly unimodal size distributions of harvested crabs.

Carapace widths (CW) for *S. serrata* and *S. paramamosain*, ranged from 83-198mm and 89-149mm, respectively (Table 3). The mean sizes of both male and female *S. serrata* were 140mm CW while for *S. paramamosain* respective means were 123 and 122mm CW. Overall, crabs were significantly larger in 2012/13 than in 2014/15. The overall size difference was attributed to a decrease in the

average size of male *S. serrata* and male *S. paramamosain*, while there were no average size differences between female *S. serrata*.

Observed declines in crab size were mainly confined to three mangrove sites – Kavulik, Tome and Tugalob. The latter two sites are those for which catches and relative substantial increases in fishing pressure were recorded between surveys. While average crab sizes were deemed to be reliable indicators of fishing pressure at a local scale (i.e. site harvesting site level), CPUE values were not due to an inverse relationship between the numbers of crabs caught per hour and average crab size. As such, people harvesting in areas suffering high fishing pressure (as indicated by small crab sizes) we still able to catch relatively high numbers of (smaller) crabs (though Kaplaman was an exception with small crab sizes and yields). Reasons for relatively high crab numbers in heavily fished sites are likely associated with continuous year-round recruitment operating at a regional scale, slower growth rates with age and density-dependent natural mortality. Nonetheless, CPUE is likely to be a reliable indicator of regional-scale fishing pressure and therefore should serve as a valuable baseline from which to compare with results from future studies.

The introduction of size limits reflecting size at crab maturity may be necessary to ensure a healthy spawning biomass and high recruitment levels, particularly if fishing efforts intensify. Size at maturity for female crabs was determined by histological examination of oocyte development. Based on this, LM50 (the size at which 50% of females are mature) was determined to be 136.5mm CW for *S. serrata*. Based on this figure, 40% of female crabs sampled during the study were functionally immature. Male crabs commenced maturing at around 100mm CW and appear to mature at a smaller average size than females. Therefore, size limits based on female maturity sizes will be sufficient to ensure the reproductive potential of male crabs.

1. INTRODUCTION

Mud crabs (*Scylla spp.*) are large portunid crabs, growing up to 24 cm carapace width and weighing over 3 kg (Le Vay, 2001). Until quite recently, *Scylla serrata* was assumed to be the sole species. However, a taxonomic revision by Keenan *et al*., (1998) provided conclusive evidence of four species – *S. paramamosain, S. tranquebarica, S. olivacea and S. serrata* – all of which are associated with mangrove and estuarine areas (both sub-tidal and inter-tidal) within tropical latitudes throughout the world. However *S. serrata* have the widest latitudinal and longitudinal distribution and are generally dominant in sympatric populations. Due to their excellent eating qualities, wide distribution, fast growth rates and ease of capture, mud crabs support many important subsistence, artisanal and commercial fisheries worldwide.

Mud crabs comprise a valuable component of small scale coastal fisheries in the western Pacific region including Papua New Guinea (PNG) where *S. serrata* and *S. paramamosain* form important subsistence and artisanal fisheries. In the Melanesian region, mud crab fisheries are generally based on digging crabs from burrows using sticks in inter-tidal mangrove areas. Throughout the broader south-east Asian region, there has been a general trend of increasing exploitation leading to decreased landings and smaller crab sizes over recent decades (Le Vay, 2001; Bomine *et al.,* 2008), illustrating the need for more effective management of this resource. While long-term population health data are not available for any mud crab fisheries in PNG, rapid human population growth and increasing levels of fisheries development suggest increasing levels of fishing pressure on mud crabs are likely. This highlights the need for assessment and monitoring of mud crab stocks to inform management initiatives and avoid stock collapses. Reported wide scale intra-specific variation in life history parameters of mud crabs also suggests that site based research is required for effective local management.

The Wildlife Conservation Society (WCS) PNG program has conducted research on the local mud crab fishery across northern New Ireland Province since 2012, as this fishery has been identified as a highly important contributor to local livelihoods for many mangrove-associated communities. WCS has collected biological data designed to better understand local fishery parameters in order to inform the sustainable use of this important resource. While this research uses catch per unit effort (CPUE) and crab size data to compare the health of different fishing grounds in New Ireland, biological parameters such as size at maturity and reproductive periodicity were also assessed in light of considerable variability within *Scylla* stocks throughout their range (Alberts-Hubatsch *et al*., 2016).

From October 2014 to August 2015, WCS collected biological, social and economic data on the mud crab fishery through a survey of crab vendors at the Kavieng market which, in the absence of an export market, is a key 'bottleneck' for assessing mud crab fishery health in northern New Ireland Province. The Kavieng market brings in sellers from the Tigak and Tsoi Islands and mainland New Ireland which has enabled an assessment of two fishery health indicators – crab size and catch per unit effort (CPUE) – across numerous mangrove sites. WCS conducted a similar mud crab survey over 2012/13 which facilitated an inter-site comparison of average crab size between the two time periods and across all sites covered by the survey. Complementary histological research was also undertaken in 2015 to determine size at maturity for female *S. serrata* and to evaluate the suitability of external abdominal examination as a means of maturity assessment.

2. OBJECTIVES

The overarching objective of the survey was to gain a better understanding of the broader mud crab fishery in northern New Ireland Province to inform local management. Given the breadth of variables examined and in view of a previous survey on the same fishery in 2012/13, sub-objectives may be categorised as those aligned with inter-survey comparisons (Category 1) and those that were not (Category 2).

Category One Objectives

- To evaluate health trends across different fishing grounds between 2012/13 and 2014/15 using average crab size as an indicator
- To compare the following variables between survey periods:
  - Species ratios (*S. serrata* and *S. paramamosain*)
  - Sex ratios
  - Supply of crabs across fishing grounds and communities
  - Market prices and price determinants
  - Basic demographics (age and gender) of crab vendors
  - Annual sales (PGK) and volumes of crabs sold at the Kavieng market

Category Two Objectives

- To assess length-frequency relationships
- To evaluate relative fishery health between fishing grounds using catch per unit effort (CPUE) data

- To determine spawning periodicity
- To assess and compare two methods to determine the size of female crab maturity
- To better understand motivations of crab vendors

3. METHODS

3.1 Site Description

The Kavieng market is located in the provincial capital of Kavieng in northern New Ireland, PNG. The market services a large area and receives mud crabs from numerous mangrove areas located within three sub-regions – mainland New Ireland, the Tigak Islands and the Tsoi Islands[1]. While vendors generally sell crabs captured from mangroves close to their community, there are some exceptions whereby vendors harvest crabs from mangrove systems further afield, through inter-community access arrangements.

Twenty one communities and 17 harvesting grounds were identified during the 2014/15 survey. For eleven harvesting grounds, crab harvesting was undertaken only by members of one community situated adjacent to the harvesting site. For the other seven harvesting grounds, multiple communities harvested crabs. The relationship between communities and harvesting grounds is outlined in Appendix 1 while the location of communities and harvesting grounds represented in the survey is shown in Figure 1.

[1] The 2012/13 mud crab survey also recorded crabs from New Hanover (Lavongai), though this region was not represented in the 2014/15 survey.

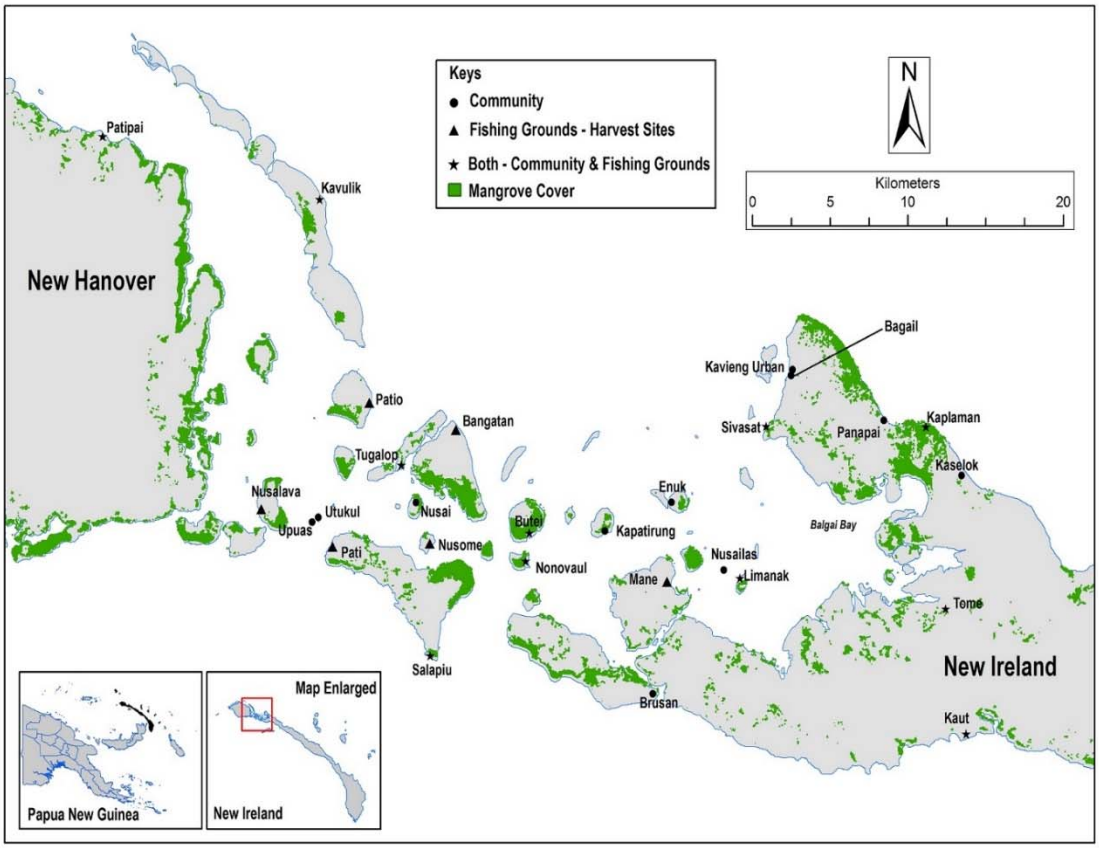

Figure 1. Map of study site including communities and harvest sites

3.2 Survey Design and Development

Recommendations from the 2012/2013 WCS New Ireland mud crab market survey report (WCS PNG, 2014) were used to inform the development of the 2104/15 survey questionnaire and sampling strategy. Given the current survey's focus on catch per unit effort (CPUE) as a fishery health indicator, changes were made to the survey format in order to capture this information. Survey development was also guided by an expanded set of objectives (compared with the 2012/13 survey) including the need to quantify annual sales volumes and values.

The survey consisted of two parts: a semi-structured interview with crab vendors and the collection of biological data from the mud crabs offered for sale by vendors (who normally also harvested the crabs). The interview was primarily designed to collect detailed effort data (harvesting hours), taking into account mediating factors such as travelling times to harvest sites, the number of people on harvesting trips and multi-day harvesting trips. Also collected were data on the following:

- The number of crabs sold prior to interview

- The location of the harvesting ground
- The community of residence of the vendor/harvester
- The selling price of crabs
- Motivations for coming to Kavieng (i.e. whether selling mud crabs was a primary or secondary motivation)
- Other goods offered for sale
- Costs associated with selling crabs at the market

The following biological information was recorded about the crabs offered for sale by vendors:

- *Species*. The two New Ireland mud crab species (*S. serrata* and *S. paramamosain*) were distinguished based on morphological characters including coloration, spination on the carpus and propodus of cheliped and polygonal patterning on appendages (Keenan *et al*., 1998)
- *Sex*. The sexes of both species were distinguished according to the width of the flap on the crab's abdomen: In males, it is narrow and V-shaped, whereas for females it is broader and rounded (Figure 2).

Figure 2. Abdominal photos of *S. serrata* illustrating the difference between mature male (A) and female (B) crabs.

- *Maturity Status (females only*[2]*)*. Two indicators of maturity status were collected. Firstly, the presence of external eggs was recorded, a condition commonly referred to as 'berried' in ovigerous females. Maturation status was also assessed according to the shape and color of

[2] It was originally intended to also assess the maturity status of male crabs by checking for the presence of mating scars. However, the way the crabs were tied and presented at the market made it impossible.

the abdominal flap which is regarded as a reliable indicator of sexual maturity for female mud crabs (Heasman *et al*., 1980; Islam *et al*., 2010). Following Islam *et al.,* (2010) female mud crabs were classified into three development stages: (1) immature; (2) intermediate; and (3) mature.

- *Carapace Width*. Measured with Vernier calipers to the nearest mm across the widest span of the carapace (at the 5th anterolateral spines) (Figure 3).

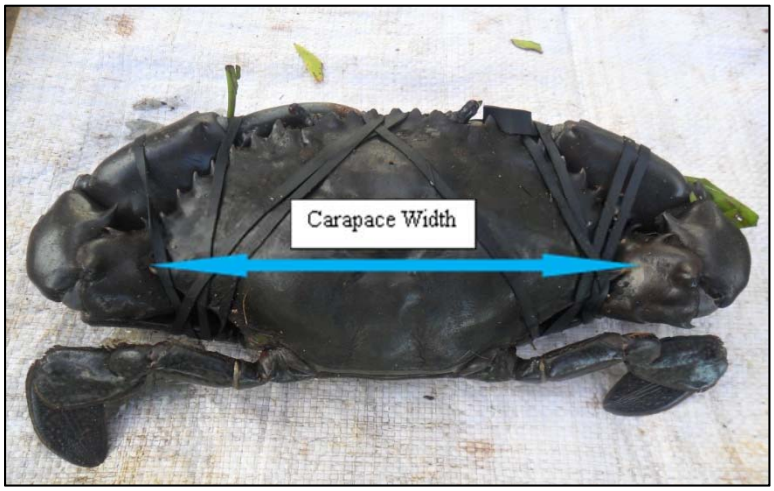

Figure 3. Measurement of carapace width of mud crabs

- *Weight*. A Pesola digital hanging scale with an increment of 10g was used. When weighing, each mud crab was placed in a plastic bag.

