ASPECTS OF THE BIOLOGY AND ECOLOGY OF THE COCONUT CRAB *BIRGUS LATRO* (LINNAEUS, 1767) ON ISLANDS WITHIN THE KISITE-MPUNGUTI MARINE PROTECTED AREA, KENYA

Jillo Katello Wato

A thesis submitted in partial fulfillment of the requirements for the Degree of Master of Environmental Science of Pwani University

June, 2017

DECLARATION

By the candidate:

I hereby declare that this thesis is my original work and has not been presented for the award of a degree in any university or institution of learning for any other award.

Signature.. Date 9/11/2017

Jillo Katello Wato

Reg. No: N50/PU/2229/13

By the supervisors:

This thesis has been submitted with our approval as university supervisors:

Signature .... Date 9/11/2017

Prof. Mlewa C. Mwatete,

Pwani University, Kenya.

Signature .... Date 10/11/2017

Dr Melckzedeck K. Osore,

Kenya Marine and Fisheries Research Institute

DEDICATION

I devote this work to my dear wife, Amina Wato, my friend and helper Dawn Goebbels and to my two wonderful sons, Mohammad and Issa.

ACKNOWLEDGEMENT

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ABSTRACT

The Coconut crab *Birgus latro* (Linnaeus, 1767) is widely distributed on remote tropical islands of the Pacific and Indian Oceans. Populations of *B. latro* are declining throughout their range, with loss of habitat and harvesting for human consumption thought to be key drivers of the decline. The species is considered data-deficient under the IUCN Red-List. In East Africa, the population of *B. latro* is poorly studied and thus little is known about their status. Although published data indicates that the western limit of the species range is Chumbe Island in Zanzibar, a population of *B. latro* has been reported on some islands of the Kisite-Mpunguti Marine Protected Area (KMMPA) in Kenya. This study was designed as a baseline investigation of the biology and ecology of the *B. latro* population within the KMMPA in Kenya. The study was conducted during February - June 2016 on the Mpunguti Lower East (4.5 ha) and West (5 ha) Islands within the MPA. These Islands are often referred to simply as Mpunguti East (MPE) and Mpunguti West (MPW). A combination of the Leslie catch-depletion method, mark-recapture and plot techniques were used to study the population (size-sex structure, morphometric characteristics, abundance and density) of *B. latro* in the two Islands of Mpunguti. A total of 304 specimens (excluding recaptures) were sampled on the two Islands during the study period: 52.3% of specimens from Mpunguti Lower West Island while 47.7% were from Mpunguti Lower East Island. Analysis of abundance showed a population density of 82.8 inds. /ha for Mpunguti Lower West and 100.6 inds. /ha for the Mpunguti Lower East Island. The mean Catch per Unit Effort (CPUE) in both Islands was 1.4 ± 0.3 crabs / bait. The highest average CPUE values of 1.8 ± 0.3 and 1.6 ± 0.3 per bait were recorded for Mpunguti Lower East in April and Mpunguti Lower West Island in February, respectively. Results of 2-way ANOVA (after normality test) indicated no variation (F (23.052), p = 0.083155) for the number of crabs caught among plots of Mpunguti Lower

West and East Islands. However, Mpunguti Lower West plots (MPW-1, MPW-2 and MPW-3) showed homogeneity within plots' captures but significant difference among plots' population means (df =2, $p < 0.05$). Mpunguti Lower East plots (MPE-1, MPE-2 and MPE-3) similarly showed homogeneity within plots captures but no significant difference among plots' population mean (df = 2, p = 0.6181). Different morphometric characters in males and females were determined from 139 males and 165 females used for these analyses. Significant ($p<0.05$) positive linear relationships between different body dimensions of the *B. latro* were observed. No significant difference ($\chi2 = 2.386$, df = 1, p = 0.122) was observed between male and female sex ratio (1:1.2). Analysis of sex morphometric data indicated that the associated size-frequency distributions were significantly different ($p< 0.05$) with males reaching a larger size than females, demonstrating a pronounced sexual size dimorphism in *B. latro*. This study presents vital information and documents Kenya as part of the range of this species.

TABLE OF CONTENT

DECLARATION ii

DEDICATION iii

ACKNOWLEDGEMENT iv

ABSTRACT v

LIST OF TABLES ix

LIST OF FIGURES x

LIST OF PLATES xi

LIST OF ABBREVIATIONS AND ACRONYMS xii

CHAPTER 1: INTRODUCTION 1

1.1 Background Information 1

1.2 Statement of the Problem and Justification of the Study 4

1.3 Objectives of the Study 5

CHAPTER 2: LITERATURE REVIEW 6

2.1 Taxonomy and Species Description 6

2.2 Behaviour and Ecology 7

2.3 Abundance and density estimates. 8

CHAPTER 3: MATERIALS AND METHODS 9

3.1 Study Area 9

3.1.2 Climate 11

3.2 Research Design 12

3.3 Baiting and Sampling Procedures 13

3.4 Data Collection Procedures 15

3.5 Data Analyses 16

3.5.1 Morphometric Analyses 17

3.5.2 Sex Ratio and Size Structure 18

3.5.3 Population Size and Density....18

CHAPTER 4: RESULTS 20

4.1 Description of *B. latro* population on the Mpunguti Islands 20

4.2 Size Structure of the *B. latro* populations....21

4.2.1 Size Frequency Distribution 23

4.3 Sex Ratio....26

4.4 Morphometric Characteristics....28

4.4.1 Interrelationships between different morphometric characters....33

4.5 Population Size and Density....35

4.5.1 Population size and density estimates from quadrant (Plots) 35

4.5.2 Population size and density estimates using CPUE....38

CHAPTER 5: DISCUSSION....45

5.1 Biological Aspects of *Birgus latro* 45

5.2 Ecological Aspects of *Birgus latro*....49

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS....53

APPENDICES 66

Appendix 1: Bait preparation process:....66

Appendix 2: Field data collection:....66

Appendix 3: Crabs climb trees with ease....67

Appendix 4: Sexing Coconut Crabs:....67

LIST OF TABLES

Table 1: Summary statistics of absolute dimensions (Mean ± SE) for male and female *B. latro* sampled from Mpunguti Lower East and West, South Coast Kenya…………. 22

Table 2: Male and female *B. latro* within five size-classes on Mpunguti Lower East and West Islands, South Coast Kenya……………………………………………………… 25

Table 3: Number and sex ratio of the *B. latro* sampled on Mpunguti Lower East (MLE) and West (MLW) Islands, in South Coast Kenya…………………………………….. 27

Table 4: Comparison of male and female *B. latro* body parameters from samples collected from Mpunguti Lower East and West Islands, South Coast Kenya…………. 28

Table 5: Allometric equations for male *B. latro* specimens from the Mpunguti Lower East and West Islands, South Coast Kenya. (n = 139)……………………………... ……. 34

Table 6: Allometric equations for females *B. latro* specimens from the two Mpunguti Lower East and West Islands, South Coast Kenya. (n = 165)………………………... 34

Table 7: Tukey Pairwise Comparison for plots of Mpunguti Lower West, South Coast Kenya………………………………………………………………………………….. 36

Table 8: Monthly catches and CPUE for each month as well as the cumulative catch for the two islands and effort expended…………………………………………………... 39

Table 9: Significance of factors in influencing the number of *B. latro* captured on the Mpunguti Lower East and West Islands. The bolded p-value indicates a significant value…………………………………………………………………………………... 44

LIST OF FIGURES

Figure 1: A map of Kenya (insert) showing location of the study sites (Mpunguti Lower West and East) Islands, South Coast Kenya…………………………………………… 10

Figure 2: Size-frequency analysis of the body parameters of female and male *B. latro* in the Mpunguti Lower East and West Islands, South Coast Kenya………………...…… 23

Figure 3**:** Thoracic length frequency distribution of males and females *B. latro* in the Mpunguti Lower West and East Islands, South Coast Kenya…………………………. 24

Figure 4: Key growth body dimensions of male and female *B. latro* in the Mpunguti Lower East and West Islands, South Coast Kenya..………………………………….. 26

Figure 5: Comparison of male and female *B. latro* body parameters on Island of Mpunguti Lower West, South Coast Kenya…………………………………………… 29

Figure 6: Comparison of male and female *B. latro* body parameters on the Island of Mpunguti Lower East (MLE), South Coast Kenya……………………………………. 30

Figure 8: Extrapolated densities (crabs/ha) pooled for all the sampling occasions in the Mpunguti Lower East (MLE) and West (MLW)……………………………………... 37

Figure 9: Monthly plot means for Mpunguti Lower East (MLE) and West (MLW)… 38

Figure 10: Cumulative catch and CPUE relationship for a series of successive field samples for Mpunguti Lower West (MLW), during March-May 2016………………. 40

Figure 11: Cumulative catch and CPUE relationship for a series of successive field samples for Mpunguti Lower West (MLW), during March-May 2016………………. 41

Figure 12**:** Monthly variation of CPUE for Mpunguti Lower East (MLE) and Mpunguti Lower West (MLW)…………………………………………………………………… 42

Figure 13: Three months population overall mean (Mean ± SE) of CPUE for the two Islands of Mpunguti Lower West (MLW) and East (MLE), South Coast Kenya……... 43

LIST OF PLATES

Plate 1: The Coconut crab *Birgus latro* on Mpunguti Island, Kenya…………………… 2

Plate 2: (A) Coconut bait secured to a tree trunk (B) Crabs feeding on the baits (Photos: Juma Mshemanga, 2016)…………………………………………………………… 14

Plate 3: Different colour morphs of *B. latro* crabs observed during the study on the two Lower Mpunguti Islands………………………………………………………….. 20

LIST OF ABBREVIATIONS AND ACRONYMS

IUCN	International Union for Conservation of Nature
KMFRI	Kenya Marine & Fisheries Research Institute
KCDP	Kenya Coastal Development Project
KWS	Kenya Wildlife Service
WIO	Western Indian Ocean
KMMP&R	Kisite-Mpunguti Marine Park and Reserve
KMMPA	Kisite-Mpunguti Marine Protected Area
GoK	Government of Kenya
GVI	Global Vision International
ITCZ	Inter-Tropical Convergence Zone
UNEP	United Nations Environmental Program
LCD	Liquid Crystal Display
MPA	Marine Protected Area
CPUE	Catch Per Unit Effort
MLE	Mpunguti Lower East
MLW	Mpunguti Lower West

CHAPTER 1: INTRODUCTION

1.1 Background Information

The Coconut crab *Birgus latro* (Linnaeus, 1767), also known as the robber crab, inhabits coastal areas of some tropical islands in the Indo-Pacific region. It belongs to the phylum Arthropoda, class Malacostraca and family Coenobitidae, which includes most of the land-based hermit crabs (Fletcher, 1993). *Birgus* is a monospecific genus and its members differ from other genera in the family Coenobitidae, where adults do not inhabit gastropod shells (Amesbury, 1980; Fletcher, 1993).