Prior to the full survey a pilot survey involving five vendors was conducted to identify deficiencies and limitations. Accordingly, minor adjustments were made to the questionnaire design and format.

3.3 Sampling Schedule and Protocol

Before the survey commenced, permission to undertake the survey was obtained from the New Ireland Provincial Administration. Crab harvesters and the general public were informed about the upcoming survey through a short radio interview on local *Tok Save* radio. Furthermore, information sheets were distributed among mud crab vendors during preliminary visits explaining the purpose of the upcoming survey and confidentiality protocols preventing the disclosure of personally identifying information in survey outputs.

The scheduling of sampling across different days of the week was informed by patterns of market activity encountered during the 2012/13 survey and through preliminary market visits in

September 2014. The market was seen to be busiest on Saturdays followed by Fridays and then other weekdays (the market is closed on Sundays and Mondays). Guided by the need to sample a large number of crabs coupled with a need to collect representative data that could be scaled up to gain annual estimates of crab volumes sold, it was decided to concentrate most sampling effort on Saturdays and Fridays, with a smaller number of sampling events on 'other weekdays'.

On sampling days, all vendors selling mud crabs were approached at the Kavieng market and asked for their participation. If approached for the first time, vendors were also asked if they were familiar with the survey – if not, the purpose of the survey was explained and they were given an information sheet. On all occasions, vendors were paid PNG Kina 5.00 (approximately US$1.80) for each interview to encourage ongoing participation over the survey period. On each survey day, the WCS surveyor attempted to survey all crab vendors. If an interview was refused, the WCS interviewer still counted all crabs offered for sale by the vendor. Sampling generally commenced between 6:30 and 7:00 am, soon after the market opened. Depending on the number of crabs for sale each survey took around 30 to 120 minutes to complete.

To augment data used to estimate marketing activity and annual sales volumes, counts of crab vendors and the number of crabs offered for sale were also performed on days when the full survey was not undertaken. 'Crab counts' occurred on weekdays and on a few weekend days when the weather made it difficult to undertake regular sampling.

3.4 Data Analysis

Catch Per Unit Effort (CPUE)

Catch rates, expressed as catch per unit effort (CPUE) are widely used in fisheries assessments to indicate spatial or temporal variability in abundance, and associated harvesting pressure. CPUE was assessed for each harvesting site according to two measures: (CPUE1) kg crab per person/harvesting hour, and; (CPUE2) numbers of crabs per person/harvesting hour. For both, effort was expressed as the number of person hours spent harvesting all of the presold and unsold crabs for sale by the seller, who was generally also the harvester. The survey was designed to make the collection of effort data as accurate as possible, accounting for low numeracy skills of some interviewees, harvesting by more than one harvester, and harvesting over multiple days. In addition, each interview was assigned a reliability score (1=reliable; 2= uncertain; 3= questionable) by the interviewer to aid the treatment of outlying data (see below).

In order to estimate total catch from which to divide by fishing effort, pre-sold crabs were included. For CPUE1, the weight of each pre-sold crab was estimated as the average weight of

unsold crabs for the seller in question. However, as sampling generally commenced soon after the market opened, reliance of respondent recall was minimized. Nonetheless, if the seller was not able to confidently state the number of pre-sold crabs, data collected during that interview was omitted for CPUE analysis.

CPUE values were checked for outliers and decisions to retain or omit data from each interview were based on the interview reliability score and the degree of deviation from the mean CPUE value for each harvest site. CPUE values that were more than twice or less than half of the mean for a harvest site were omitted if the reliability score was '3'. For reliability scores of '2', CPUE values were omitted if they were more than three times of less than one third of the mean for a harvest site. Outliers with a reliability score of '1' were included. Fourteen percent of values were excluded in this manner.

3.5 Histology

Sampling and Sample Preparation

Between March and August 2016, female *S. serrata* were purchased from the Kavieng market for histological examination to determine size at maturity. Crabs were selected according to size and their 'abdominal maturity', as described above, and in more detail by Islam *et al*., (2010). It was intended to sample crabs across all maturity stages and sizes, though sample selection was particularly focused on sizes thought to coincide with the transition from immature to mature stages.

All crabs were measured to the nearest 1.0 mm using Vernier calipers and weighed to the nearest 1.0 gram using a digital electronic balance. After being euthanized with a metal spike to the brain, the carapace was removed, exposing the ovaries. All ovarian tissue was removed and weighed on an electronic balance to the nearest 0.001 grams. This was to determine gonadosomatic indices (GSI), expressed as a percentage of the ovarian weight relative to body weight. A small portion of the ovary (approximately 3x3x3 mm) was placed in Dietrich's fixative for at least 24 hours prior to histological examination.

Histological Procedures

Ovary samples were removed from Dietrich's fixative, dehydrated in ascending ethanol concentrations (50% and 95%) and embedded in plastic embedding medium. Tissues were sectioned to 7 µm and stained with Toluidine Blue before being examined at 40x magnification. Determination of maturity stage was made through both external and histological examination

according to the five stages of development outlined for *S. olivacea* by Islam *et al.,* (2010). These stages are summarized as follows:

1. *Immature ovary (Stage I).* Oogonia are concentrated mainly around the periphery of the ovary, are translucent and sometimes difficult to distinguish from surrounding digestive gland tissue. Oogonium (5-10 μm) are spherical and the cytoplasm is hardly visible.
2. *Previtellogenic ovary (Stage II).* The ovary is creamy white and easily distinguished from surrounding digestive tissue. During this stage, primary oocytes (45–100 μm) are formed and follicle cells may be observed at the periphery of the cytoplasm. Vacuolated globules are present in the cytoplasm.
3. *Primary vitellogenic ovary (Stage III).* The ovary is yellow to light orange, oocyte diameter increases from 80–150 μm and vacuolated globules are no longer present in the cytoplasm. Small yolk globules begin to appear from the periphery of ooctye cytoplasm.
4. *Secondary vitellogenic ovary (Stage IV).* The ovary is yellow to light orange and the lobules are sufficiently developed to obscure the digestive gland when viewed dorsally. In this stage, ooctyes grow rapidly (120–200 μm) while the nucleus attains 30–40 μm in diameter. Yolk globules occupy the entire cytoplasm with larger globular inclusions towards the periphery. At this stage, follicle cells are hardly visible.
5. *Tertiary vitellogenic ovary (Stage V).* Ovary colour ranges from dark yellow to red-orange and the volume of the ovary is generally sufficient to cover the hepatopancreas and the majority of the cardiac stomach. Oocytes increase in diameter (150–250 μm) and the nucleus is barely visible. Yolk globules are partly fused to each other.

A sixth development stage – the spent ovary – was also used[3]. Quinitio *et al*., (2007) describes this post-spawning ovarian stage as being similar to Stage 2 or 3 in external appearance, often flaccid and sometimes retaining unspawned eggs as indicated by patches of dark orange. Histologically, oocytes resemble Stages 2 or 3 though there may be ooctyes of various stages present.

Following Islam *et al*., (2010), crabs in maturity stages three to six were deemed to be sexually mature.

[3] This development stage was not used by Islam *et al.,* (2010) because spent ovaries were not encountered in their research.

4. RESULTS

4.1 Summary of Sampling Activity

Between 3 October 2014 and 29 August 2015, WCS PNG conducted 38 sampling trips to the Kavieng market – 17 Saturdays, 18 Fridays and 3 weekdays (other than Fridays). In addition, counts of crabs and vendors at the market over this period were also conducted on 19 occasions – 5 Saturdays, 6 Fridays and 8 weekdays (other than Fridays). While crab count days were planned for weekdays only, counts performed on Saturdays and Fridays were due to changed plans owing to heavy rain preventing a full survey.

Overall, 356 interviews were conducted among crab vendors, with data captured from 21 communities and 17 sites in northern New Ireland (Table 1). A total of 76 interviews were refused and in these cases only crab counts were undertaken, and biological or harvesting effort data were not collected.

Over the 11 month sampling period, total of 3195 crabs were sampled; a mean of 84.1 and 9.0 crabs per sampling date and vendor, respectively. The number of crabs sold by each vendor prior to interview was also recorded; a mean of 32.2 and 3.4 crabs per sampling date and vendor respectively. The distribution of the number of crabs (sampled and pre-sold) per vendor is shown is Figure 4.

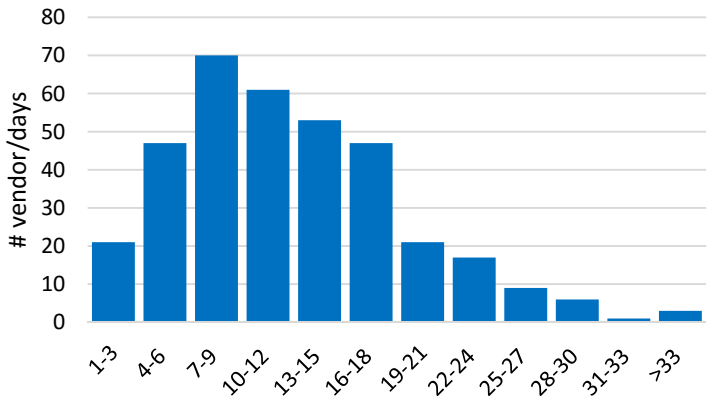

Figure 4. Frequency distribution of the number of mud crabs sold by individual vendors

Indications of differing levels of crab selling activity between Saturdays, Fridays and other weekdays during preliminary market visits were confirmed throughout the study. The mean

number of vendors on Saturdays, Fridays and other weekdays was 11.7, 10.1 and 6.5, respectively (Table 2). Respective values for the number of crabs for sale at the market (including pre-sold crabs) were 135.5, 117.9 and 72.9. However, there was little difference in the average number of crabs for sale by each vendor across sampling days.

Table 1. Summary of sampling statistics for the 2012/13 and 2014/15 Kavieng market mud crab surveys

Summary statistics	2012/13	2014/15
Sampling days	20	38
Non-sampling days when crabs counts were done[1]	N/A	19
Number of communities represented	21	21
Number of harvesting grounds represented	16	17
Number of interviews conducted	125	356
Number of interviews refused[2]	N/A	76
Number of individual vendors interviewed	92	157
Number of crabs sampled	893	3195
Number of pre-sold crabs recorded[3]	N/A	1223
Number of crabs counted on non-sampling days[1]	N/A	1381
Mean number of crabs per market day[4]	74.6	119.5
Mean number of vendors per market day[4]	7.5	10.3
Mean number of crabs per vendor[4]	9.9	12.4

[1] Counts of crabs and vendors were not undertaken on non-sampling days in 2012/13

[2] Refused interviews were not recorded in 2012/13

[3] Pre-sold crabs were not recorded in 2012/13

[4] Values for 2012/13 were reconstructed using correction factors derived from the relative proportions of sampled and pre-sold crabs and accepted and rejected interviews encountered during the 2014/15 survey

Comparisons with 2012/13

Comparative sampling values are provided in Tables 1 and 2. Overall, sampling efforts were intensified in 2014/15, with a greater number of sampling events, interviews conducted and crabs sampled (Table 1). The results also indicate a considerable increase in local crab production in the second survey period owing to a greater number of vendors and an increase in the average number of crabs sold per vendor. The latter variable, a combination of sampled and pre-sold crabs, was estimated for 2012/13 using a correction factor based on the relative proportions of sampled and pre-sold crabs in the 2014/15 survey. A correction factor based on 2014/15 data was also applied to estimate the number of refused interviews in 2012/13.

Due to logistical considerations, the 2012/13 survey focused the bulk of sampling efforts on Fridays: sampling occurred on two Saturday and two weekdays only (Table 2). Despite this,

comparisons may be considered indicative of general trends. While the average number of vendors and crabs brought to market was lower in 2012/13 on each of the three sampling day 'types', the trend was similar to the 2104/15 survey i.e. the market was busiest on Saturdays, then Fridays followed by other weekdays.

Table 2. Summary of sampling statistics for different survey days (Saturdays, Fridays and other weekdays) for the 2012/13 and 2014/15 mud crab surveys. Values for 2012/13 were reconstructed using correction factors derived from the relative proportions of sampled and pre-sold crabs and accepted and rejected interviews encountered during the 2014/15 survey.

Description	Saturdays		Fridays		Weekdays	
	2012/13	2014/15	2012/13	2014/15	2012/13	2014/15
	n=2	*n*=23	*n*=16	*n*=26	*n*=2	*n*=7
Mean number of crabs at market	86.2	135.5	73.9	117.9	61.7	72.9
Mean number of vendors	8.5	11.7	7.6	10.1	4.8	6.5
Mean number of crabs p/vendor	10.2	11.5	9.7	11.6	12.8	11.2
Range of crabs per market day	52–120	1–266	23-156	6–205	2-63	6–157
Range of crabs per vendor	3-20	1–58	3-29	1–42	6-23	1–33

4.2 Crab Harvest by Fishing Ground

On sampling days, crabs were supplied to the Kavieng market by vendors from 17 different mangrove sites (Figure 5). Most sites are discrete mangrove systems while the expansive Balgai Bay mangrove forests encompass multiple harvesting sites (i.e. Kaplaman, Sivasat and Tome). Results were highly skewed: almost 87% of the crabs were harvested from five sites – Tugalob (26%), Tome (21%), Kavulik (19%), Kaplaman (11%) and Salapiu (9%). By sub-region, the relative crab numbers sampled for Mainland New Ireland, the Tigak Islands and the Tsoi Islands were 33%, 48% and 19% respectively.

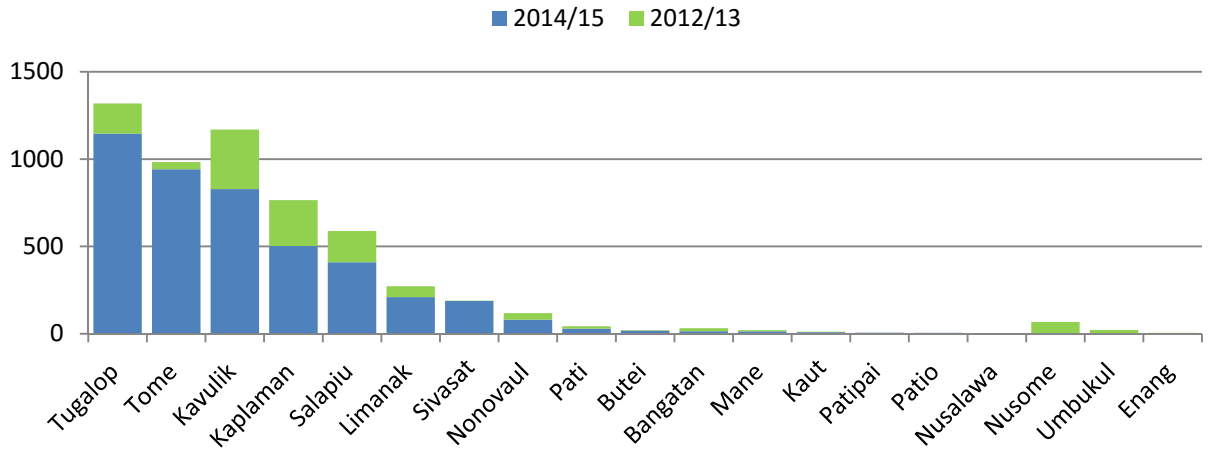

Figure 5. Frequency distribution of harvesting grounds that supplied crabs sampled during the 2012/13 (green) and 2014/15 (blue) Kavieng market mud crab surveys

Comparisons with 2012/13

- Sixteen fishing grounds were identified during the 2012/13 survey, 14 of which were also identified during the 2014/15 survey. The two harvesting sites that weren't represented in the 2014/15 survey were Umbukul and Enang.
- The relative contributions among the 16 sites were also highly skewed and the most prominent ones were similar to 2014/15: almost 83% of crabs surveyed were harvested from the following sites – Kavulik (28%), Kaplaman (21%), Salapiu (14%), Tugalop (14%), and Nusome (5%).
- Of the eight harvest sites that supplied more than a combined total of 50 crabs between the two surveys (not including pre-sales), proportional increases were observed in 2014/15 for Sivasat (95%), Tome (73%) and Tugalob (30%) (Figure 6). Conversely, there were proportional decreases for Kaplaman (30%), Nonovaul (25%), Salipiu (22%), Kavulik (19%) and Liminack (3%).
- By sub-region, the relative proportions of crabs sampled in 2012/13 (and percentage changes observed during the 2014/15 survey) for Mainland New Ireland, the Tigak Islands and the Tsoi Islands were 25% (+8%), 46% (+2%) and 28% (-9%) respectively. A further 2% of sampled crabs were harvested from Lavongai (New Hanover) in 2012/13, which was not represented in the 2014/15 survey.

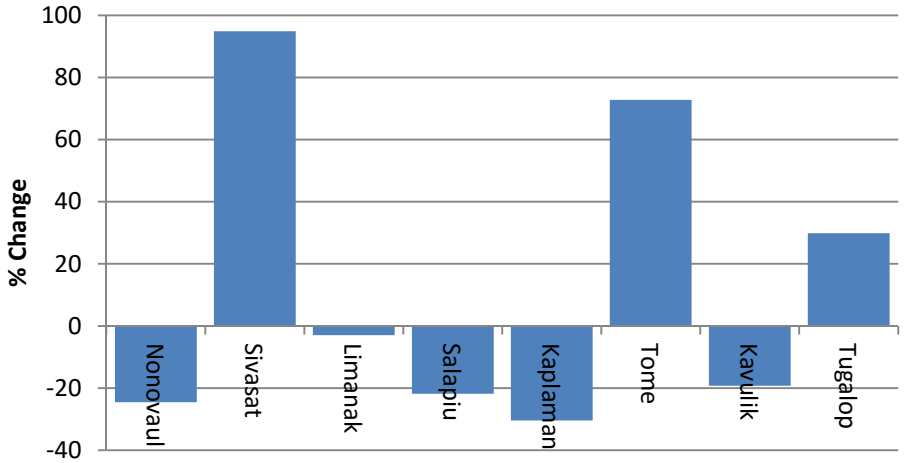

Figure 6. Changes in the relative percentage of crabs sold harvested from different harvesting sites between the 2012/13 and 2014/15 Kavieng market mud crab surveys. Only harvesting sites that supplied more than a combined total of 50 crabs between the two surveys (not including pre-sales) are represented.

4.3 Economic Impact

Crab Pricing and Daily Vendor Returns

Crab prices were determined according to a visual estimation of size (sellers do not use scales) and generally offered for sale in 5 kina increments. Prices ranged from PGK 0.5 to PGK 30, with a mean of PGK 11.55 (n=3195, SD=7.3). Based on a mean of 12.4 crabs per vendor, mean daily sales were PGK 143.20 per vendor. However, travel costs to access the Kavieng market averaged PGK 12.20 per seller/day (n=356, SD=5.3). As such, average estimated profit per seller/day was PGK 131.00. Approximately 48% of sellers also sold other items including fresh and smoked marine products and raw and processed (i.e. smoked or cooked) garden produce.

Mud crabs have become increasingly expensive since the 2012/13 survey (Figure 11). Mean prices for a 1kg crab in 2012/13 and 2014/15 were PGK 12.5 (n=893, SD=4.9) and PGK 16.2 (n=893, SD=4.9), respectively. This represents a significant price increase (t=12.9; p<0.001) of around 30% in two years against a backdrop of 7.1% inflation[4] for the same period.

Annual Sales Summary

Data collected in the 2014/15 survey suggests that around 28,000 crabs (20 tonnes) are sold at the Kavieng market annually, equating to gross sales of around PGK 324,000 per year (US$ 108,000). With around 150 individual sellers (125 interviewed and 25 refused), average annual estimated income per vendor is PGK 2,150, not including sales from other items. As travel costs associated with accessing the Kavieng market represented 8.5% of sales, average annual profit per vendor is estimated at PGK 1,970.

Data collected during the 2012/13 survey suggests that around 20,750 crabs were brought to the Kavieng market over a 12 month period. Based on an average crab weight of 0.79 kg, annual crab volumes are estimated at 16.4 tonnes. Given the average sales price for crabs over the 2012/13 period was PGK 9.9, a total annual sales figure of around PGK 204,500 is estimated.

Comparative values suggest that the volume of crabs being sold at the Kavieng market has increased considerably over the two years between survey periods. In financial terms, annual sales have increased 57%; a combined result of increased volumes and higher prices. However, comparisons using data from the 2012/13 survey need to be viewed in light of data limitations discussed in Section 4.1.

[4] http://www.tradingeconomics.com/papua-new-guinea/inflation-cpi

Sales by Communities

Over the 2014/15 survey period, vendors were recorded from 21 communities. Observations on both sampling and counting days suggests that there are unlikely to be many more individual vendors (and therefore communities represented) than those canvassed throughout the survey. As such, the results presented in Table 3 are likely to be a reasonable indication of relative sales patterns between all communities supplying crabs to the Kavieng market.

Despite the large number of communities selling crabs, 85% of crabs surveyed and counted were sold by residents of five communities – Tugalob (26.3%), Tome (21.5%), Kavulik (19.3%), Kaplaman (10.1%) and Salipiu (7.8%). At the other end of the scale, eight communities contributed less than 2% of sampled crabs. Accounting for differences in average crab sizes sold between communities, respective values for annual volumes (as a proportion of total market volumes) and associated financial returns were are follows: Tugalob (30.6%), Tome (18.1%), Kavulik (17.6%), Kaplaman (8.2%) and Salipiu (9.5%).

In Table 3, community-specific sales data for both surveys are presented and extrapolated to provide annual estimates of crab numbers, crab volumes and financial returns. Key comparisons are listed below:

- Twenty-one communities supplied crabs to the Kavieng market in 2012/13, 13 of which also supplied crabs during the 2014/15 survey
- Of the eight communities not represented in the 2014/15 survey, two were from Lavongai (Ao and Umbukul).
- The relative contributions among the 21 communities were also highly skewed in 2012/13: 73% of crabs surveyed were sold by residents of five communities – Kavulik (25.1%), Kaplaman (15.1%), Tugalop (12.7%), Salapiu (8.6%) and Nusome (4.9%). Accounting for differences in average crab sizes, respective values for annual volumes and financial returns were are follows: Kavulik (24.5%), Kaplaman (12.3%), Tugalop (18.1%), Salapiu (10.7%) and Nusome (6.0%).
- Of the ten communities who supplied more than a combined total of 50 crabs between the two surveys (not including pre-sales), proportional increases in crab numbers were observed in 2014/15 for Sivasat (94%), Tome (71%) and Tugalob (32%) (Figure 6). Conversely, and in order of prominence, there were proportional decreases for Utukul, Kaselock, Nonovaul, Kaplaman, Kavulik, Salipiu and Liminack.

Table 3. Comparison of community-specific mud crab sales data from the Kavieng market: 2012/13 and 2014/15

		2012/13					2014/15				
Community	**Mangrove/s**	**# crabs**	**Avg. kg/crab***	**total kg**	**tot. ann. kg**	**PGK (annual)**	**# crabs**	**Avg. kg/crab***	**total kg**	**total ann. kg**	**PGK (annual)**
Tugalob	Tugalob, Nonovaul, Patio, Banagatan	125	1.02	127.5	2955	36943	1162	0.83	964.5	6108	99071
Tome	Tome	30	0.77	23.1	535	6693	949	0.6	569.4	3606	58489
Kavulik	Kavulik, Tugalob	247	0.7	172.9	4008	50098	852	0.65	553.8	3507	56887
Kaplaman	Kaplaman	149	0.58	86.4	2003	25040	448	0.6	268.8	1702	27611
Salapiu	Salapiu	85	0.89	75.7	1754	21920	347	0.86	298.4	1890	30654
Limanack	Limanack	45	0.78	35.1	814	10170	210	0.7	147.0	931	15100
Sivasat	Sivasat	1	0.79	0.8	18	229	131	0.69	90.4	572	9285
Nonovaul	Nonovaul	24	0.96	23.0	534	6676	74	0.99	73.3	464	7525
Utukul	Utukul, Salapiu, Kapula	44	1.03	45.3	1051	13131	61	0.95	58.0	367	5953
Kaselok	Kaplaman	34	0.58	19.7	457	5714	40	0.6	24.0	152	2465
Nusailas	Sivasat	0	0	0.0	0	0	27	0.69	18.6	118	1914
Upuas	Salapiu	0	0	0.0	0	0	22	0.86	18.9	120	1943
Butei	Butei	2	0.79	1.6	37	458	18	0.72	13.0	82	1331
Kavieng	Sivasat	2	0.79	1.6	37	458	18	0.69	12.4	79	1276
Balgai	Sivasat	0	0	0.0	0	0	14	0.69	9.7	61	992
Panapai	Kaplaman	7	0.58	4.1	94	1176	14	0.6	8.4	53	863
Enuk	Enuk	0	0	0.0	0	0	13	0.72	9.4	59	961
Kaut	Kaut	2	0.79	1.6	37	458	9	0.72	6.5	41	666
Patipai	Kavulik	0	0	0.0	0	0	6	0.65	3.9	25	401
Brusan	Sivasat	0	0	0.0	0	0	3	0.69	2.1	13	213
Kapatirung	Kapatirung	5	0.79	4.0	92	1145	3	0.72	2.2	14	222
Ao	Ao	12	1.18	14.2	328	4103	0	0	0.0	0	0
Bangatan	Bangatan	12	0.85	10.2	236	2955	0	0	0.0	0	0
Enang	Enang	4	0.79	3.2	73	916	0	0	0.0	0	0
Kulinus	Kulinus	3	0.79	2.4	55	687	0	0	0.0	0	0
Nusome	Bangatan	48	0.88	42.2	979	12239	0	0	0.0	0	0
Pati	Pati	10	0.79	7.9	183	2289	0	0	0.0	0	0
Umbukul	Umbukul	4	0.79	3.2	73	916	0	0	0.0	0	0
TOTAL		**895**		**705**	**16353**	**204413**	**4421**		**3152**	**19964**	**323823**

* Where more than 25 crabs were sampled for a community, average crab weights were used for calculations. Where less than 25 crabs were sampled, the average crab weight harvested within the same mangrove system (irrespective of which community harvested it) was used for calculations.

4.4 Socio-demographic Profiles of Crab Vendors

- Ninety five percent of crab vendors in 2014/15 surveys were women.
- Over 90% of crab vendors were also harvesters. Non-harvesting sellers were usually a friend or a relative of the harvester and in all cases lived in the same village as the harvester.
- Ages of vendors ranged from 15 to 70 years old, with a mean age of 34.3 years (SD=11.1) and a modal mean of 25-34. However, 22% of vendors interviewed did not know their age.
- Harvesters generally accessed harvesting grounds from their villages by a canoe (62%) or on foot (32%). Other categories were both canoe and walk (2%), dinghy (0.8%) and unknown (3.2%).
- Harvesters were asked for their primary motivation for coming to Kavieng from their villages (which were all outside the Kavieng village district). Almost 70% indicated the opportunity to sell goods at the market, less than 1% indicated coming "into town" to access services (whereby crab selling would be a secondary motivation) and almost 30% indicated other non-disclosed reasons.

Comparisons with 2012/13

- The proportion of harvesters who were women was the same as for the 2014/15 survey (95%)
- Ages of vendors ranged from 16 to 73 years old, with a mean age of 37.0 years (SD=11.6) and a modal mean of 25-34.
- Data were collected on the number of years experiencing harvesting and selling mud crabs. Responses were as follows: 1-5 years (42%); 6-10 years (11%); 11-15 years (16%); >15 years (31%).

4.5 Crab Population Characteristics

Taxonomic status and sex ratio

Overall, 3195 crabs were sampled in the 2014/15 survey. Of these, *Scylla serrata* and *S. paramamosain* comprised 93% and 7% of crabs respectively. In 2012/13, the relative proportions of *Scylla serrata* and *S. paramamosain* were also 93% and 7%. Male crabs dominated catches for both *S. serrata* (66%) and *S. paramamosain* (91%) in 2014/15 and also in 2012/13 where the proportion of male crabs for *S. serrata* and *S. paramamosain* was 73% and 89% respectively.