After attaining a thoracic length of approximately 8–10 mm, juveniles abandon their shells and migrate to terrestrial habitats (Brown & Fielder, 1991; Drew *et al.*, 2010). They live up to 60 years (Fielder, 1991; Kessler, 2006) with individuals weighing up to 4 kg (Brown & Fielder, 1991). Adults live a purely terrestrial life scavenging in the forest and main return to the ocean to spawn (Amesbury, 1980; Fletcher *et al.*, 1991; Kessler, 2006). Amesbury (1980) observed that *B. latro* spend the daylight hours in their burrows but emerged at night to scavenge for food. They have, however, been found to be diurnal on islands without human settlements but nocturnal on inhabited islands (Fletcher *et al.*, 1991).

The species prefer to inhabit coastal habitats, particularly those with dense forest cover, (Fletcher *et al.*, 1991). Several studies (Amesbury, 1980; Wells *et al.*, 1983; Fletcher *et al.*, 1991) found that *B. latro* inhabit rock crevices and sand burrows along the coastline, although preferences vary between islands and their choice may depend on the habitat available. For example, on Olango Island in the Philippines, they live in burrows in coral rock and in thick undergrowth, while on Guam Island in Oceania, they establish burrows within porous limestone substrates (Wells *et al.*, 1983). Lavery *et al.*

(1996) and Anagnostou and Schubart (2014) reported that *B. latro* is widely distributed, primarily on isolated tropical islands throughout the Indian and western Pacific Oceans; from Chumbe Island (Zanzibar) in the Indian Ocean to the Gambier Islands/ French Polynesia in the Pacific.

A few subtropical populations also occur in the Ryukyu Islands of in southern Japan (Sato & Yoseda, 2008; Hamasaki *et al.*, 2009; Drew *et al.*, 2010).

Plate 1: The Coconut crab *Birgus latro* on Mpunguti Island, Kenya

There has been concern on the decline of *B. latro* populations in many regions for over 30 years, while in some places including Madagascar, Seychelles and Mauritius; it was thought that the populations were virtually extinct (Amesbury, 1980; Fletcher, 1993; Drew *et al.*, 2010). Fletcher (1993) suggested that the species appears to be very susceptible to both overexploitation and the impacts of urbanization including habitat alienation and the invasion by exotic predators such as rats, putting the stability of its populations in many areas of its range in serious doubt.

Brown and Fielder (1991) noted that *B. latro* had not been recorded in the East African regions of the West Indian Ocean (WIO). Subsequent authors (Lavery *et al.*, 1996; Drew *et al.*, 2010; Hamasaki *et al.*, 2011; Buden, 2012) noted the extend of the species range to an isolated coral island off the East coast of Africa near Zanzibar. Poupin *et al.* (2013) recorded that the western limit of distribution of this species as Chumbe Island which is a private nature reserve off Zanzibar, Tanzania, where a viable population of *B. latro* was documented. Initially, the species had been listed as "vulnerable" on the International Union for Conservation of Nature (IUCN) RedList since 1981 but was downgraded to "data deficient" in 1996, not because populations were known to have recovered, but simply because it was recognized that there was insufficient data for proper categorization of this species (Eldredge, 1996; Poupin *et al.*, 2013).

Poupin *et al.* (2013) and Anagnostou & Schubart (2014) noted that in the Western Indian Ocean (WIO) only a few islands were known to have populations of *B. latro* since the species has become locally extinct in most of its other previously occupied habitats in this region. Intensive harvesting for human consumption (Fletcher, 1993; Anagnostou & Schubart, 2014) and the consequences of habitat destruction (Brown & Fielder, 1991; Eldredge, 1996; Anagnostou & Schubart, 2014) are major causes of population decline. In addition, Fletcher (1993) observed that most of the published data on the distribution of *B. latro* suggests that its distribution range has contracted.

The natural geographical distribution range of *B. latro* in East Africa has not been well documented. Published data and information indicates that the only East African site where the species was known to occur is on an island off Zanzibar, Tanzania (Lavery *et* *al.*, 1996; Anagnostou & Schubart, 2014). However, anecdotal records (KWS, 2014) indicate that Kenya had a population of *B. latro* on some small islands in the Kisite-Mpunguti Marine Protected Area (KMMPA), which is clearly beyond the hitherto known natural distribution range for the species. Although such unpublished reports and grey literature indicated the likely occurrence of the species on the islands within the Kisite-Mpunguti Marine Park and Reserve (KMMP&R) in Kenya (KWS, 2014), there is no documented scientific literature of the extension of the species natural distribution range to include these populations on the KMMP&R Islands.

1.2 Statement of the Problem and Justification of the Study

There is little scientific information available on the population of *B. latro* in Kenya except for scanty grey literature on its existence on protected islands of Kisite-Mpunguti (KWS, 2014). Therefore, the paucity of scientific information presented a significant knowledge gap. Such information is necessary to inform decision making regarding the management and conservation of the species, especially by the Kenya Wildlife Service (KWS) which is responsible for the management of national parks and protected areas.

The Kisite-Mpunguti Marine Conservation Management Plan (2015) identified the species as an exceptional Marine Park resource and as a potential tourist attraction. The management plan however, cited the lack of scientific data and information as an issue of concern for the conservation and management of the species. The KWS prioritized the carrying out of a baseline population assessment for *B. latro* in Kisite-Mpunguti Marine Park and Reserve (KMMP&R) to provide data to aid the formulation of policies and design of strategies for the management of the population of *B. latro* in this region. This study was, therefore, designed to collate scientific information on the *B. latro* population of the Kisite-Mpunguti Islands, including population size, density and some aspects of its biology and ecology. The findings will also aid formulating strategies to guide the rational management of the Kisite-Mpunguti Marine Park and Reserve (KMMP&R) as a tourist destination while ensuring conservation of the population of these ecologically important crabs.

1.3 Objectives of the Study

The broad objective of this study was to collate baseline scientific information to aid conservation and management of *B. latro* in the Kisite-Mpunguti Marine Protected Area. The specific objectives of the study were to:

1. Determine the size and sex-structure of *B. latro* on the Mpunguti Lower East and West Islands of the Kisite-Mpunguti MPA.

2. Determine the morphometric characteristics of *B. latro* on the Mpunguti Lower East and West Islands of the Kisite-Mpunguti MPA.

3. Estimate the population size and density of *B. latro* on the Mpunguti Lower East and West Islands of the Kisite-Mpunguti MPA.

CHAPTER 2: LITERATURE REVIEW

2.1 Taxonomy and Species Description

The Coconut crab *Birgus latro* (Linnaeus, 1767) belongs to a monospecific genus within the Family Coenobitidae in the Order Decapod and Phylum Arthropoda. It is the largest of the land crabs (Amesbury, 1980; Schiller, 1992; Hamasaki *et al.*, 2011). Taxonomic information indicates that the species acquired its name from an unsubstantiated reputation for stealing nuts from the top of coconut trees, hence the specific name *'latro'* which is Latin for "robber" (Brown & Fielder, 1991; Fletcher, 1993). Although closely related to the hermit crabs, adult *B. latro* do not inhabit discarded mollusc shells and have little need for access to the sea except for larval release (Brown & Fielder, 1991; Schiller *et al.*, 1991).

It is a terrestrial species whose adults are known to possess powerful crushing claws and elongate, pointed legs which allow them to climb rocks and trees with comparative ease (Brown & Fielder, 1991). They have two chelae (claws), the larger left claw and a smaller right claw, both of which have a denticulate appearance, as well as a smaller pair of appendages equipped with small claws (Fletcher, 1993). *Birgus latro* has been documented to exert a greater pinching force using their claws than many animals do with other appendages; its measured pinch force is greater than the bite force of most terrestrial predators (Oka *et al.*, 2016).

The species is sexually dimorphic, with the female pleopods having three biramous setaceous appendages on the left side of the abdomen which are absent in males (Anagnostou & Schubart, 2014). The colour of the carapace varies between regions and among individuals within the same area (Amesbury, 1980; Brown & Fielder, 1991;

Fletcher, 1993). They have been found to occur in two different colour morphs; blue and red, but the colours are not age or sex specific (McCormack, 2007).

Several studies have reported differences in the size structures of the sexes, with males attaining much larger sizes than females (Amesbury, 1980; Fletcher, 1993; Drew *et al.*, 2013). Recently, Anagnostou & Schubart (2014) and Oka *et al.* (2015) observed pronounced sexual dimorphism in the body size for *B. latro*, with males attaining bigger sizes than females. Observed differences in the mean size of individuals between regions have been attributed to variations in environmental conditions (Helfman, 1977; Fletcher, 1993) and harvesting patterns (Amesbury, 1980; Fletcher *et al.*, 1991). The variation in size between sexes is not unusual in crustaceans and is potentially associated with the energy costs of reproduction and/or the sexual selection processes associated with choice of mate (Drew *et al.*, 2013).

2.2 Behaviour and Ecology

Unlike the hermit crab, *B. latro* is secretive, living a solitary existence except for gravid females which aggregate in large densities (Schiller *et al.*, 1991). The species may be nocturnal, diurnal or both, and it appears that their behavioural pattern is dependent upon local population density and possibly the level of human activity (Brown & Fielder, 1991).

In areas where they occur at high density with low exploitation, the crabs can be found outside their hiding places during both day and night (Fletcher, 1993). However, where the densities are lower, especially because of harvesting, *B. latro* emerges from hiding only at night (Amesbury, 1980; Fletcher *et al.*, 1990b). Individuals occasionally travel to reach a source of seawater to maintain osmotic balance or they may move away from rocky cliff regions into sandy areas to molt (Amesbury, 1980; Fletcher *et al.*, 1990a).

They do not normally disperse from an area regularly and are found to have a narrow home range, venturing only about 30 m from their burrows in search of food (Fletcher *et al.*, 1990a).