Carapace width – weight relationships

The relationship between body weight and carapace width shows that, for both species, males became proportionally heavier with increased carapace widths compared with female crabs (Figure 7 & 8). The BW-CW relationship between male and female *S. serrata* was estimated as:

$y=30.236e^{0.0226x}$ ($R^2=0.881$; $n=1953$) and $y=47.851e^{0.0178x}$ ($R^2=0.897$, $n=1020$) respectively. For male and female *S. paramamosain*, the BW-CW relationship was estimated as: $y=35.404e^{0.0227x}$ ($R^2=0.76$; $n=225$) and $y=30.393e^{0.021x}$ ($R^2=0.876$, $n=17$) respectively. Allometric differences between sexes, which are largely attributed to the development of large chelae of males upon reaching sexual maturity, are consistent with other authors (Chakrabarti 1981; Bomine *et al* 2008; Ikhwannudin 2011). For *S. serrata*, the divergence in the width-weight relationship occurred at around 100mm CW, which is presumed to mark the onset of sexual maturity in male crabs (see Section 4.6). For *S. paramamosain*, it appears that the BW-CW divergence between male and female crabs may occur at smaller sizes. However, insufficient data, particularly for female crabs and small crabs precludes confident estimations.

For the carapace width range for which there were comparative data (98-149mm), male *S. paramamosain* were considerably heavier than male *S. serrata*, though the slope of the relationship curve was very similar. For female crabs, BW-CW relationships were very similar across species despite the low numbers of *S. paramamosain* in the sample.

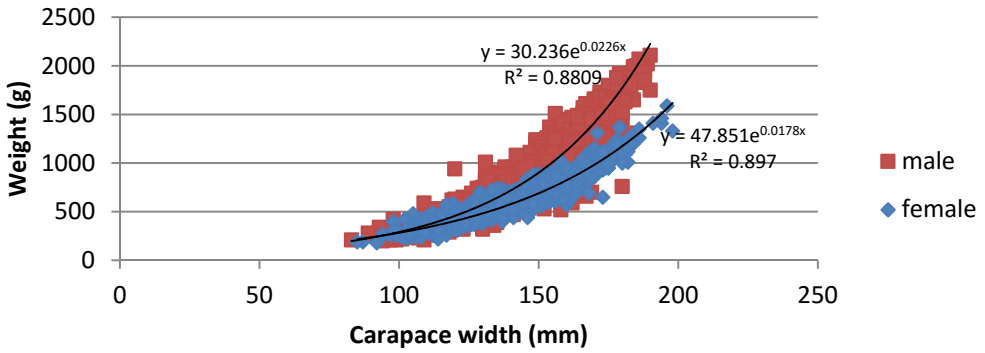

Figure 7. Carapace width - body weight relationships for male (red) and female (blue) *S. serrata*

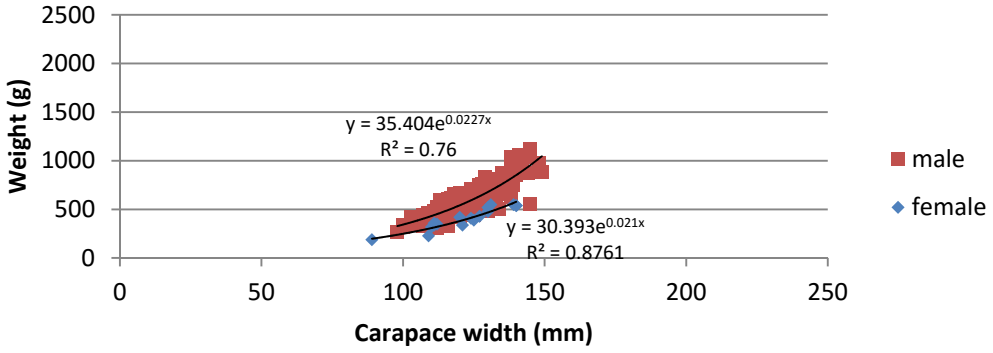

Figure 8. Carapace width - body weight relationships for male (red) and female (blue) *S. paramamosain*

Size Frequency Distributions

For *S. serrata* and *S. paramamosain*, carapace widths ranged from 83-198mm and 89-149mm, respectively (Table 4). The mean sizes of both male and female *S. serrata* were 140mm CW while for *S. paramamosain* respective means were 123 and 122mm CW. Size-frequency distributions for both species (Figures 9 and 10) were unimodal and male: female ratios were relatively uniform across size categories. Unimodal distributions of *S. serrata* were also observed during each sampling month (Fig 20), indicating year-round spawning and recruitment.

Table 4. Summary of numbers and sizes of *S. serrata* and *S. paramamosain* sampled in 2014/13 and 2014/15. Statistical comparisons were undertaken using Students T-tests assuming equal variances.

		Weight (kg)					Carapace Width (cm)*				
	n	range	mean	SD	t	*p*	range	mean	SD	t	*p*
***S. serrata* - males**											
2014/15	1953	0.20-2.11	0.78	0.34	4.97	<0.001	8.3-19.0	14.0	1.8	4.11	<0.001
2012/13	606	0.19-2.00	0.86	0.35			8.6-18.0	14.3	1.8		
***S. serrata* - females**											
2014/15	1020	0.18-1.59	0.62	0.23	-0.62	0.266	8.5-19.8	14.0	2	-0.95	0.3302
2012/13	224	0.44-1.32	0.61	0.23			8.4-19.7	13.9	1.9		
***S. paramamosain* - males**											
2014/15	205	0.27-1.12	0.60	0.16	5.09	<0.001	9.8-14.9	12.3	1.1	9.18	<0.001
2012/13	56	0.35-1.57	0.75	0.26			10.3-17.0	13.9	1.5		
***S. paramamosain* - females**											
2014/15	17	0.19-0.55	0.41	0.11	1.31	0.102	8.9-14.0	12.2	1.5	1.13	0.094
2012/13	7	0.36-0.69	0.47	0.11			11.0-16.4	13.5	1.8		

* As carapace width data were not collected in 2012/13, data were reconstructed using carapace width - body weight relationships established for crabs sampled in 2014/15

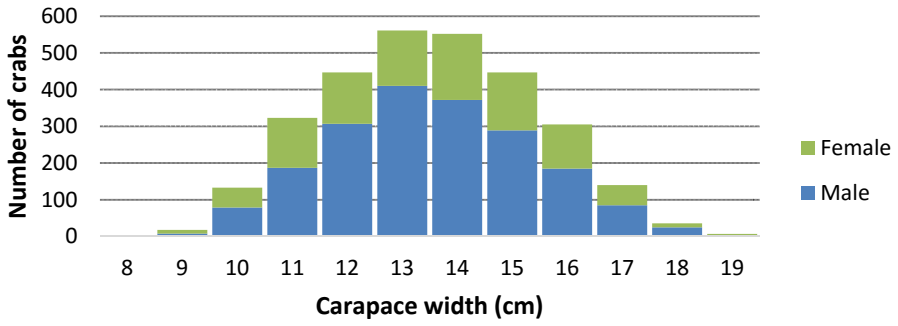

Figure 9. Length-frequency distribution of *S. serrata* sampled at the Kavieng market (2014/15)

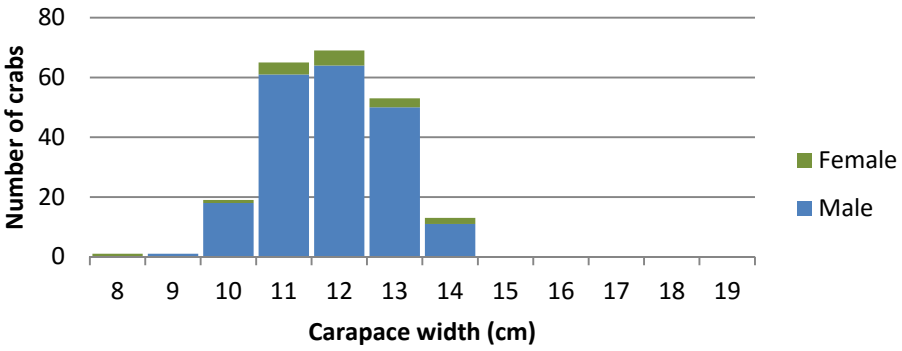

Figure 10. Length-frequency distributions of *S. paramamosain* sampled at the Kavieng market (2014/15)

Comparisons with 2012/13

Overall, crabs were significantly wider[5] (t=4.25; p<0.001) and heavier (t=5.95; p<0.001) in 2012/13 than in 2014/15 (Table 3). The overall size difference was attributed to a decrease in the average size of male *S. serrata* (CW; t=4.11, p<0.001: Kg; t=4.97, p<0.001) and male *S. paramamosain* (CW; t=9.19, p<0.001: Kg; t=5.09, p<0.001), while there were no average size differences between female *S. serrata* (CW; t=-0.98, p=0.33: Kg; t=-0.62, p=0.27) or female *S. paramamosain* (CW; t=-1.13, p=0.09: Kg; t=1.31, p=1.10). However, the statistical values and low sample sizes for *S. paramamosain* suggest that significant differences may be observed with a larger sample size.

4.6 Size at Maturity by Abdominal Examination

Scylla serrata

Male and female crabs comprised 65.7% and 34.3% of samples, respectively. Sex ratios were relatively uniform across all size categories (Figure 15). The proportions of Stage 1 (immature abdomen), Stage 2 (intermediate abdomen) and Stage 3 (mature abdomen) female crabs was 5.4, 20.5 and 74.5% and respective carapace width ranges were 85-123, 89-141 and 109-198mm (Figure 11). Only 18 berried females (0.6% of all females sampled) were recorded with a size range from 140-160mm CW.

[5] As carapace width data were not collected in 2012/13, data were reconstructed using carapace width – body weight relationships established for crabs sampled in 2014/15

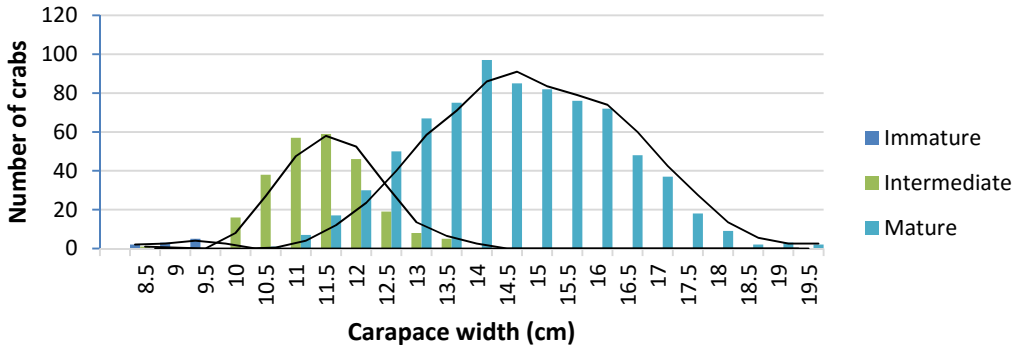

Figure 11. Size-frequency distributions of female *S. seratta* according to abdominal shape denoting maturity status - immature, intermediate and mature

The median size of the attainment of female mature abdomen form (LM_{50}) was determined as 123mm CW by calculating the proportion of females with a mature abdomen within the sample for each size class (1mm) represented (Figure 12). Further, LM_{100} – the size at which all females had undergone their maturity molt – was deemed to be 142mm CW.

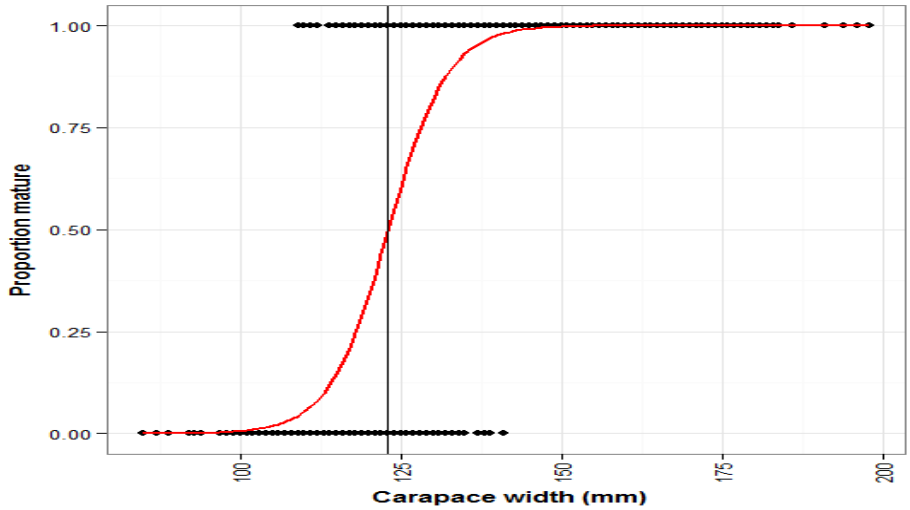

Figure 12. Proportion of female *S. serrata* achieving abdominal maturity scale as predicted by logistic regression (red) through abdominal examination. Black vertical line represents LM_{50}.

Assessing maturity status for male crabs from external characters is less straightforward. However, due to the development of larger chelae (relative to female crabs) during the pubertal molt, the onset of first male maturity within the population can be estimated by comparing sex-specific weight-length relationships (Figure 13 and 14). From this relationship, it appears that early

maturing males attain maturity at around 100mm CW. However, LM_{50} and LM_{100} cannot be determined from this data.

Scylla paramamosain

Male and female crabs comprised 92.3 and 7.7% of samples respectively and sex ratios were relatively uniform across all size categories (Figure 16). Of the 17 females recorded, only one crab was immature (89mm CW). Mature (Stage 3) female crabs ranged from 110-140mm CW, though the size at first maturity could not be estimated due to low crab numbers, especially at smaller sizes (only one immature crab was sampled). Also, due to the low number of female crabs sampled, LM_{50} and LM_{100} could not be determined. Furthermore, low female crab numbers precluded a confident assessment of male maturity onset through comparing length-weight relationships between males and females. However, the limited data presented in Figure 14 suggests that male *S. paramamosain* may mature at a smaller size than male *S. serrata* (i.e. < 100mm CW).