2.3 Abundance and density estimates.

Transects and quadrants survey techniques have been used to estimate Coconut crab density and abundance on the small Christmas Islands in the Indian Ocean off Australia and Tokelau in the Pacific (Schiller, 1992; Pasilio *et al.,* 2013). Schiller (1992) indicated that since *B. latro* are relatively immobile, they are well suited to both area and time sampling. This method is not appropriate only for large areas with rugged terrain (Fletcher & Amos, 1994).

CHAPTER 3: MATERIALS AND METHODS

3.1 Study Area

The study was conducted on two Islands (Figure 1): Mpunguti Lower East straddling 4°41'29.12"S 39°22'6.26"E and Mpunguti Lower West straddling 4°41'13.16"S 39°24'8.72"E. These Islands are located within the Kisite-Mpunguti Marine Park and Reserve (KMMP&R) about 10 km offshore from the Kenyan mainland (GoK, 2017). The Mpunguti Lower West and East Islands measure 5 ha and 4.5 ha respectively, making a total of approximately 9.5 ha.

Kisite-Mpunguti Marine Park and Reserve (KMMP&R) was gazetted in 1978 as a Marine Protected Area (MPA) in Coast Province, Kwale County, Kenya (GoK, 1978). The Kisite Marine Park covers an area of 28 km^2, whereas the Mpunguti Marine Reserve covers an area of 11km^2 and comprises of several islands including the study sites in the Lower Mpunguti East and West Islands (GoK, 2017).

The Kisite-Mpunguti Marine Protected Area (KMMPA) includes the National Park surrounding Kisite Island; a no-take zone where all fishing is prohibited, and the Marine Reserve surrounding the Mpunguti Islands where only traditional fishing methods are allowed. The KMMPA and the marine wildlife it contains are an important tourist attraction and, as a result, an important resource for Shimoni and the surrounding communities (Jorge, 2016; GoK, 2017).

The KMMPA is managed by the Kenya Wildlife Service (KWS), a state corporation charged with the conservation and management of wildlife in Kenya (Emerton & Tessema, 2001). The KMMPA lies south of Wasini Island at the southern tip of the Kenya-Tanzania border at 04°42′50″S 39°21′44″E (Pérez *et al.*, 2015).

The area has a rapidly growing human population with nearly 60% of the communities dependent on marine and coastal resources for their livelihoods (Emerton & Tessema, 2001; GoK, 2017). Overfishing, illegal and destructive fishing practices have drastically depleted the

. Other negative impacts include increased sedimentation because of poor agricultural practices and coastal coral rag forest destruction (GVI, 2014). Furthermore, climate change and its associated negative impacts have intensified the vulnerability of species and local ecosystems (GoK, 2017).

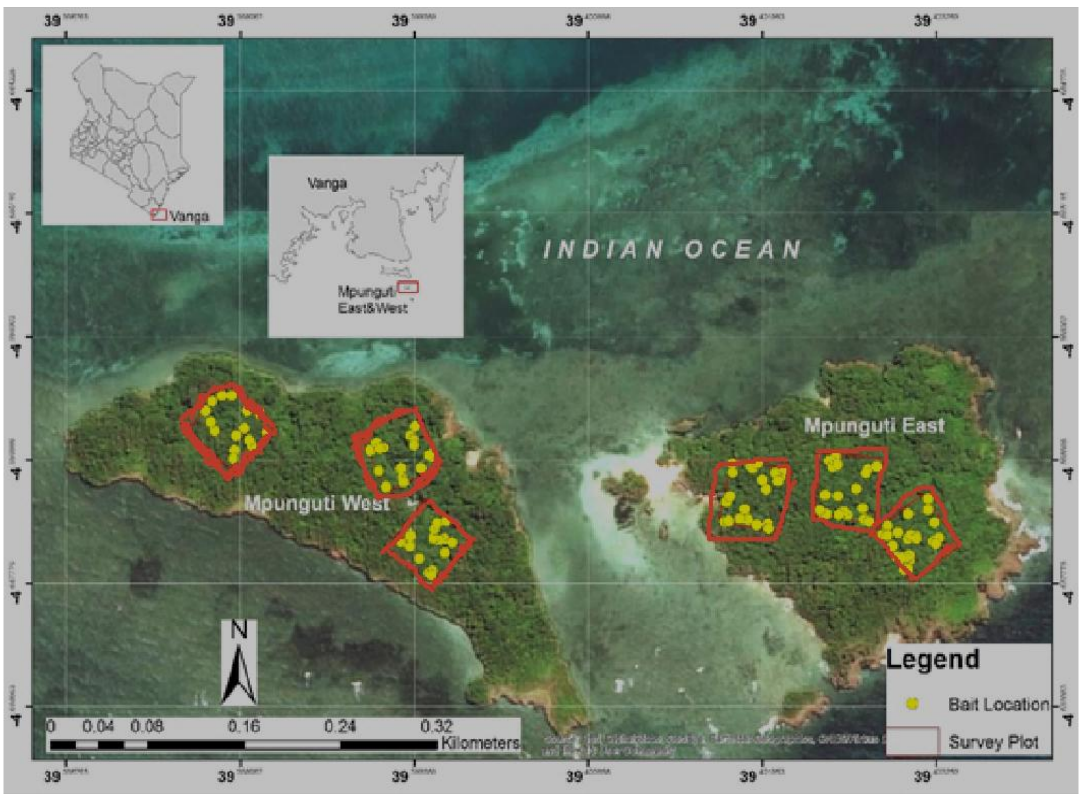

Figure 1: A map of Kenya (insert) showing location of the study sites (Mpunguti Lower West and East)[1] Islands, South Coast Kenya

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[1] The red squares were plots and yellow dots were the randomly laid baits (J. Katello, 2016). The two primary sites are the ones marked Mpunguti Lower West and East.

Rocky cliffs rise from the reef flats surrounding the islands. The cliffs are formed by fossilized reefs of 3 m height (John Wambua, pers. comm.). The cliffs contain many holes and crevices which are favourable habitats for *B. latro.* The top of each island is relatively flat and is covered by coral rag coastal forests that extend from the edge of cliffs to the interior of each island (GVI, 2014). However, some parts of the cliff edges of the islands have impenetrable, thorny, coastal shrub. Although the islands vary in size, they are relatively homogenous in terms of habitat structure (pers. observ.).

3.1.2 Climate

The seasonal distribution of rainfall in these Islands is influenced by the Inter-tropical Convergence Zone (ITCZ) and moonsoons winds (McClanahan, 1988). The area experiences a bi-modal rainfall regime, with long rains running from March-May when winds are predominantly westwards (CES, 2000).

The short rains run from October-December and are much less pronounced. Between the two wet seasons, the January and February period forms the only dry and hot period of the year along the South Coast of Kenya (CES, 2000). The relatively cool period from July-September is generally marked by slightly higher rainfall totals than the so-called ‘short rains’. Average temperature of 26^{o} C, a mean monthly maximum of approximately 30^{o} C, and a monthly minimum close to 22^{o} C have been recorded. The period from November-April is relatively warm, with minimum monthly temperatures of $26\text{-}28^{o}$ C, and a maximum average of 30^{o} C in March. During the rest of the year, May-October, monthly average temperatures range between 23- 26^{o} C, with July-August being the coolest period (Tychsen & Klinge, 2006).

3.2 Research Design

The present study covered a small area measuring 9.45 ha for the two Islands, with a relatively homogeneous coral rag forest habitat and a thin peripheral strip of impenetrable coastal scrubland. The landscape is relatively flat at the top with only sparse uneven terrain. The present study was conducted during February 2016 through June 2016. The study sites were selected based on accessibility and availability of resources. Field sampling was done for six (6) consecutive days each month.

Assessment of the density, size and sex-structure of the *B. latro* population was done using the simple random sampling technique that utilizes trapping grids as described by Munch-Petersen *et al*. (1982) and Drew *et al.* (2012). The two Islands; Mpunguti Lower East and West were stratified into grids (plots) of 40 m by 40 m. Three (3) plots were then randomly selected on each island; Mpunguti Lower East had 3 plots (MPE-1, MPE-2, and MPE-3) and Mpunguti Lower West also had 3 plots (MPW-1, MPW-2, and MPW-3) and the plots were randomly allocated to each Island using a random number table. Each plot was geo-referenced, and the boundaries were marked using sisal ropes. Within each plot, ten (10) bait stations were randomly placed to sample *B. latro.*

The general procedure involved capturing *B. latro* and marking the individuals using permanent, waterproof, chlorinated paints for each monthly sampling occasion (Fletcher *et al.*, 1989; Saber, 1982). The marked *B. latro* were then released and left for about a month to redistribute themselves within their habitat. Thereafter, individuals in the population were again captured and counted each month from the census population including individuals that had been marked and others which were unmarked, as observed in typical studies on mark-recapture abundance estimations (Otis *et al.*, 1978).

Estimates of the Coconut crab populations using the mark-recapture method have also been made on several small islands, although the recapture rates on larger islands were too low for reasonable estimates to be made (Fielder, 1991; Schiller, 1992). The present study was also unable to use recapture techniques as an estimator of population because of the low recapture rate during sampling.

Therefore, *B. latro* density and population size estimates were derived from two methods; Catch per Unit Effort (CPUE) using the Leslie catch-depletion method and Swept-area method using defined plots as a sampling unit.

3.3 Baiting and Sampling Procedures

Following the procedure described by Fletcher & Amos (1994), whole coconuts were used as bait (Appendix 1). In this study, the opened coconuts were tied to a stable tree trunk, stump, root or a crevice using a thin wire through two or three holes drilled into the coconut through the "eye" (Plate 2). It was found best to leave as much liquid in the coconut as possible and have a hole only big enough for a crab to reach the coconut fleshy part with one claw. This allowed the scent to diffuse and attract crabs, while preventing the crab from finishing the contents quickly and leaving the scene. On average, a three-person team baited the entire study area in about three hours. The coconut bait was only used once and replaced with new bait for each of the subsequent monthly sampling occasions. Baiting continued throughout the study period from February through June 2016.

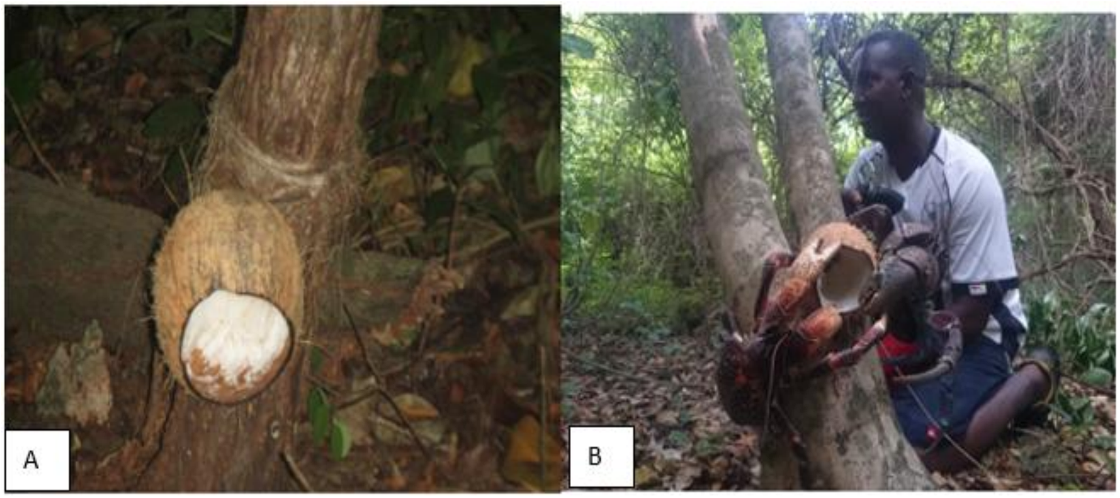

Plate 2: (A) Coconut bait secured to a tree trunk (B) Crabs feeding on the baits (Photos: Juma Mshemanga, 2016).

Due to extreme weather and insurmountable ocean conditions, the Mpunguti Lower East Island was not sampled in February. However, amount of effort expended in terms of baiting across the other three months was uniform. In every month, during days of data collection, ten (10) coconut baits were secured randomly within each established plot in the late afternoon once each month within the three plots on each of the two Islands; Mpunguti Lower East and West Islands making a total of 30 coconut baits per month per island.

Baiting was done late in the evening from 5 pm to 7 pm since *B. latro* are normally nocturnal (Fletcher & Amos, 1994). Baited sites were marked with red plastic tapes while the plot boundaries were lightly cleared and marked all round with sisal ropes to make them visible. The plots were geo-referenced for ease of finding them during subsequent sampling. A team of three persons visited each baited plot at around 9 pm to sample any crabs which had come to the baits. Each plot was sampled three (3x) times during the study.

3.4 Data Collection Procedures

All *B. latro* found at or near the baits was counted, picked safely by hand (Sato *et al.*, 2013, appendix 2), and their morphometric measurements taken to the nearest 0.01 mm using Vernier calipers (Carrera Precision CP5908 8-Inch Digital Caliper). The morphometric measurements taken included carapace length (CL), carapace width (CW), right chelae propondus and dactylus length (RCPL, RCDL), thoracic length (TL) and thoracic width (TW) as defined in Anagnostou & Schubart (2014). Individual body weight (BW) was determined to the nearest 1.0 g using a digital weighing balance (Ashton Meyers® 7767). Individuals were sexed based on the presence (female) or absence (male) of pleopods on the left ventral surface (Anagnostou & Schubart, 2014). The presence or absence of eggs for females was also noted. Colour morphs, which ranged from reddish, bluish or intermediate, was also recorded for each individual. Additional information and data recorded included the sampling date, the coordinates of the crab capture location, and time of collection. Weather and habitat type were also noted. Each sampled *B. latro* was marked with waterproof paint on their dorsal carapace to allow recording of recaptures during subsequent sampling occasions. This method was based on previous studies which found no negative effects in the use of the paint markers on the *B. latro* individuals (Oka *et al.*, 2013; Drew, 2014). The marked specimens were then released at the site of capture and left to integrate into the rest of the population(Anagnostou & Schubart, 2014).

The mean crab population for each of the plots for each month was calculated. Since the area of the study plots was known, the population estimate was extrapolated to the entire area of interest using the Swept-area approach.

CPUE is a relative estimate of abundance. In this study, it was defined as the number of crabs caught within the plot compared with the number of baits set. CPUE values can be considered as an index of absolute abundance and therefore in this study, they were used to compare population density between different areas. Crab densities during different months within the plots of both the Mpunguti Lower East and West Island were compared.

3.5 Data Analyses

Catch per unit effort (CPUE) (number of crabs per bait) and number of crabs per plot were used to estimate the density and relative abundance of *B. latro* in the two Islands (Dunn *et al*., 2000). Based on the Leslie catch-depletion method, the CPUE was plotted against the cumulative catch using the generalized linear model (GLM)(Allen & Punsly, 1984; Daniels, 2001). Morphological information was used in determining the relationship between different body dimensions and to assess body-size differences of the crabs between the two Islands. Colour was also recorded as morphs under morphology. Data on sex was used for determination of sex ratio and sex-specific size structures, comparing male and female body size classes and differences in sex ratios.

All data were entered in Microsoft Excel® spreadsheets while cross-checking to detect and remove any errors. Descriptive analysis for means, standard deviations, ranges and relative abundance was conducted in Microsoft Excel® ver. 2016.

The distribution patterns in the data and deviation from a normality of distribution (based on equal means) was tested using the Shapiro Wilk test (Shapiro & Wilk, 1965). Similarly, the data was tested for homoscedastic (equality of variances which is a characteristic of normal distribution) was done using Levene's test (Levene, 1960) before subjecting the data to detailed statistical analyses. Wherever data did not meet the normal distribution threshold and requirements for parametric analysis (t-test and ANOVA test), it was log transformed. Differences in the CPUE between sites, months and sexes were the analyzed using 2-way ANOVA.

Further, ANOVA, Linear regression, Chi-square and t-test were used to determine whether significant differences existed between *B. latro* population densities, sex structure and size-structure between and within the two islands. Whenever significant differences were detected, a post-hoc pair-wise comparison using the Tukey HSD test was applied to confirm which groups actually differed (Tukey, 1980). These tests were conducted using Minitab (Minitab, ver. 17) and PAST software (Hammer *et al.*, 2001).

3.5.1 Morphometric Analyses

Body length-weight relationships for both sexes were determined using the power function: $W = aL^b$,

Where: W = body weight (g), a = regression intercept, L = thoracic length (mm) and b = regression slope. A logarithmic transformation was used to fit a linear regression to the length-weight data (Zar, 2010) since the variability in weight usually increases with length, and the transformation stabilized the variance of weight, hence used the expression: Log W = Log a + b Log TL.

To study the interrelationships between different morphometric characters in males and females, thoracic length (TL) was plotted against thoracic width (TW) and carapace length (CL). The relationship between TW and CL was also determined. A total of 139 males and 165 females were used for the analyses. Length-Weight (thoracic length/carapace length-body weight) relationship was established for both males and females. The values of the correlation coefficient (r) were calculated to detect the pattern of association between body dimensions (Snedecor & Cochran, 1967) with the aim of establishing body growth pattern for both sexes of *B. latro* crabs in the Mpunguti Lower Islands.

3.5.2 Sex Ratio and Size Structure

The sex ratio was estimated using the formula: $S_o = (M_o - F_o)/ (M_o + F_o)$ where S_o is the sex ratio, M_o is the number of males in the sample and F_o is the number of females in the sample (Christiansen *et al.*, 1990; Daniels, 2001). The Chi-square test (χ^2) was used to determine whether there was a significant difference between the number of males and females and if the sex ratio of *B. latro* deviated significantly from the expected sex ratio of 1:1 (Spalding, 2010).

Two-sample t-test analysis (at α=0.05) was used to determine whether significant differences existed between male and female *B. latro* size structures and whether mean body parameters of crabs from the two Islands differed significantly.

3.5.3 Population Size and Density

The Leslie catch-depletion regression model (Leslie & Davis, 1939) was used to estimate the population size of *B. latro* on the two Islands of Kisite-Mpunguti MPA. The method uses the relationship between Catch per Unit Effort (CPUE) and abundance (Knight & Cooper, 2008). The initial population size was estimated by plotting a regression line of CPUE against cumulative catch (Leslie & Davis, 1939; Allen & Punsly, 1984). Data obtained from the trapping grids was used to compute population size using the formula: -

$$\frac{Ct}{ft} = q\,(No - \sum C)$$

In this Leslie regression model, the slope of the regression line is an estimation of the catchability (q); the Y-axis intercept is the product of the original population (N_o), and the catchability (q). The generalized linear model (GLM) regression was applied to analyze the relationship between Catch per Unit Effort (Ct/ft) against the cumulative catch (∑C), and the linear regression projected to the X-intercept to estimate the initial population.

The Swept area method was used, therefore, to estimate crab abundance using the calculated plot area of 1600 m^2 (40 m by 40 m). Estimates of density were then obtained from the numbers of crabs counted within the plots, divided by the area (m^2) of the sampled plots. The mean density estimates of *B. latro* were then multiplied by the size of the study areas for population size estimates using the formula:

$$P = S * \frac{A}{a}$$

Where: P = population, S = counted animals in sample, A = total area under investigation, a = swept area.

CHAPTER 4: RESULTS

4.1 Description of *B. latro* population on the Mpunguti Islands

The *B. latro* crabs found on the Mpunguti Islands, like those elsewhere, have a symmetric body shape except for the front appendages and claws. They have a hard exoskeleton with a soft abdomen which is protected by tucking under the carapace. The anterior appendages have large chelae which are used to open and crush food items. Different colour morphs ranging from light orange to deep red and from light blue through dark blue to brown and black were observed during the study (Plate 3).

Plate 3: Different colour morphs [2] of *B. latro* crabs observed during the study on the two Lower Mpunguti Islands.

Coconut crabs on the Mpunguti Lower East and West Islands roam freely during both day and night, although they frequently hide during midday; in crevices, under logs and

[2] *NB: A = reddish, B = black / reddish, C = blackish, D = orange, and E = completely black*

tree roots, in burrows which they dig in loose soil, and even high in trees. A higher number of individuals were observed to scavenge for food at night rather than during the day. At the KWS rangers' camp on the Mpunguti Lower West Islands, the crabs emerged when rangers were cooking food in the mornings and evenings. Individuals were observed to constantly flicker their antennae as they approached potential food items, sometimes from considerable distances. The crabs on the Mpunguti Lower West Island which is habited, exploited a wider range of food items including left-over human food such as maize meal and fish. In one instance, during the present study, a crab was observed consuming fruits of a baobab tree *Adansonia digitata* by opening the pod with its strong chelae.