4.7 Size at Maturity by Histological Examination

Forty nine female *S. serrata* (92.0 – 173.0 mm CW) were biopsied to determine stage of ovarian development. This was undertaken to provide a more definitive assessment of female maturity size, thus allowing the efficacy of external morphological examination as a means of assessing maturity sizes to be assessed. The number of crabs examined with an immature, intermediate and mature abdominal form was 2, 14 and 33, respectively. Based on macroscopic and histological assessments (as described by Islam *et al.,* 2010), both crabs with an immature abdomen were deemed to have immature (Stage 1) ovaries while al 13 crabs with an 'intermediate' abdomen were found to possess previtellogenic (Stage 2) ovaries. For crabs with a mature abdomen, ovarian condition ranged from Stage 2 to Stage 6 (Figure 13). Nine crabs (26% of crabs with mature abdomens) were found to have Stage 2 immature ovaries, suggesting that maturity, as determined by vitellogenic condition, may occur after the pubertal molt and the attainment of a mature abdominal form.

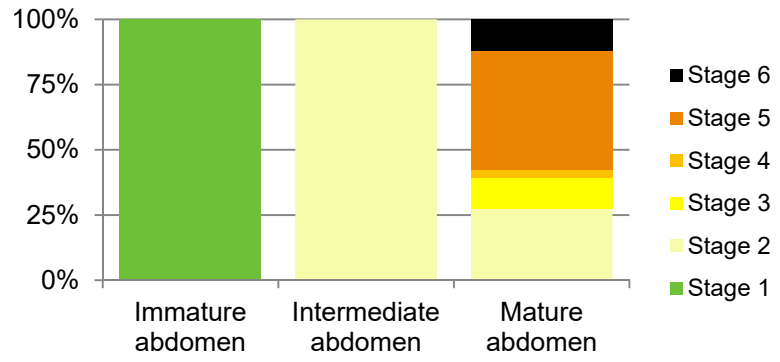

Figure 13. Frequency of occurrence of each ovarian development stage for the three categories of abdominal maturity for *S. serrata*

The smallest mature (Stage 3) crab examined was 127 mm. Using logistic regression, the size at which 50% of female crabs attain sexual maturity (LM_{50}) was estimated at 136.5mm CW (Figure 14).

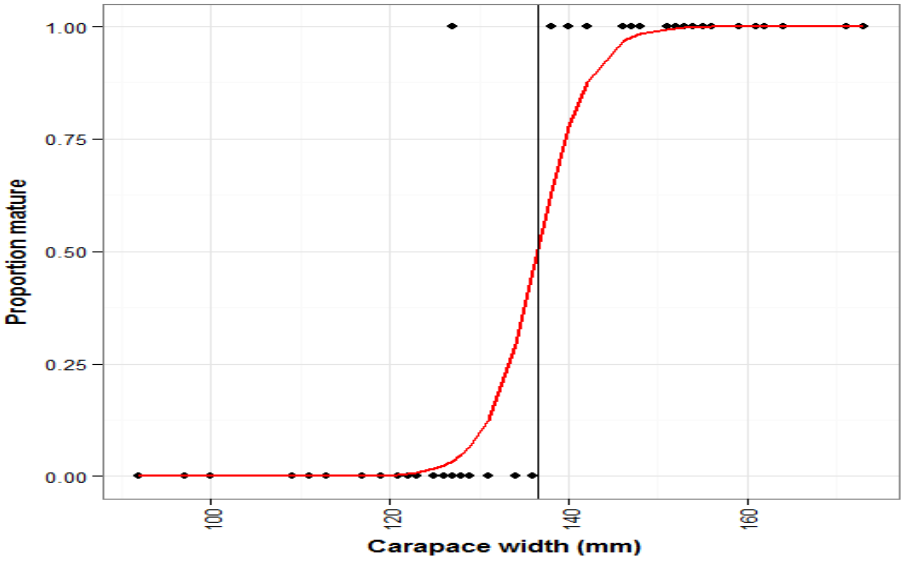

Figure 14. Proportion of female *S. serrata* achieving abdominal maturity scale as predicted by logistic regression (red) through histological examination. Black vertical line represents LM_{50}.

4.8 Timing of Spawning

During offshore spawning migrations, female crabs are not available to be harvested in mangroves. As such, ratios of male and female *S. serrata* were assessed for each sampling month to indicate temporal spawning trends (Figure 15). As males comprised greater than 50% of catches for each month (range: 55.3-74.1%), it appears likely that some level of spawning occurs year-round. Assuming a population sex ratio of 1:1, all sampling months except August showed a

predominance of male crabs at $p < 0.01$ (Figure 16), whilst August was significant at $p < 0.05$. Figure 16 also indicates that there may be a period of heightened spawning activity in March and April. Despite this, all 17 berried crabs encountered in this study were harvested in early October 2014.

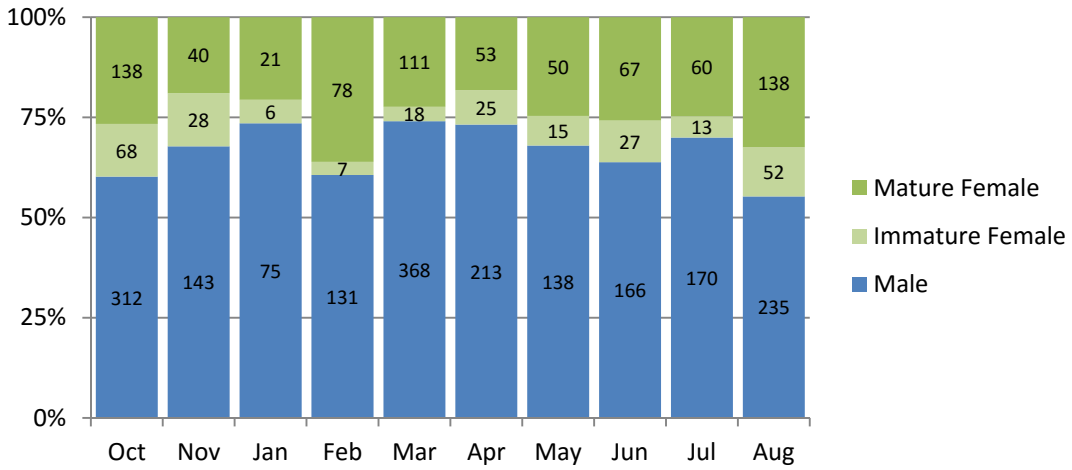

Figure 15. Relative proportions and absolute numbers of male and female (mature and immature) mud crabs sampled during each of the months over the 2014/15 sampling period for which data were collected

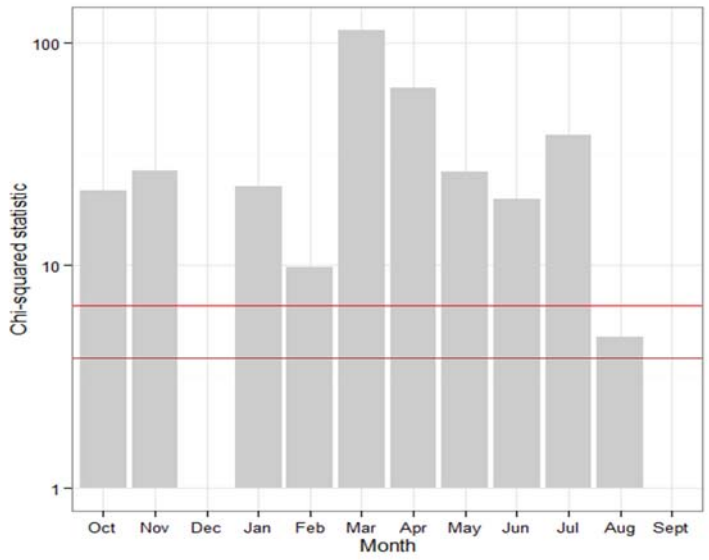

Figure 16. Results of Chi-squared statistics for independence to determine the likelihood of 1:1 ratios of male and female crabs. The lower line (brown) and red line (upper) indicate significant departure from parity at p= 0.05 and 0.01 respectively.

Assessing length-frequency data for the presence of cohorts can also indicate the presence of defined periods of recruitment, and by proxy, spawning. However, size distributions were

unimodal (Figure 17) for both annual and monthly data, indicating that recruitment and spawning occur year-round in the northern New Ireland region.

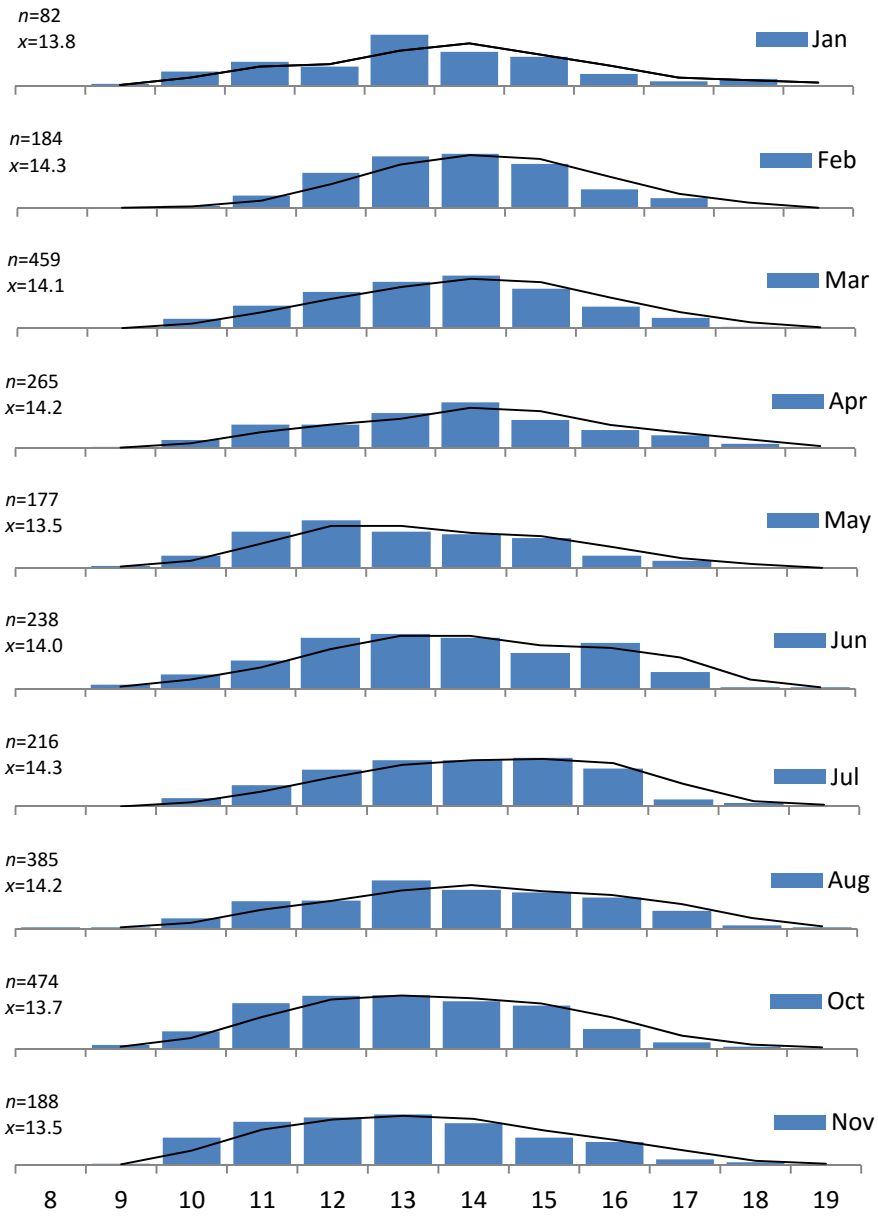

Figure 17. Size-frequency distributions of mud crabs during each of the months over the 2014/15 sampling period for which data were collected

Comparisons with 2012/13

- A smaller proportion of *S. serrata* females were sampled in 2012/13 (24%) compared with the 33% for the 2014/15 survey. However, male-female ratios were very similar for *S. paramamosain* – 92.3%: 7.7% (2012/13) and 92.5%: 7.5% (2014/15).

- As per the 2104/15 survey, sex ratios for *S. serrata* were relatively uniform across all size categories.

- Sex-specific weight-length relationships from 2012/13 data also suggest that the onset of first male *S. serrata* maturity is around 100mm CW.

- Differences in methodologies between surveys precluded assessments of length based sexual maturity in females. Nonetheless, based on the results from this study, the percentages of female *S. serrata* harvested below LM_{50} (123mm CW) in the 2012/13 and 2014/15 studies was 21.0% and 24.3% respectively. The percentages of female *S. serrata* harvested below LM_{100} (142mm CW) in the 2012/13 and 2014/15 studies was 53.1% and 53.7% respectively

4.9 Crab Size by Harvesting Site

Assuming no differences in size-selective harvesting behaviour at different sites, size comparisons of crabs can be used to indicate spatial differences in fishing pressure. To do this, the average size of crabs from nine harvesting grounds deemed to provide a sufficient number of crabs (>25) were compared (Figure 18). These harvesting grounds supplied 98% of all crabs sampled during the survey.