Coconut crabs were often observed climbing trees (appendix 3) especially for the smaller individuals as they waited to feed after the bigger stronger crabs feeding on the coconut baits. Sometimes during midday especially on hot days, the crabs could also be found up high on the trees and crevices such as holes on baobab tree trunks.

On both the Mpunguti Lower East and West Islands, wild rats *Rattus rattus* were often observed competing with Coconut crabs for the bait. Although the rats appeared very cautious about getting too close to large crabs, their nuisance behaviour of jumping around in large numbers caused the crabs to leave the baits and food items when scared.

4.2 Size Structure of the *B. latro* populations

The body parameters for the *B. latro* specimens measured during this study are summarized in Table 1. The minimum thoracic length was 25.1 mm and the maximum 70.28 mm, with a Mean±SE of 39.4±0.4 mm. Thoracic width recorded showed a maximum of 142.56 mm and a minimum of 36.82, with a Mean±SE of 82.8±1.0 mm. The largest crab had a carapace length of 136.54 mm and the smallest a CL of 53.21

mm, with the Mean±SE being 84.2±0.9 mm. The heaviest *B. latro* weighed 2.355 kg and the lightest crab was only 115 grams.

Table 1: Summary statistics of absolute dimensions (Mean ± SE) for male and female *B. latro* sampled from Mpunguti Lower East and West, South Coast Kenya.

Parameters	**Females (N = 165)**		**Males (N= 139)**	
	Mean ± SE	**Range**	**Mean ± SE**	**Range**
TL (mm)	36.29±0.4	25.1-50.2	43.10±0.90	27.10-70.30
TW (mm)	77.09±0.9	36.8-110.4	89.70±1.90	55.20-142.60
CL (mm)	78.27±0.8	53.2-112.4	91.30±1.70	58.20-136.50
RCPL (mm)	48.34±0.8	23.1-80.3	58.30±1.30	27.10-110.50
RCDL (mm)	38.68±1.10	20.1-90.4	47.20±1.60	20.10-105.40
BW (kg)	0.476±0.02	0.115-1.165	0.788±0.040	0.185-2.355

NB: Body dimensions: Sample size (n), W = weight, TL = thoracic length, CL = carapace length, CW = carapace width, TW = thoracic width, RCPL = right chelae propondus length and RCDL = right chelae dactylus length.

Size frequency analysis of the absolute data of the various body parameters revealed that males were noticeably larger than females with a broader range of sizes in all body parameters (Figure 2).

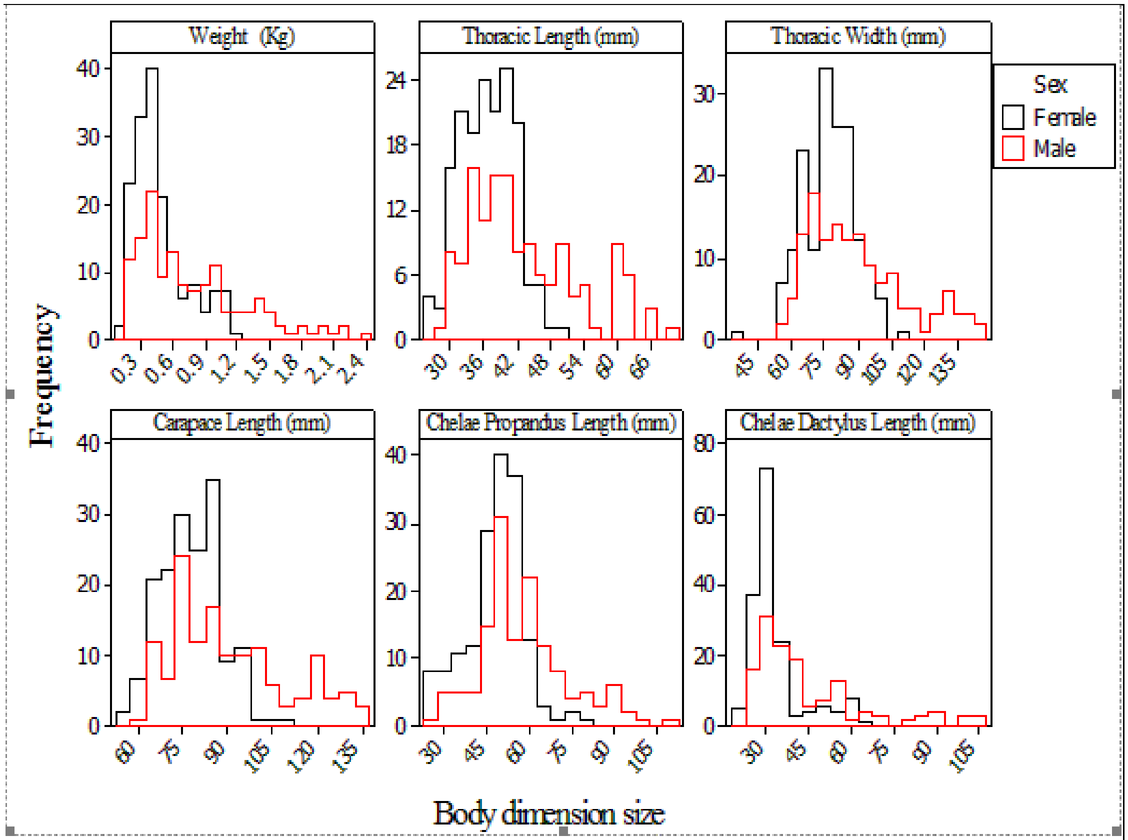

Figure 2: Size-frequency analysis of the body parameters of female and male *B. latro* in the Mpunguti Lower East and West Islands, South Coast Kenya

4.2.1 Size Frequency Distribution

Analyses of results for male and female size-frequency distributions show that the male Coconut crabs were significantly bigger with a larger range of size-classes compared to the female crabs (Figure 3). The absence of small size-classes was evident in both sexes within the population of *B. latro* on both the Mpunguti Lower East and West Islands with the smallest individuals measuring TL> 25 mm). Most of the specimens were in the 30-34.5 mm to 40-44.5 mm TL size classes which were mostly dominated by females. However, males attained larger sizes than females. Size range for females peaked at 54.5 with size classes TL<55 and TL>70 mm was only recorded in males.

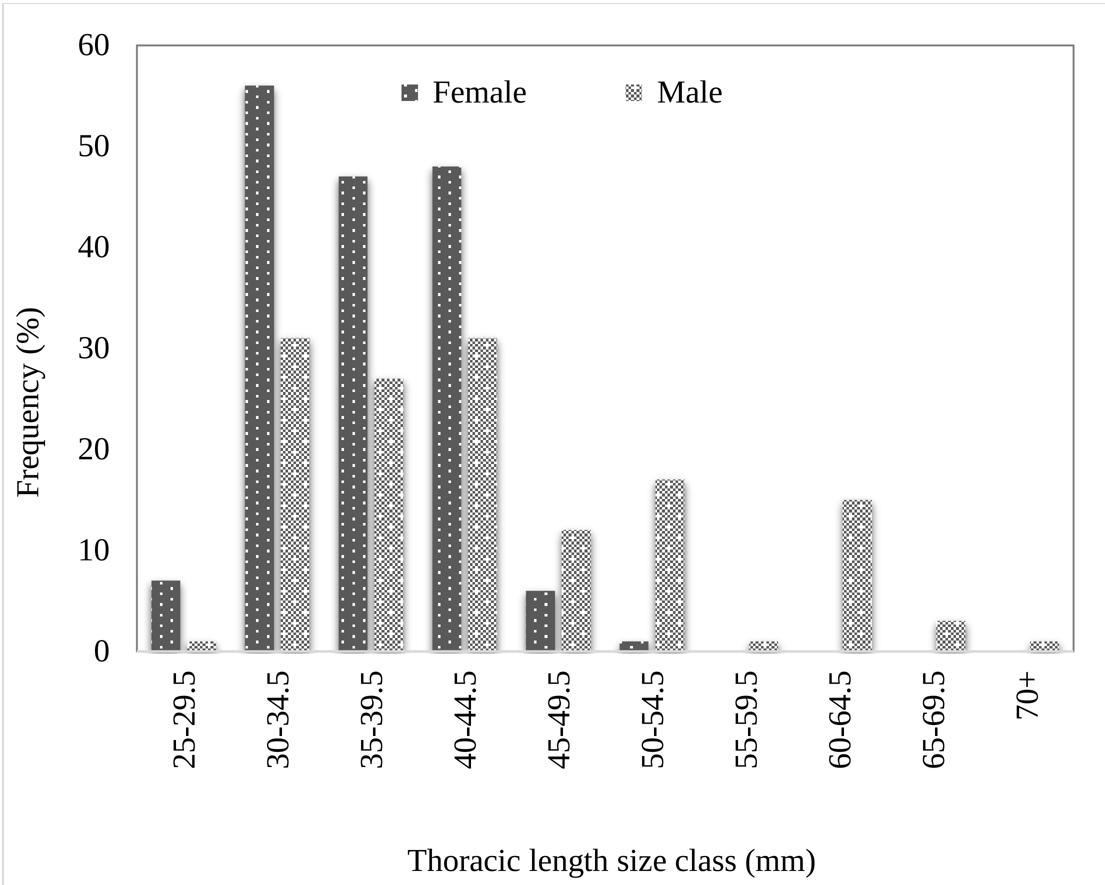

Figure 3**:** Thoracic length frequency distribution of males and females *B. latro* in the Mpunguti Lower West and East Islands, South Coast Kenya

The thoracic lengths of all specimens collected were categorized into five major classes for both males and females and compared between the islands. The set size classes are represented in Table 2. Examination of morphometric data revealed differences between sexes and between the populations on the two Islands of the Lower Mpunguti. The population of *B. latro* on the Mpunguti Lower East and West Islands is size sexually dimorphic, with males on average attaining much larger sizes than females in the same locations. It was noted that the 31-40 TL size class was the modal class for both male and female *B. latro* of the two Islands.

Table 2: Male and female *B. latro* within five size-classes on Mpunguti Lower East and West Islands, South Coast Kenya

	Mpunguti Lower West		**Mpunguti Lower East**	
Size-class (mm)	**Male**	**Female**	**Male**	**Female**
≤30	3	7	6	15
31-40	**22**	**55**	**40**	**53**
41-50	18	31	21	4
51-60	15	0	4	0
>60	8	0	2	0
n	93	66	73	72

NB**:** *The bolded class was the class with the highest frequency of both male and female B. latro from the Mpunguti Lower West and East. (n = sample size)*

Though many body parameters were measured in this study, major body measurements used in determining crab body size were compared between sexes and graphically analysed (Figure 4). The means thoracic length of females was 36.29±0.38 mm (Mean±SE) while the mean±SE for TL of males was 43.06±0.85 mm and carapace length of 78.3±0.79 mm (Mean±SE) for females and whereas the mean±SE for males was 91.3±1.7 mm CL. Similarly the mean thoracic width of females and males were 77.1±0.92 mm and 89.7±1.9 mm (Mean±SE), respectively.

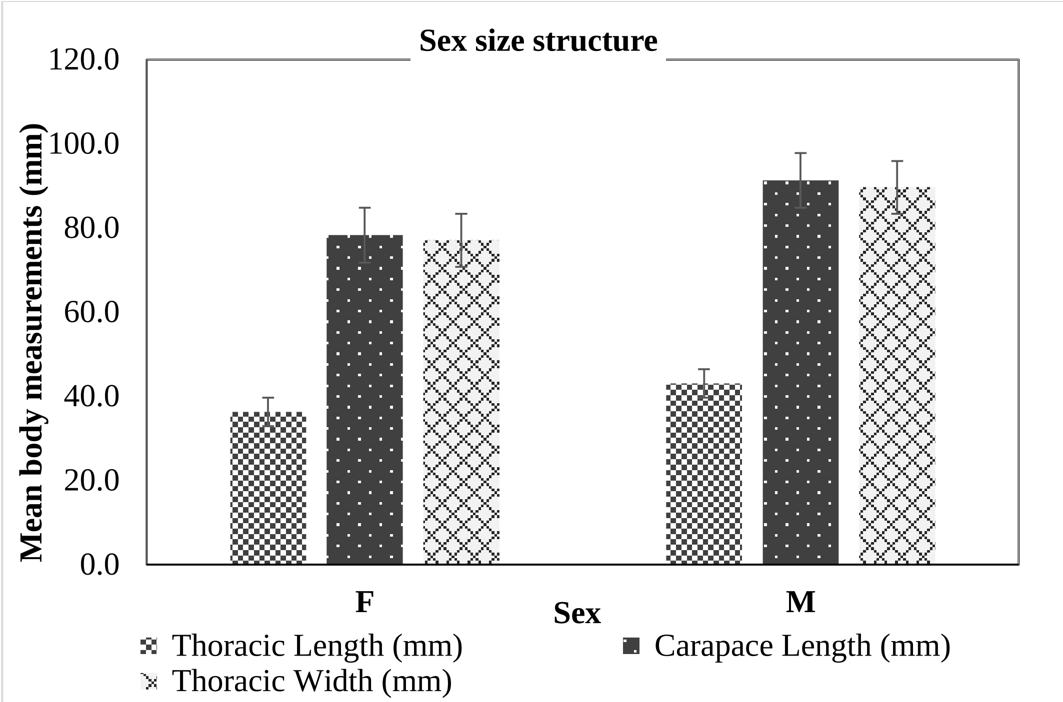

Figure 4: Key growth body dimensions of male and female *B. latro* in the Mpunguti Lower East and West Islands, South Coast Kenya.

4.3 Sex Ratio

A total of 304 individuals were sampled on the two Islands during the study and sexed (appendix 4); 159 on the Mpunguti Lower West and 145 on the Mpunguti Lower East (Table 3). Out of the total 304 *B. latro* specimens sampled, 165 were females and 139 were males resulting in an overall male: female sex ratio of 1:1.2 for the combined data from both Islands. Results of the Chi-square test indicated that this ratio did not differ significantly from the expected 1:1 ratio ($\chi 2 = 2.386$, df = 1, p = 0.122). However, the sex ratio within Mpunguti Lower West was significantly different from expected 1:1 sex ratio with more females than males ($\chi 2 = 8.794$, df = 1, p = 0.012), but not significantly different from the expected 1:1 sex ratio for Mpunguti Lower East ($\chi^2 = 2.724$, df = 1, p = 0.256).

Table 3: Number and sex ratio of the *B. latro* sampled on Mpunguti Lower East (MLE) and West (MLW) Islands, in South Coast Kenya.

Island	**Male (n)**	**Female (n)**	**total**	**sex ratio (M: F)**	χ^2	**df**	**P**
MLW	66	93	159	1: 1.4*	8.794	1	0.012
MLE	73	72	145	1:1	2.724	1	0.256
TOTAL	139	165	304	1:1.2	2.386	1	0.122

(* Significant at $\alpha = 0.05$ and n = sample size).

The independent two sample t-test was used to compare mean differences in male and female body parameters. Table 4 shows that there was a significant difference between male and female body parameters.

Table 4: Comparison of male and female *B. latro* body parameters from samples collected from Mpunguti Lower East and West Islands, South Coast Kenya

N=304:(F=165 M=139)

Body dimension	**Sex**	**Mean ± SE**	**Results of independent sample t-test**
TL (mm)	F	36.3±0.40	t = -7.44, p = 0.0005, df = 302
	M	43.10±0.90	
TW (mm)	F	77.10±0.90	t = -5.97, p = 0.0005, df = 302
	M	89.70±1.90	
CL (mm)	F	78.30±0.80	t = -7.17, p = 0.0005, df = 302
	M	91.30±1.70	
RCPL (mm)	F	48.30±0.80	t = -6.19, p <0.05, df = 302
	M	58.30±1.30	
RCDL (mm)	F	33.20± 0.80	t = 0.78, p <0.05, df = 302
	M	45.10 ±1.70	
W (kg)	F	0.476±0.020	t = -6.55, p = 0.0005 df = 302
	M	0.788±0.040	

NB***:*** *Body parameters- are given as mean ± standard error (SE), sample size (n), the results of the independent sample t-tests for each of the parameters. Parameters: W = weight, TL = thoracic length, TW = thoracic width, CL = carapace length, RCPL = right chelae propondus length, and RCDL = right chelae dactylus length.*

Further analysis of variance for all *B. latro* body dimensions using the generalized linear model (GLM) revealed significant differences in the body dimensions ($p < 0.05$) between male and female for all body measurements.

4.4 Morphometric Characteristics

Figures 5 and 6 compare body parameters between sexes on each of the two Islands of Lower Mpunguti. Analysis of male and female morphometric data indicates that the measured body parameters are significantly different (t-test, $p < 0.05$) with males reaching a larger size than females. The absolute measurements of the body parameters of weight, thoracic length, carapace length, and thoracic width as well as cheliped lengths (right dactylus length and right propondus length) of males were noticeably larger than those of females. Examination of morphometric data for the two Islands revealed that much variation exists both within and between Islands. It was found that both the maximum and the mean sizes of males recorded on both Islands were significantly higher than those of females. A highly significant difference was found between sexes of the same island and between the same sex on different islands.

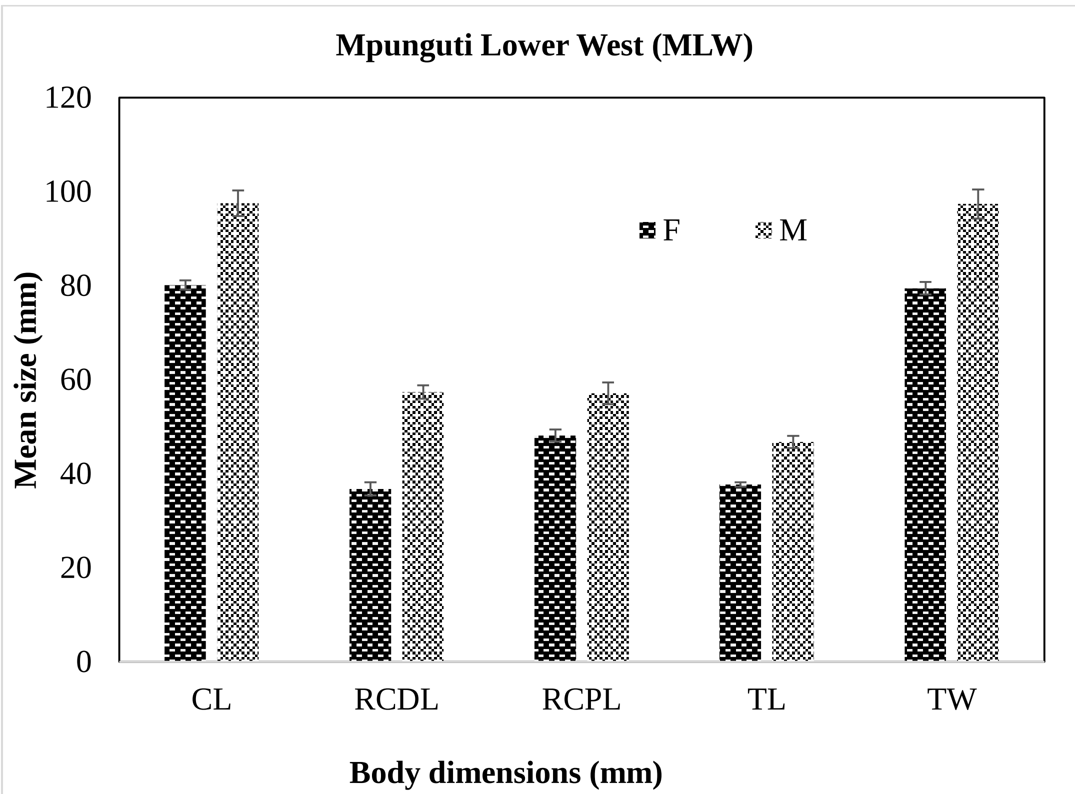

Figure 5: Comparison of male and female *B. latro* body parameters[3] on Island of Mpunguti Lower West, South Coast Kenya.