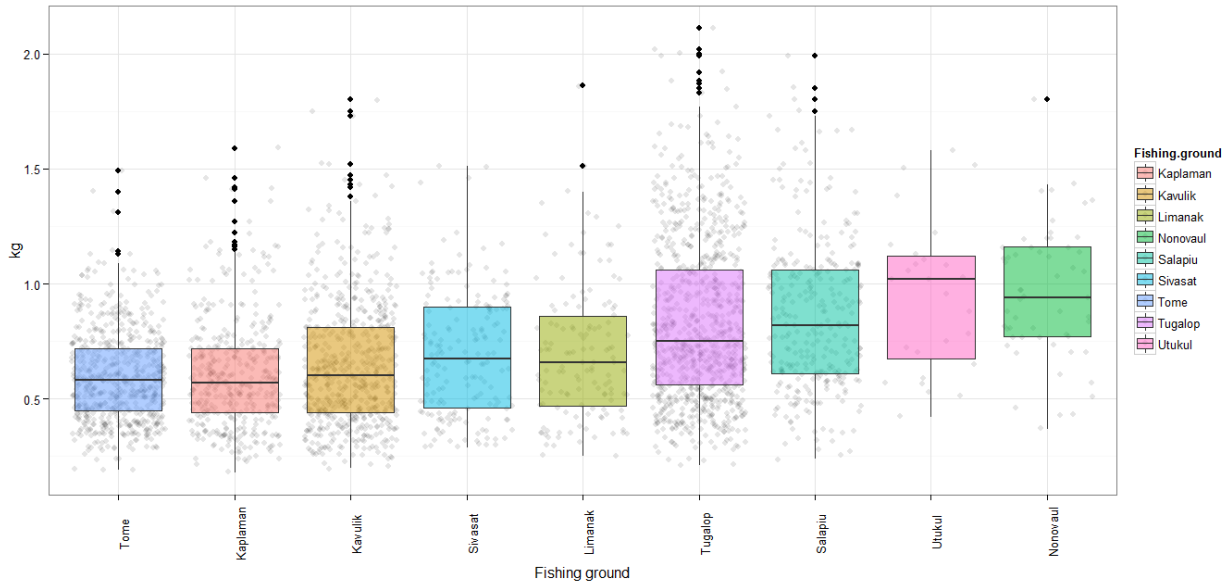

Figure 18. Box and whisker plots showing crab weights for all harvest sites that provided a minimum of 25 crabs for the survey

The largest crabs were harvested from Tigak Island sites: Utukul (*n*=27, avg wt=0.96kg, avg CW=15.4cm), Nonovaul (*n*=53, avg wt=0.96kg, avg CW=15.2cm) and Salipiu (*n*=281, avg wt=0.86kg, avg CW=14.5cm). The smallest crabs were harvested from the Balgai Bay sites of Tome (*n*=618,

avg wt=0.60kg, avg CW=13.1cm) and Kaplaman (*n*=393, avg wt=0.60kg, avg CW=13.4cm) followed by Kavulik (*n*=580, avg wt=0.65kg, avg CW=13.4cm) in the Tsoi Islands.

There were significant differences in average crab weight between harvesting sites (one-way ANOVA: F=57.99, p=2.2e^{-16}). Using Tukey's post-hoc tests, there were significant differences for 24 out of 36 pairwise comparisons (Table 5).

Table 5. Tukey's HSD pairwise comparisons to test for differences in crab weight between harvest sites that provided a minimum of 25 crabs for the survey (p<0.05: S=significant; NS=non-significant).

	Tome	Kaplaman	Kavuilik	Sivasat	Liminack	Tugalob	Salapiu	Utukul
Kaplaman	NS							
Kavuilik	NS	NS						
Sivasat	S	S	NS					
Liminack	S	S	NS	NS				
Tugalob	S	S	S	NS	S			
Salapiu	S	S	S	S	S	NS		
Utukul	S	S	S	S	S	NS	NS	
Nonovaul	S	S	S	S	S	S	NS	NS

Comparisons with 2012/13

There were sufficient data (>25 crabs) from the 2012/13 survey to enable inter-survey comparisons of average crab weight between eight of the nine harvesting sites in Figure 21. Student's T-tests indicate that the average weight of crabs has decreased significantly (alpha = 0.01) at three sites – Tugalob, Tome and Kavulik (Table 6). These three sites are those from which the greatest numbers of crabs were harvested in 2014/15 and two of the three top harvest sites for the 2012/13 survey, suggesting growth overfishing linked to intensive harvesting.

Table 6. Crab sample sizes, weight ranges and means for eight harvesting grounds – 2012/13 and 2014/15. For each harvesting ground, Student's T-tests were used to compare average weights between surveys. Asterisks indicate significant differences.

			Weight (kg)				
		n	range	mean	SD	t	*p*
Utukul	2014/15	27	0.42-1.58	0.95	0.36	0.963	0.169
	2012/13	44	0.37-1.72	1.03	0.32		
Tugalob	2014/15	857	0.21-2.11	0.83	0.35	5.671	< 0.001*
	2012/13	125	0.29-1.81	1.02	0.39		
Tome	2014/15	618	0.19-1.49	0.60	0.39	4.741	< 0.001*
	2012/13	30	0.49-1.26	0.77	0.33		
Salapiu	2014/15	281	0.24-1.99	0.86	0.34	0.782	0.217
	2012/13	85	0.34-1.52	0.89	0.3		
Kaplaman	2014/15	393	0.18-1.59	0.6	0.24	-0.891	0.187
	2012/13	190	0.19-1.4	0.58	0.24		
Nonovaul	2014/15	53	0.37-1.80	0.96	0.29	-0.689	0.246
	2012/13	24	0.44-1.49	0.91	0.27		
Liminack	2014/15	133	0.25-1.86	0.7	0.29	1.612	0.054
	2012/13	45	0.38-1.45	0.78	0.27		
Kavulik	2014/15	580	0.20-1.80	0.65	0.28	2.321	0.010*
	2012/13	247	0.25-1.56	0.7	0.24		

4.10 Catch per Unit Effort

Catch rates were compared across the main eight harvesting grounds according to the following two measures: (1) weight of crab (kg) per person/harvesting hour (CPUE1), and; (2) numbers of crabs per person/harvesting hour (CPUE2). For CPUE1, values ranged between 0.79 kg/hr^{-1} (Kaplaman) and 1.57 kg/hr^{-1} (Kavulik), suggesting that harvesting sites at Kavulik are twice as productive as those at Kaplaman (Figure 19). The other six sites ranged between 1.2 and 1.5 kg/hr^{-1}.

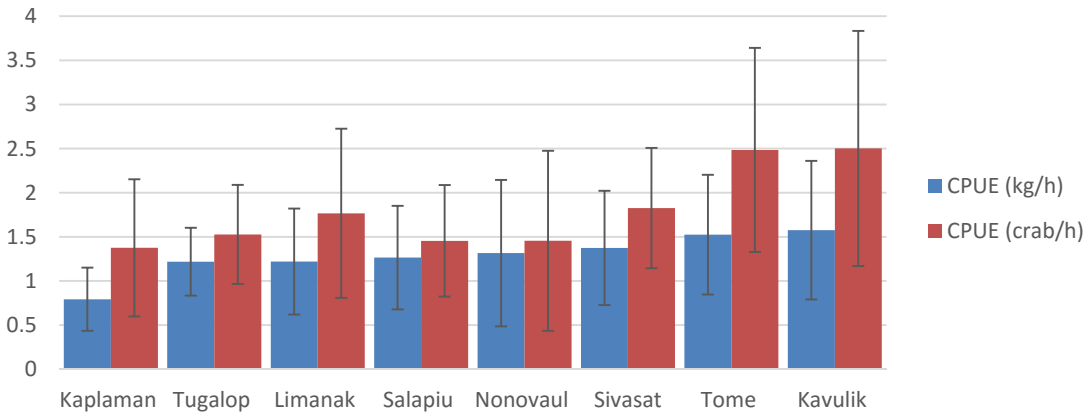

Figure 19. CPUE1 (kg/hr) and CPUE2 (crabs/hr) for eight harvesting grounds

There were significant differences in CPUE1 between harvesting sites (one-way ANOVA: F=7.35, p=4.82e^{-8}). Tukey's post-hoc tests on log transformed data (due to homeoscedascity) indicated 6 significant differences from a total of 28 pairwise comparisons (Table 7). Five of the differences were associated with Kaplaman which had significantly lower CPUE1 values than all sites with the exception of Liminack and Nonovaul.

Table 7. Results of Tukey's HSD post-hoc tests comparing log transformed CPUE1 values between eight harvesting grounds (S=significant [p=0.05], NS=non-significant)

	Kaplaman	Tugalob	Liminack	Salapiu	Nonovaul	Sivasat	Tome
Tugalob	S						
Liminack	NS	NS					
Salapiu	S	NS	NS				
Nonovaul	NS	NS	NS	NS			
Sivasat	S	NS	NS	NS	NS		
Tome	S	NS	NS	NS	NS	NS	
Kavuilik	S	S	NS	NS	NS	NS	NS

CPUE2 values ranged from 1.28 (Kaplaman) to 2.50 (Kavulik) and differences across sites were highly significant (one-way ANOVA: F=9.84, p=7.42e^{11}). Tukey's post-hoc tests comparing CPUE2 between each site indicated 6 significant differences from a total of 28 comparisons (Table 8): The sites with the highest CPUE2 – Kavulik and Tome – were significantly different to Kaplaman, Tugalob and Salipiu.

Table 8. Results of Tukey's HSD post-hoc tests comparing CPUE2 values between eight harvesting grounds (S=significant [p=0.05], NS=non-significant)

	Kaplaman	Tugalob	Liminack	Salapiu	Nonovaul	Sivasat	Tome
Tugalob	NS						
Liminack	NS	NS					
Salapiu	NS	NS	NS				
Nonovaul	NS	NS	NS	NS			
Sivasat	NS	NS	NS	NS	NS		
Tome	S	S	NS	S	NS	NS	
Kavuilik	S	S	NS	S	NS	NS	NS

There was a positive correlation between CPUE1 and CPUE2, though this was not as strong as expected (R^2=0.607; p <0.05). This weaker than expected relationship can be understood in light

of a linear regression examining the effects of site and average crab weight on CPUE2 values. Across sites, average crab sizes decreased significantly with increases in CPUE2 (F=12.9: Multiple R^2=0.441: p=2.2e^{-16}). However, some sites contributed more strongly to this relationship than others, whilst this relationship was not apparent for Salipiu and Sivasat (Figure 23). As a result, there was no relationship (R^2=0.0002: p=0.97) between two measures of fishery health – CPUE1 and average crab size (Fig 24).

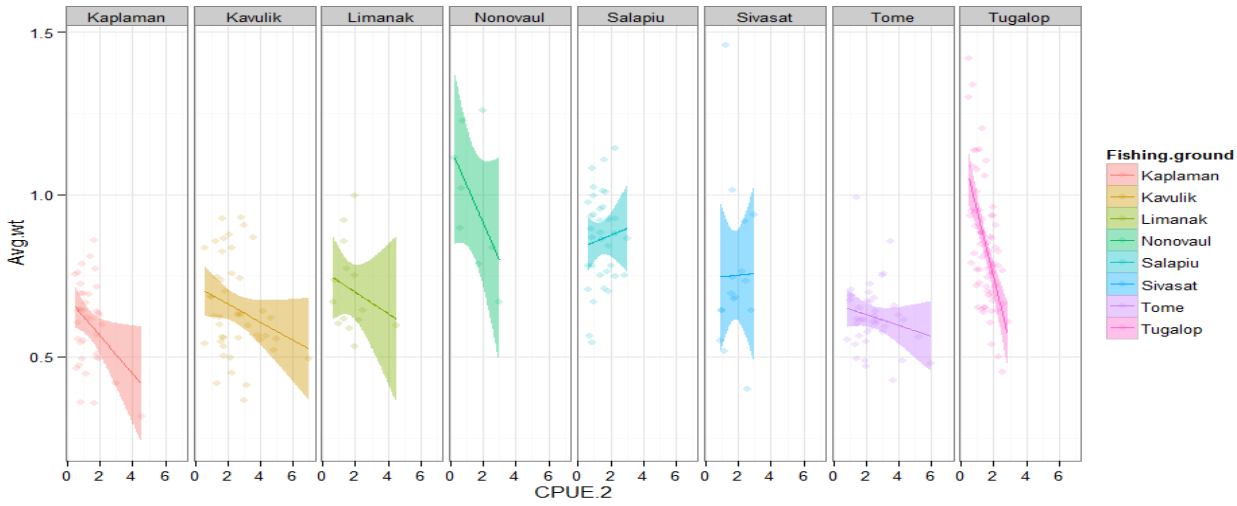

Figure 20. Relationship between CPUE2 and crab size, shaded areas represent 95% confidence intervals around the resultant linear regression

5. DISCUSSION

5.1 Crab sales

Data extrapolation from the 2014/15 survey suggests that around 28,000 crabs with a combined weight of 19.9 tonnes are sold at the Kavieng market annually. At an average selling price of PGK 11.55, this equates to around PGK 323,000 per year. By comparison, annual respective estimates from the 2012/13 survey are 20,750 crabs and 16.4 tonnes. This suggests that crab volumes by numbers and weight have increased by around 35% and 21% respectively between surveys. While these figures indicate a considerable increase in the volume of crabs being brought to market, the discrepancy in the values expressed as crab numbers and tonnages reflect the smaller size of crabs sampled in 2014/15 (discussed in more detail later). In terms of estimated annual sales however, financial returns to sellers in 2104/15 increased by 57% due to a combination of increased volumes and higher prices. Regarding the latter, mean prices per kilogram of mud crab were approximately PGK 12.5 and 16.2 in 2012/13 and 2014/15, respectively – a price increase of around 30% in only two years. Reasons for increases in demand and supply are unclear though conversations with vendor suggest that a locally increasing human population with higher disposal incomes, including the Chinese community, may be implicated.

5.2 Crab harvest by fishing ground

Crabs were supplied to the Kavieng market by vendors from 17 different mangrove sites. However, 87% of crabs were harvested from only five sites - Tugalob, Tome, Kavulik , Kaplaman and Salapiu. With the exception of Tome, these sites were also the most prominent harvest areas in 2012/13. Nonetheless, between surveys there were large proportional increases in the crab harvesting reported from the New Ireland mainland sites of Sivasat (95%) and Tome (73%) while proportional decreases were more evenly spread across a larger number of harvesting sites. The large increase in crab production from Sivasat and Tome reflects an overall 8% relative increase in crabs sourced from mainland New Ireland. Conversely, the proportion of crabs sourced from the most remote region canvassed by the survey – the Tsoi Islands – decreased by 9%. Reasons underpinning the apparent intensification of crab harvesting activity at sites closer to Kavieng are unclear but may reflect increasing logistical constraints (e.g. rising fuel prices) imposed on more remote communities.