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[3] *W = weight, TL = thoracic length, RCPL = right chelae propondus length, CL = carapace length, RCDL = right chelae dactylus length and TW = thoracic width.*

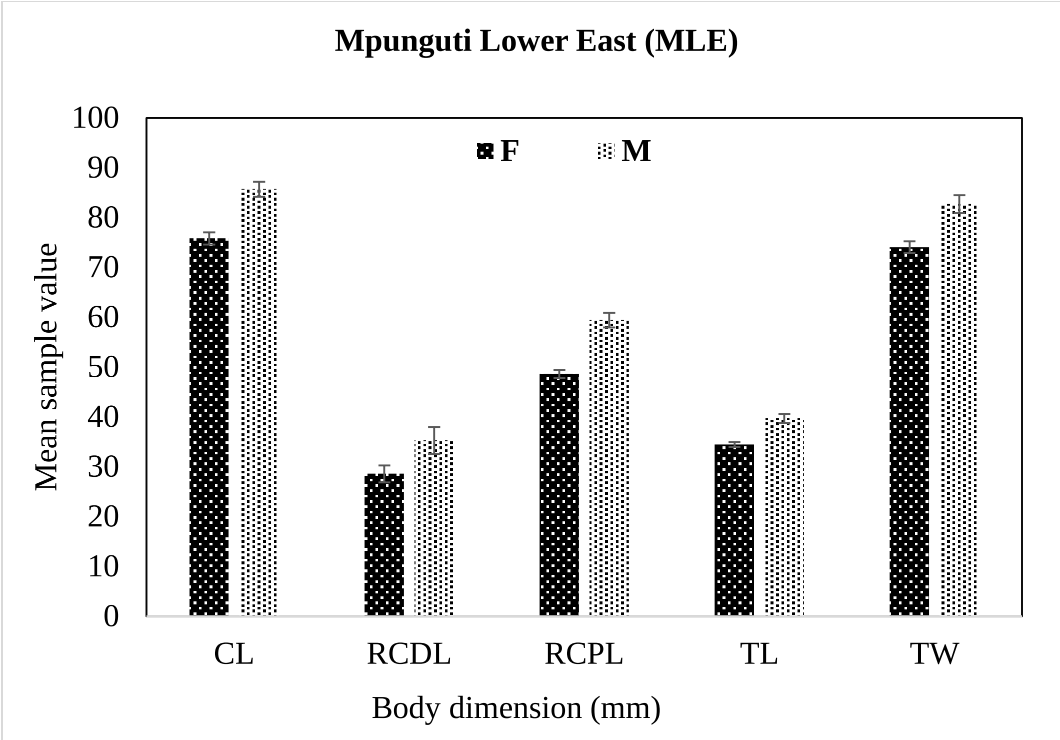

Figure 6: Comparison of male and female *B. latro* body parameters[4] on the Island of Mpunguti Lower East (MLE), South Coast Kenya.

Comparison of body parameters within and between sexes

Thoracic Length

Thoracic lengths between sexes were compared between Islands to determine whether indeed there was a difference in mean thoracic length. Females from Mpunguti Lower West had a higher thoracic length mean 37.71±0.5 mm compared to their female counterparts on Mpunguti Lower East with a mean of 34.46±0.5 mm. A two-sample t-test showed significant difference between the Islands. ($t = 4.52$, $p < 0.05$, $df = 163$). The test on TL for males from Mpunguti Lower West gave a mean of 46.8±1.3 mm and

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[4] *W = weight, TL = thoracic length, RCPL = right chelae propondus length, CL = carapace length, RCDL = right chelae dactylus length and TW = thoracic width.*

39.54±0.9 mm (Mean±SE) for Mpunguti Lower East. This revealed a significant difference between the two islands ($t = 4.55$, $p < 0.05$, $df = 136$).

Thoracic Width

The thoracic width of female crabs was compared between the two Islands. Mpunguti Lower West females recorded a mean thoracic width of 79.4±1.3 mm (Mean±SE) while Mpunguti East females recorded a mean of 74.05±1.2 mm (Mean±SE). Test for significance using the student t-test ($t = 2.97$, $p = 0.003$, $df = 163$) showed significant differences between the means of the female populations from the two Islands. Comparison between the thoracic width of Mpunguti West males 97.4±3.1 mm (Mean±SE) and the Mpunguti Lower East males 82.3±1.8 mm (Mean±SE) also confirmed a significant difference (t-value = 7.07 $p < 0.05$ df= 136).

Carapace Length

The carapace length of female crabs was compared between Islands. Mpunguti Lower West females had a mean carapace length of 80.15±1.1 mm (Mean±SE) while Mpunguti Lower East females had a mean of 75.83±1.2 mm (Mean±SE). Test for significance using the student t-test ($t = 2.77$, $p = 0.006$, $df = 163$) confirmed a significant difference between the means of CL of the female populations in the two Islands. The mean carapace length of the Mpunguti Lower West males (97.5±2.7 mm) and Mpunguti Lower East males (85.3±1.8) (Mean±SE) was found to be significantly different ($t = 3.85$, $p < 0.05$, $df =136$).

Weight

The difference in mean body weight for the female populations of the two Islands was analyzed. Female crabs from Mpunguti Lower West had a mean body weight of 0.58±0.03 kg (Mean±SE), whereas females from Mpunguti Lower East had a mean body weight of 0.35±0.02 kg (Mean±SE). A two-sample t-test ($t = 6.45$, $p = 0.05$, $df = 163$) confirmed the difference of the population means. A comparison of the Mpunguti Lower West male body weight means of 1.059±0.07 kg (Mean±SE) with the Mpunguti Lower East males 0.535±0.034 kg (Mean±SE) confirmed a significant difference between the body weight of males between the two Islands ($t = 7.07$, $p < 0.05$, $df = 136$).

Overall Body Measurements

Overall, *B. latro* morphometric data from the two study locations showed that individuals collected from the Mpunguti Lower West had higher mean measurements of all body parameters measured than the population from the Mpunguti Lower East (Figure 7). Mpunguti East *B. latro* had a mean thoracic length of 37.1±0.6 mm (Mean±SE), thoracic width of 78.4±1.2 mm (Mean±SE), carapace length 80.8±1.2 mm (Mean±SE), right chelae dactylus length 39.7±1.6 mm (Mean±SE) and right chelae propondus length of 54.1±1.0 mm (Mean±SE). The Mpunguti Lower West population had mean thoracic length of 41.5±0.7 mm (Mean±SE), thoracic width 86.9±1.6 mm (Mean±SE), carapace length 87.4±1.4 mm (Mean±SE), right chelae dactylus length 45.3 ± 1.1 mm (Mean±SE) and right chelae propondus length of 51.9±0.1 mm (Mean±SE)

The body weight of the crabs between the Islands also showed considerable difference. The Mpunguti Lower West crabs had a mean weight of 0.8±0.04 kg (Mean±SE), while the Mpunguti Lower East crabs had a mean of 0.45±0.02 kg (Mean±SE). On many of the body aspects measured, Mpunguti Lower West crabs were significantly larger than the Mpunguti Lower East crabs.

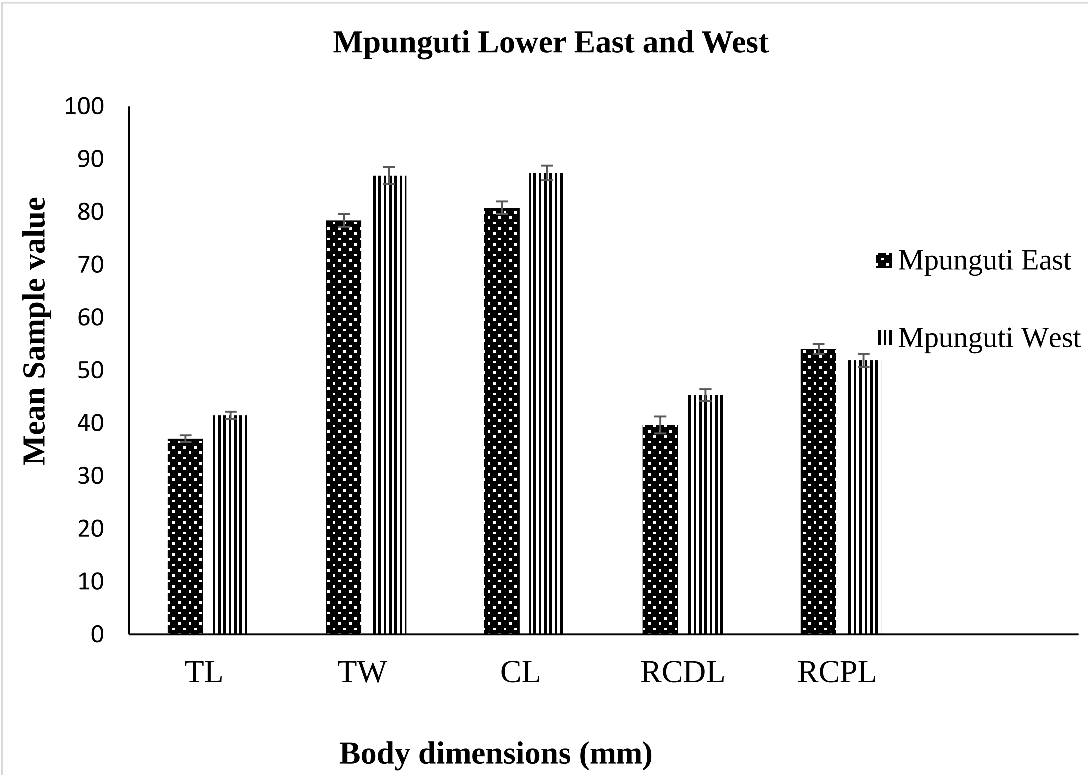

Figure 7: Comparison of Body Dimensions between the populations of Mpunguti Lower East and West Islands, South Coast Kenya.

One-way ANOVA (F (5,181) = 1.0, p <0.05), showed significant differences between mean for all body dimensions of the Mpunguti Lower East and West populations.

4.4.1 Interrelationships between different morphometric characters

Significant positive linear relationships were observed between thoracic length, width, carapace length and body weight; thoracic length, carapace length and thoracic width. The regression equation for relationships is shown in Tables 5 and 6. The regression equation was calculated from log transformed data using both sexes in the calculations.