5.3 Crab population characteristics

Species Composition

The results from both surveys reported that the ratio of *Scylla serrata* to *S. paramamosain* brought to the Kavieng market is around 13:1. These results are comparable with a study on the mud crab fishery near Lae PNG where the species ratio of *S. serrata* and *S. paramamosain* brought to market was 17:1 (Quinn and Kojis, 1987). However, in a survey of all marine products offered for sale at the Kavieng market in 2004/05, no *S. paramamosain* were recorded, despite sampling 2883 crabs over a 12 month period (NFA, 2005). This may be due to surveyors not distinguishing the two species, which are morphologically very similar without close examination.

The predominance of one *Scylla* species in catches is generally observed in studies of multi-species mud crab fisheries (Christensen *et al*., 2004; Moser, 2005; Walton *et al*., 2006; LeBata, 2007; Ikhwanuddin, 2011). However, the findings of this study do not necessarily suggest the ratio of *S. serrata* and *S. paramamosain* landings are indicative of the relative abundance of the two species in northern New Ireland. Some authors suggest that adult *S. paramamosain* prefer sub-tidal habitats on the seaward side of the mangrove fringe (LeVay, 2001; LeVay *et al*., 2001; Walton *et al*., 2006) and may therefore avoid capture as the New Ireland fishery is almost exclusively based on digging crabs from inter-tidal mangrove flats.

Sex Composition

Male crabs dominated catches among *S. serrata* (66%) and *S. paramamosain* (91%). Male crabs also dominated catches in 2012/13: *S. serrata* (73%) and *S. paramamosain* (89%). The predominance of male crabs in catches has been observed in other studies studies (Hill, 1975; Perrine, 1978; Quinn and Kojis, 1987; Nandi and Dev Roy 1990; La Sara, 2002; Pillans *et al*., 2005; Bomine *et al.,* 2008). Heasman (1980) explained this phenomenon by females exiting mangrove areas during offshore spawning migrations. As such, spawning females are not available to be caught in mangrove areas during these times. A South African study on two crab populations – one population with open sea access and one temporarily landlocked estuarine population – concurs with this explanation: roughly equal gender ratios were observed among landlocked crabs whilst highly male-skewed crab samples were collected for the 'open sea' (Hill, 1975). Consistent with this, Bomine *et al* (2008) suggest that the skew towards males may be greater in areas more isolated from the open sea.

Despite the general predominance of male crabs from landings reported across studies, a seafood survey of the Kavieng market reported almost identical quantities of male (51%) and female (49%) crabs among almost 3000 crabs sampled in 2004/05 (NFA, 2005). The reasons for the discrepancy with the current survey results are unclear but could indicate a shift in fishing methods and/or

target habitats. Given reports of sex based habitat partitioning (adult males are more commonly found in mangrove channels or burrows within mangrove forests while adult females are more commonly found on sub-tidal reef flats) by some authors (Hill, 1975; Perrine, 1978; Nandi and Dev Roy, 1990; Bomine *et al*., 2008), it is possible that harvesting strategies may have changed to favour the collection of male crabs in the years between surveys. However, changes in harvesting practices have not been mentioned during focus groups with local crab fishers. As such, it appears more likely that sampling errors in the NFA study accounted for this discrepancy.

Carapace width–weight relationships and crab size

Carapace width (CW) and body weight (BW) are the most frequently used dimensions in the study of crustaceans. The CW–BW relationship can be used in condition indices and ontogenetic analyses and in the study of crustacean population dynamics. Regarding ontogenetic analyses, different allometric growth patterns between male and female mud crabs, particularly from the onset of sexual maturity, is well understood (Heasman, 1980; Chakrabarti 1981; Keenan, 1999 Bomine *et al* 2008; Ikhwannudin, 2011). In short, males become proportionally heavier at a given carapace width due to disproportionate growth of their chelae, which they use to compete with other males for breeding access to females. In this study, allometric diversion occurred at a larger size for *S. serrata* than for S. *paramamosain*, indicating that the two species mature at different sizes (discussed in the next ~~Section~~section). This study also observed that male *S. paramamosain* were heavier than male *S. serrata* for a given carapace width.

Size-frequency distributions for both species were unimodal indicating continuous year-round recruitment. The mean sizes of both male and female *S. serrata* were 140mm CW while for *S. paramamosain* respective means were 123 and 122mm CW. The larger relative size of *S. serrata* compared with *S. paramamosain* in samples concurs with reported maximum respective sizes of 24cm and 15cm (Le Vay, 2001).

Size at Sexual Maturity

Determination of size at maturity is important for fisheries management, particularly when implementing size selective input or output controls. Studies on the size at maturity for mud crabs, which mature at different sizes across a wide latitudinal range, indicate that this will need to be determined for each regional population.

External examination of the shape and colour of the abdominal flap is often used to indicate the attainment of a maturity moult, and thus female sexual maturity in females (Heasman, 1980; Robertson and Kruger, 1994; Tongdee, 2001; La Sara, 2002; Hamasaki et al., 2011; Ikhwannudin,

2011). Based on this method, female *S. serrata* were recorded reaching maturity between 109 and 141 mm while LM_{50} – the size at which 50% of female *S. serrata* were mature – was determined to be 123 mm.

However, some researchers have reported differences between maturity indicated by the attainment of a pubertal/maturity moult ('abdominal maturity') and functional maturity i.e. the size at which crabs produce viable eggs (Robertson and Kruger, 1994; Walton *et al*., 2006). A difference was also recorded in the current study whereby LM50 based on functional maturity was 138.5mm CW – 15.5mm larger than LM50 for abdominal maturity. The time lag between the two 'maturity states' may be due to crabs not mating during their maturity moult and females storing sperm in their spermathecae for months before 'choosing' to release the sperm to fertilise ooctyes at a favourable time (Kruger and Robertson, 1994). Also, newly mature females, while capable of copulation, may not have sufficiently developed ovaries for successful reproduction (Kruger and Robertson, 1994). While functional LM50 determined in this study was based on a limited sample size (49 crabs), it should be sufficient to inform mud crab management in the region. A LM50 of 136.5mm CW also indicates that approximately 40% of the female crabs sampled in this study were functionally immature.

The onset of male crab maturity was not comprehensively addressed in this study but may be inferred through allometic changes between male and female crabs owing to the development of large male chelae, coinciding with sexual maturity (Campbell and Eagles, 1983; Knuckey, 1996). Using this measure, the smallest maturing males were around 100mm CW. However, allometric change assessment does not enable size of the maturity onset window or average size of maturity onset (LM50) to be assessed. Determining these is difficult for male crabs and commonly applied indicators including the presence of sperm in the vas deferens and the presence of mating scars often yield inconsistent results suggesting a lag between physiological maturity and functional maturity. This lag period is likely to be longer with greater mating competition from larger males (Robertson and Kruger, 1994).

Despite the uncertainty, studies typically report a smaller size of male maturity compared with females (Robertson and Kruger, 1994; Hamasaki et al., 2011). Accordingly, size-based management informed by female maturity sizes will be sufficient to protect male crabs.

Timing of Spawning

Assessing species ratios from samples is sometimes used to infer spawning seasonality in mud crabs. This approach is based on the premise that female mud crabs on spawning migrations are

not available to be caught in mangroves, thus affecting sex ratios. In this study, the composition of male crabs was significantly greater than 50% in each monthly sample, ranging from 64 to 82%. Therefore, it appears that some level of spawning activity occurs in northern New Ireland year-round – an observation supported by monthly unimodal size-frequency data (discussed above) suggesting that recruitment (and by proxy, spawning) occurs year-round.

Despite this, analyses suggest that there may be a period of heightened spawning activity in March and April coinciding with the monsoon season in New Ireland. Similar male: female ratios were also reported for January (also within the monsoon period) but lower numbers of sampled crabs in that month did not provide results of the same statistical power. Whilst it is commonly understood that mud crab spawning behaviour is less seasonal (or not at all) at lower latitudes, Heasman (1980; 1985) suggests that in some equatorial regions, spawning activity may be heightened during periods of high rainfall as nutrient run-off from rainfall events provides conditions conducive to larval survival. In another PNG study, Quinn and Kojis (1987) also suggested the existence of weak seasonal spawning peaks coinciding with the change of seasons based on changes in gonadosomatic indices among female crabs.

Crab Size by Harvest Site

Average carapace widths ranged from 13.4 to 15.4cm CW among the nine harvesting grounds that supplied 92% of all crabs sampled during the survey. The smallest crabs were from the mainland sites of Tome and Kaplaman while the largest crabs were harvested from the Tigak Island sites of Nonovaul and Utukul. Inter-site differences could be due to various factors including variation in size-selective harvesting or natural factors including recruitment, growth and natural mortality. However, they are most plausibly linked to harvesting pressure coupled with a lack of size-selective management. This assessment is supported by a significant decline in the size of crabs from the three most intensively harvested sites (in terms of the number of crabs sold through the Kavieng market) - Tugalob, Tome and Kavulik – since 2012/13, highlighting the need for careful management of the fishery.

Catch per Unit Effort

Average hourly yields (CPUE1) ranged from 0.79 kg/hr^{-1} (Kaplaman) to 1.57 kg/hr^{-1} (Kavulik). The other six sites were quite similar, ranging between 1.2 and 1.5 kg/hr.$^{-1}$ Significant differences were observed for 6 of 28 inter-site comparisons and five of these were associated with Kaplaman. For the other catch rate investigated – the number of crabs caught per hour (CPUE2) – Kaplaman (1.28) and Kavulik (2.50) again had the highest and lowest values, respectively. Overall however,

the relationship between CPUE1 and CPUE2 was not as strong as expected and was tempered by an inverse relationship between the number and size of crabs harvested: on trips where high crab numbers per hour were harvested, crabs tended to be smaller. However, there were site effects indicating that this relationship was not apparent for Salipiu and Sivasat.

The results indicate a non-existent site-based relationship between two commonly recognised indicators of fishery health – CPUE1 and average animal size. The results further indicate that average crab size is a better indicator of local fishing pressure than CPUE (especially CPUE2) and recruitment processes occur at a regional rather than a local level. The observation of relatively healthy crab numbers from more heavily fished mangrove sites (as indicated by average crab sizes) indicates a high degree of recruitment connectivity between sites. Therefore, if localised harvesting pressure were sufficient to decrease localised spawning potential, the results suggest that recruitment will be subsidised by greater spawning potential from less heavily fished sites in the region. This assertion, which is supported by the results of this study, is consistent with contemporary knowledge of mud crab spawning and recruitment dynamics (Alberts-Hubatsch *et al*., 2006). Female crabs often undergo extensive offshore spawning migrations and pelagic larvae take between 23 and 31 days to recruit to suitable habitats (Marichamy and Rajapackiam, 1992). Mud crab larvae have little capacity for horizontal movement and are therefore dependent on favourable currents for successful recruitment into nursery areas (Macintosh et al., 1999). During this time, larvae are likely to recruit considerable distances from spawning sites.

While recruitment interconnectivity between mangrove systems in the region likely provides a recruitment 'safety net' for more heavily fished sites, there is also likely to be some degree of variability in the numbers and consistency of juveniles recruiting to different sites due to different degrees of exposure to hydrological forces. Sites closest to oceanic quality water and currents may receive higher numbers and a more consistent supply of larvae. As such, relatively low crab numbers at Kaplaman, as inferred by CPUE2 results, may be related to its sheltered location, deep inside a large shallow bay.

Juvenile mortality among mud crabs is typically very high (Le Vay and Walton, 2007) and likely to be density dependent. It is therefore likely to temper inter-site differences in the numbers of crabs that recruit to the fishery, thus evening out crab densities among sites with different levels of recruitment exposure. Density dependent mortality among larger crabs can also explain why sites with higher CPUE2 values tended to yield smaller average crabs, an assertion supported by the territorial and cannibalistic nature of mud crabs, particularly after reaching maturity. These biological traits impose a natural limitation on the carrying capacities of mangrove systems and

the amount of space required for individual crabs increases with increasing crab size (Shelley, 2008). Such traits, coupled with high fecundity and fast growth rates, also explain why Le Vay and Walton (2007) observed a low rate of fishing mortality relative to overall mortality in a heavily fished region in Vietnam. While this indicates that mud crab fisheries can absorb a high level of fishing pressure, management initiatives are required to insulate fisheries from potential variability in natural processes and fishing impacts underpinning recruitment. Given the high proportion of crabs harvested below functional maturity size thresholds in this study, size-based management should be implemented to prevent potential region-wide recruitment overfishing, particularly if fishing pressure intensifies.

6. CONCLUSIONS AND MANAGEMENT RECOMMENDATIONS

The two mud crab surveys conducted by WCS at the Kavieng market produced a valuable time-series dataset enabling a detailed understanding of the local mud crab fishery at a sub-regional, mangrove and community level. We are confident that the results generated from data collected at the market are broadly representative of biological, social and economic dimensions of the northern New Ireland fishery. While some crabs are sold directly to restaurants and resorts, and were therefore not canvassed by this project, anecdotal reports indicate that the majority of crabs harvested in the region are sold through the Kavieng market. Over the study period, crabs were reportedly harvested from 17 sites across three New Ireland sub-regions – The Tigak Islands, the Tsoi Islands and northern mainland New Ireland. However, 87% of crabs were harvested from only five sites - Tugalob, Tome, Kavulik , Kaplaman and Salapiu.

Current estimates suggest that around 28,000 crabs (~20 tonnes) are sold through the Kavieng market annually. At an average selling price of PGK 11.55, this equates to around PGK 323,000 per year. Comparative estimates between both surveys suggest that mud crab sales by numbers and weight have increased by around 35% and 21% respectively since 2012/13. In financial terms, sales have increased by 57% due to a combination of increased volumes and higher prices. In fact, in only two years, prices per kilogram have increased by 30%, despite an increase in production. The reasons for this price increase are not entirely clear but likely reflect growing levels of disposable income from various sectors of the community such as expatriates (including a fast growing Chinese population), the hospitality industry, workers from nearby mining industries and a growing transient population of PNG nationals.

The large increase in demand and production has provided additional livelihood opportunities for harvesters and sellers. However, current trends urge caution to safeguard this important fishery from overexploitation. In only two years, the average crab size has declined significantly at three mangrove sites – Tugalob, Tome and Kavulik. Incidentally, these are the sites from which the greatest numbers of crabs were harvested in 2014/15 and two of three sites from which production has increased considerably over the last few years. As such these size decreases are likely linked to intensive harvesting rather than changes in harvesting practices.

The results from this study also indicate that average crab size is a reliable indicator of harvesting pressure at the scale of individual mangrove sites while CPUE is not. However, CPUE is likely to be a reliable indicator of harvesting pressure at a regional scale. The lack of sensitivity of CPUE to harvesting pressure at a local scale is likely related to broad-scale larval dispersal patterns, consistent levels of year-round recruitment, fast growth rates that decrease with age/size and a

high degree of density dependent natural mortality. On the face of it, sustaining good yields in heavily fished sites may indicate that management interventions are not necessary. However, due to a combination of mud crab life history processes and oceanographic factors, it is likely that juvenile recruitment to heavily fished sites is being subsidised by the greater spawning potential of less heavily fished sites. If the fishery continues to expand in scale and intensity – a likely scenario – the capacity for such subsidisation to replenish depleted sites may diminish. So, while mud crabs possess life history characteristics that make them quiet resilient to fishing pressure, studies have shown that recruitment overfishing can occur in heavily fished areas, necessitating the supplementation of wild stocks with hatchery reared juveniles (Lebata *et al*., 2006; 2007; 2009).

Size limits based on size at maturity have commonly been applied to safeguard spawning stock biomasses and therefore prevent recruitment overfishing and stock collapses in mud crab fisheries worldwide. As there is considerable variation in size at maturity between mud crabs across their wide geographic range, size limits need to be informed by local research. The results of this study suggest that, for female crabs, LM50 based on functional maturity occurs at 136.5mm CW. Rounding up, a minimum size limit of 140mm CW would also enable the majority of male crabs – which appear to mature at a smaller carapace width than females – to mate at least once before entering the fishery. A smaller size limit for male crabs could be considered, though this may make administration and enforcement more complex. Comparisons of fishery yields between sites with different sized crabs in this study suggest that implementing size limits would not adversely affect catches.

Some studies suggest that mud crab fisheries can be exploited relatively heavily without affecting recruitment due to the high fecundity of female crabs and their ability to spawn multiple times. The resilience of mud crab fisheries is also likely to be greater in areas where crabs spawn year-round, such as in New Ireland, as reported in this study. However, for a particular mangrove area, the spawning stock biomass required to replenish fisheries will depend on its exposure to hydrological forces that transport larvae. Relatively low CPUE2 values experienced at Kaplaman may therefore be due to its sheltered location, a considerable distance from ocean currents and oceanic quality water. This finding reinforces the need for minimum size limits as some sites will be disproportionately affected by a lower regional spawning potential than other sites. If mud crab farming based on collecting wild caught juveniles is to be considered in the region, the need for size-based management would be even greater.

Prohibiting the capture of ovigerous females is another commonly applied rule for mud crab fisheries. However, for fishing methods focussed on intertidal areas such as in New Ireland, berried females are rarely captured (only 17 were recorded in this study), implying that prohibitions would have little impact. However, if the fishery was expanded to sub-tidal areas (using crab traps or similar technologies), a larger proportion of berried females would likely be encountered, necessitating a consideration of this course of action.

It is intuitive that adequate protection of mangrove habitats will benefit the health of mud crab fisheries. This point is particularly salient given that most mud crab fisheries (with the exception of a few highly depleted ones) are likely to be habitat limited rather than recruitment limited. In other words, due to the high reproductive success of mud crabs, the productive potential for healthy fisheries will be limited by the amount and condition of suitable habitat rather than larval availability. Also, as mud crabs undergo ontogenetic shifts in habitat use within mangrove systems as they develop, practices that degrade a limited area or habitat within a mangrove system may have disproportionate impacts of the productivity of the fishery. For example, studies show that *S. serrata* typically recruit among mangrove roost and pneumatophores high in the intertidal zone (Alberts-Habatsch *et al*., 2014; 2016). Timber harvesting and other disturbances in this zone could directly impact the number of juveniles recruiting to the fishery.

Another recommendation arising from this study is for the continuation of monitoring efforts through similar studies. While this study was able to report on crab size changes over time, changes in fishery health indicators such as this need ongoing monitoring, particularly if fishing pressure intensifies in the region. CPUE values and average crab sizes reported in this study represent an important baseline which should prove valuable for assessing changes in future studies.

REFERENCES

Alberts-Hubatsch, H., S. Y. Lee, K. Diele, M. Wolff and I. Nordhaus (2014). Microhabitat use of early benthic stage mud crabs, *Scylla serrata* (Forskal, 1775), in eastern Australia. *Journal of Crustacean Biology*, 34: 604–610.

Alberts-Hubatsch, H., S. Y. Lee, J. Meynecke, K. Diele, I. Nordhaus and M. Wolff (2016). Life-history, movement, and habitat use of *Scylla serrata* (Decapoda, Portunidae): current knowledge and future challenges. *Hydrobiologia*, 763; 5-21.

Bonine, K. M., E. P. Bjorkstedt, K. C. Ewel and M. Palik, (2008). Population characteristics of the mangrove crab *Scylla serrata* (Decapoda: Portunidae) in Kosrae, Federated States of Micronesia: effects of harvest and implications for management. *Pacific Science*, 62: 1–19.

Campbell, A., and M. D. Eagles, (1983). Size at maturity and fecundity of rock crabs, *Cancer irroratus*, from the Bay of Fundy and south-western Nova Scotia. *Fishery Bulletin*, 81: 357-362.

Chakrabarti, K. (1981). A growth study of the crab *Scylla serrata* (Forskal) in the Sundarbans. *Indian Journal of Forest Ecology*. 4: 102-106.

Christensen, S.M., D.J. Macintosh and N.T. Phuong (2004). Pond production of the mud crabs *Scylla paramamosain* (Estampador) and *S. olivacea* (Herbst) in the Mekong Delta, Vietnam, using two different supplementary diets. *Aquaculture Research*, 35; 1013–1024

Escritor, E.L. (1972). Observations on the culture of mud crab, *Scylla serrata*. In: Coastal Aquaculture of the Indo-Pacific Region (Pillay, T.V.R ed.). Fishing News (Books), Surrey; 355-361.

Hamasaki, K. and Matsui, N. (2011). Size at sexual maturity and body size composition of mud crabs *Scylla* spp. caught in Don Sak, Bandon Bay, Gulf of Thailand. *Fisheries Science*, 77; 49-57.

Hartnoll, R.G. (1969). Mating in the Brachyura. *Crustaceana*, 16; 161-181.

Heasman, M. P. (1980). Aspects of the general biology and fishery of the mud crab *Scylla serrata* (Forskal) in Moreton Bay, Queensland. PhD thesis, University of Queensland.

Heasman, M. P., D. R. Fielder and R. K. Shepherd (1985). Mating and spawning in the mudcrab, *Scylla serrata* (Forskal) (Decapoda: Portunidae), in Moreton Bay, Queensland. *Journal of Freshwater and Marine Research*, 36: 773–783.

Hill, B.J., (1975). Abundance, breeding and growth of the crab *Scylla serrata* in two South African estuaries. Marine Biology. 32, 119–126.

Ikhwannudin, M., G. Azime, Juariah, H.M. and Ambak, M.A. (2011). Biological information and population features of mud crab, genus *Scylla* from mangrove areas of Sarawak, Malaysia. *Fisheries Research*, 108; 299-306.

Islam, M.S., K. Kodama and H. Korokura, (2010). Ovarian development and size at maturity of the mud crab *Scylla olivacea* in Pak Phanang mangrove swamps, Thailand. *Marine Biology Research*, 6; 503-510.

Kosuge, T. (2001). Brief assessment of stock of mud crabs *Scylla* spp. in Matang Mangrove Forest, Malaysia and proposal for resources management. *Japanese Agricultural Research Quarterly*, 35: 145–148.

Keenan, C. P., P. Davie and D. Mann, (1998). A revision of the genus *Scylla* De Haan, 1833 (Crustacea: Decapoda: Brachyura: Portunidae). *The Raffles Bulletin of Zoology,* 46: 217–245.

Keenan, C.P. (1999). Aquaculture of the mud crab, genus Scylla – past, present and future. In: Mud Crab Aquaculture and Biology (eds. C.P. Keenan and A. Bradshaw). ACIAR Proceedings 78; 9-13.

Knuckey, I. A. (1996). Maturity in male mud crabs, *Scylla serrata*, and the use of mating scars as a functional indicator. *Journal of Crustacean Biology*, 16: 487–495.

Lebata, M. J. (2006). Stock enhancement of the mud crabs *Scylla* spp. in the mangroves of Naisud and Bugtong Bato, Ibajay, Aklan, Philippines. Ph.D. Diss., University of Wales, Bangor, Anglesey, United Kingdom. 274 p.

Lebata, M.J., L. Le Vay, J.H. Primavera, M.E. Walton and J.B. Bintas, (2007). Baseline assessment of fisheries for three species of mud crabs (*Scylla* spp.) in the mangroves of Ibajay, Aklan, Philippines. *Bulletin of Marine Science*, 80: 891–904.

Lebata, M.J., L. Le Vay, M.E. Walton, J.B. Binas, E.B. Quenitio, E.M. Rodriguez and A.H. Primevera (2009). Evaluation of hatchery based enhancement of the mud crab, *Scylla* spp. fisheries in mangroves: comparison of species and release strategies. *Marine and Freshwater Research*, 60; 58-69.

Le Vay, L. (2001). Ecology and management of mud crab *Scylla* spp. *Asian Fisheries Science*, 14; 101-111.

Le Vay, L., V.N. Ut and Walton, M. (2007). Population ecology of the mud crab *Scylla paramamosain* (Estampador) in an estuarine mangrove system; a mark-recapture study. *Marine Biology*, 151; 1127-1135.

Le Vay L., N.V. Ut and D.A. Jones (2001). Seasonal abundance and recruitment in an estuarine population of mud crabs, *Scylla paramamosain*, in the Mekong Delta, Vietnam. *Hydrobiologia*, 449: 231–239.

Macintosh, D. J., F. Goncalves, A. M. V. M. Soares, S. M. Moser, and N. Paphavisit, (1999). Transport mechanisms of crab megalopae in mangrove ecosystems, with special reference to a mangrove estuary in Ranong, Thailand. Mud Crab Aquaculture and Biology ACIAR Proceedings, Proceedings of an International Scientific Forum, Darwin Australia 78: 178–186.

Marichamy, R., M. Manickaraja and S. Rajapackiam (1986). Culture of the mud crab *Scylla serrata* (Forskal) in Tuticorn Bay. *Proceedings of the Symposium on Coastal Aquaculture*, 4; 1176-1182.

Moser, S., D. Macintosh, S. Laoprasert and N. Tongdee (2005). Population ecology of the mud crab *Scylla olivacea*: a study in the Ranong mangrove ecosystem, Thailand, with emphasis on juvenile recruitment and mortality. *Fisheries Research*, 71; 27-41.

Nandi, N. C. and Dev Roy, M. K. (1990). Burrowing activity and distribution of *Scylla serrata* (Forskal) from Hooghly and Matla estuaries, Sundarban, West Bengal. *Journal of Bombay Natural History and Sociology*, 88:167–171.

NFA (2005). Small scale fisheries in New Ireland Province: landing, market and buyer surveys in Kavieng. National Fisheries Authority, Papua New Guinea. 77p.

Perrine, D., (1978). The mangrove crab on Ponape. Marine Resources Division, Ponape, Eastern Caroline Islands Marine Resources Division, Ponape, Eastern Caroline Is. pp. 66.

Pillans, S., Pillans, R.D., Johnstone, R.W., Kraft, P.G., Haywood, M.D. and Possingham, H.P. (2005). Effects of marine reserve protection on the mud crab *Scylla serrata* in a sex-biased fishery in subtropical Australia. *Marine Ecology Progress Series*, 295; 201-213.

Quinn, B. and Kojis, L. (1987). Reproductive biology of *Scylla* sp. (Crustacea: Portunidae) in the Labu Estuary, Papua New Guinea. *Bulletin of Marine Science*, 42; 234-241.

Robertson, W.D. (1989). Factors affecting catches of the crab *Scylla serrata* (Forskal) (Decapoda, Portunidae) in baited traps-soak time, time of day and accessibility of the bait. *Estuarine, Coastal and Shelf Science*, 29; 161–170.

Robertson, W.D. and Kruger, A. (1994). Size at maturity, mating and spawning of the Portunid crab, *Scylla serrata* in Natal, South Africa. *Estuarine, Coastal and Shelf Science*, 39; 185-200.

Shelley, C. (2008). Capture based aquaculture of mud crabs, Scylla spp. In: Capture based aquaculture: global review.

Tongdee N. (2001). Size distribution, sex ratio and size at maturity of mud crab (*Scylla* spp.) in Ranong Province, Thailand. *Asian Fisheries Science*, 14; 113-20.

Walton ME, L. Le Vay, L.M. Truong and V.N Ut (2006). Significance of mangrove-mudflat boundaries as nursery grounds for the mud crab, *Scylla paramamosain*. *Marine Biology*, 149: 1119–1207.

Walton, M.E., L. Le Vay, J.H. Lebata, J. Binas and J.H. Primavera (2006). Seasonal abundance, distribution and recruitment of mud crabs (*Scylla* spp.) in replanted mangroves. *Estuarine, Coastal and Shelf Science*, 66; 493–500.

Williams M.J. and Hill B.J. (1982) Factors influencing pot catches and population estimates of the portunid crab *Scylla serrata*. *Marine Biology* 71; 187–192.