Table 5: Allometric equations for male *B. latro* specimens from the Mpunguti Lower East and West Islands, South Coast Kenya. (n = 139)

Independent variable	**Dependent**	**Allometric growth equation**	**R^2**
Carapace length (mm)	Thoracic length (mm)	Log TL = 0.907 Log CL - 0.478	0.94
Thoracic width (mm)	Thoracic length (mm)	Log TL = 1.02 Log TW - 0.2897	0.93
Carapace length (mm)	Thoracic width (mm)	Log TW = 0.861 Log CL -0.281	0.93
Thoracic length (mm)	Body Weight (kg)	Log W = 0.315Log TL - 1.683	0.82
Carapace length (mm)	Body Weight (kg)	Log W = 0.288 Log CL - 2.006	0.79
Thoracic width (mm)	Body Weight (kg)	Log W = 0.322 Log TW - 2.002	0.79

Table 6: Allometric equations for females *B. latro* specimens from the two Mpunguti Lower East and West Islands, South Coast Kenya. (n = 165)

Independent variable	**Dependent**	**Allometric growth equation**	**R^2**
Carapace length (mm)	Thoracic length (mm)	Log TL = 0.864 Log CL - 0.546	0.80
Thoracic width (mm)	Thoracic length (mm)	Log TL = 1.036 Log TW - 0.270	0.77
Carapace length (mm)	Thoracic width (mm)	Log TW = 0.725 Log CL - 0.527	0.79
Thoracic length (mm)	Body Weight (kg)	Log W = 0.215 Log TL - 1.637	0.64
Carapace length (mm)	Body Weight (kg)	Log W = 0.1824 Log CL - 1.959	0.49
Thoracic width (mm)	Body Weight (kg)	Log W = 0.2124 Log TW - 1.962	0.45

The values of the coefficient "*b*" for the relationships between thoracic length, carapace length and thoracic width to body weight in males were 1.68, 2.006 and 2.002, respectively, and 1.637, 1.959 and 1.962 in females, respectively. The coefficient "*b*" values are lower than the isometric growth ($b < 3$), indicating negative allometric growth for both males and females in the two Islands of Lower Mpunguti. The coefficient of determination (r^2) for the carapace length and thoracic width to body weight relationship showed positive correlation, with higher for males (r^2 ranged 0.82-0.79) compared to females with a r^2 range of 0.64- 0.45.

4.5 Population Size and Density

4.5.1 Population size and density estimates from quadrant (Plots)

A total of 304 Coconut crabs (excluding recaptures) were sampled in both Islands during the study period with 52.3 % (159) from Mpunguti Lower West and 47.7 % (145) from Mpunguti Lower East. Mpunguti Lower West had a mean density of 13.25 crabs/plot while Mpunguti East had a mean of 16.78 crabs/plot. An extrapolation analysis of density showed that the population density was 100.6 individuals/ ha for Mpunguti Lower East, while Mpunguti Lower West had 82.5 individuals/ ha. The population estimate of *B. latro* for the 4.5-ha Mpunguti Lower East Island was therefore estimated at 453 crabs and 414 crabs for the 5-ha Mpunguti Lower West Island. This extrapolation method for population estimates was, however, quite deficient since capture variations in terms of plots population mean was quite high, particularly for the plots in the Mpunguti Lower West Island.

Two-way ANOVA of crabs captured between plots for Mpunguti Lower West and East Islands showed that there was no significant difference between the two Islands means (F (23.052) $p = 0.0832$). However, comparison using Levene´s test for homogeneity of variance from means within Mpunguti Lower West plots showed existence of homogeneity but significant difference among plots means (df = 2, p = 0.0035). The Mpunguti Lower East plot means showed no significant differences among the plots (df = 2, p = 0.6181).

Tukey Pairwise Comparison of carb density (Nos./plot) for Mpunguti Lower West Island showed a highly significant difference between MPW-1 and MPW-2 (p = 0.0068), as well as with MPW-3 (p = 0.0044). However, there was no significant difference between MPW-2 and MPW-3 (p = 0.6986) as shown in Table 7.

Table 7: Tukey Pairwise Comparison for plots of Mpunguti Lower West, South Coast Kenya

Plot Mpunguti Lower West	**MPW-1**	**MPW-2**	**MPW-3**
MPW-1		**0.007**	**0.004**
MPW-2	9.1		0.7
MPW-3	10.3	1.2	

NB: *bold numbers denote significant differences between plots.*

Observing Figure 8, Mpunguti Lower West Island had a higher level of variation in terms of density (Nos/ha), which was explained by the high variations of capture between the plots. In the study, MPW-1 plot in Mpunguti Lower West recorded the highest catch compared to the other two plots (MPW-2 and MPW-3) on the island.

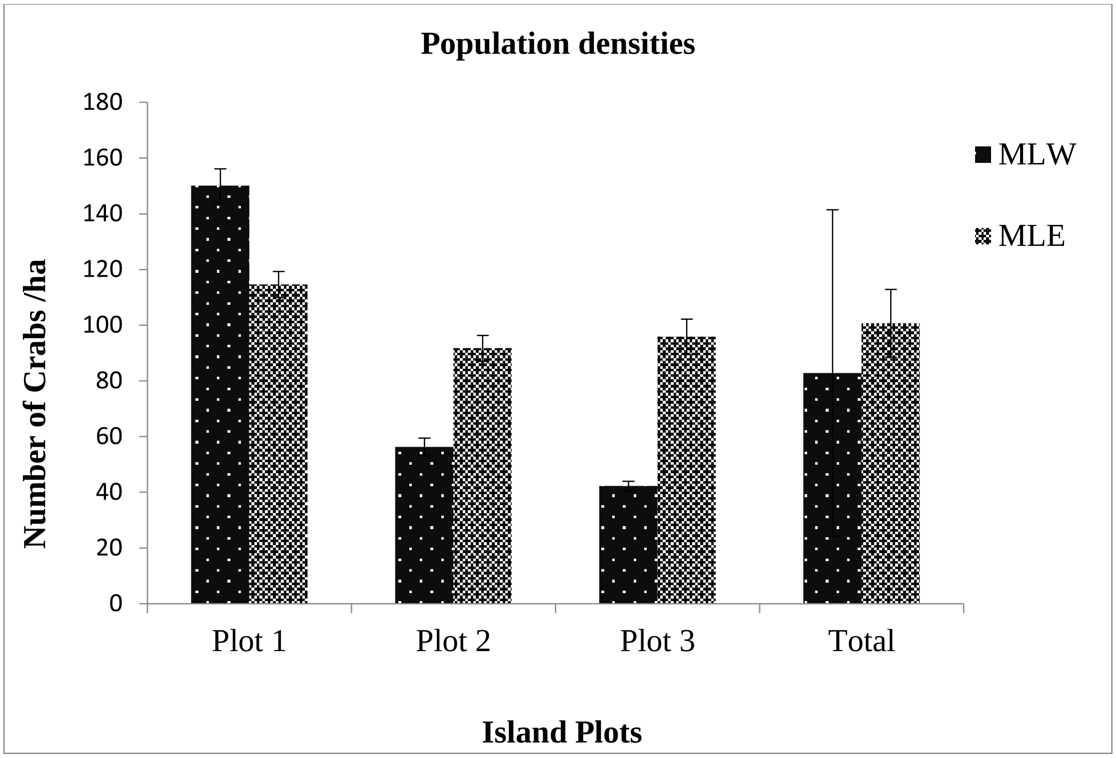

Figure 8: Extrapolated densities (crabs/ha) pooled for all the sampling occasions in the Mpunguti Lower East (MLE) and West (MLW).

There was a slight temporal variation in the number of crabs caught during the sampling period. The highest numbers were captured in April, at 96 accounting for 31.6% of the total numbers, followed closely by March with 91 individuals (29.9%); May with 69 (22.7%) and February with 48 (15.8%). However, Mpunguti Lower East was not sampled in February because of severe ocean conditions, which can account for the lower numbers recorded in the island. ANOVA test of mean catches showed no significant difference across the months [F (6) = 0.84, p = 0.555]. The monthly plots population mean shows that athough Mpunguti East wasn't sampled in February; population plot means were considerably higher in Mpunguti Lower East compared to West Island.

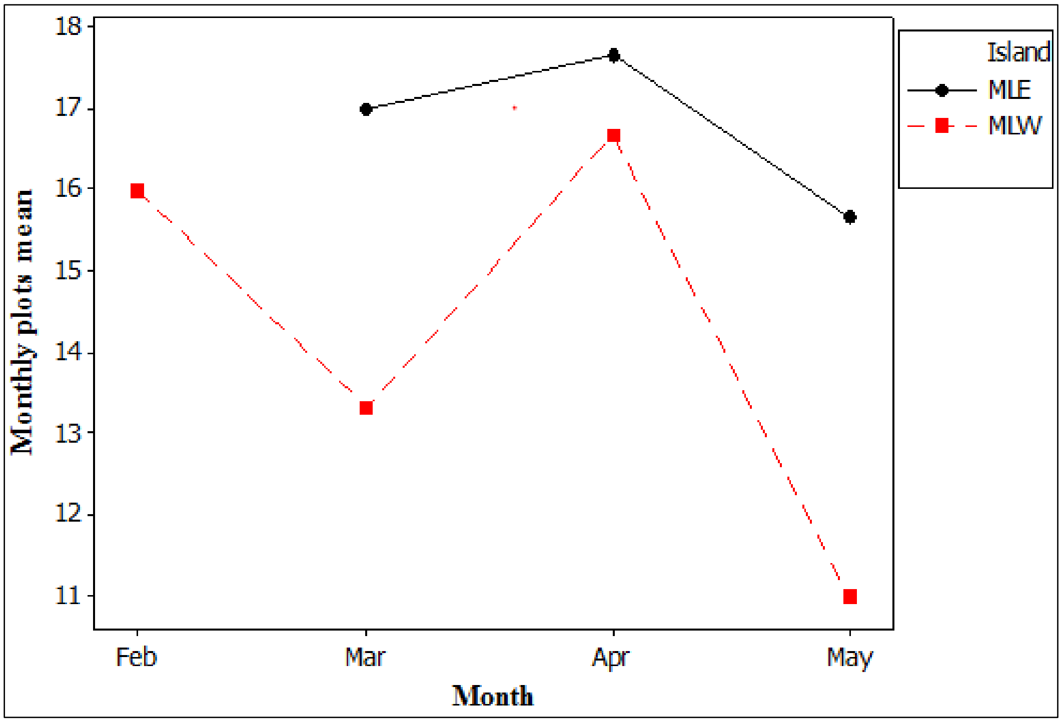

Figure 9: Monthly plot means for Mpunguti Lower East (MLE) and West (MLW).

4.5.2 Population size and density estimates using CPUE

The average CPUE for Mpunguti Lower East was 1.7 individuals/bait compared to Mpunguti Lower West at 1.3 crabs /bait. The mean CPUE for females was 0.78±0.02 while males had a mean CPUE of 0.67±0.08 individuals/bait.

Overall CPUE estimate for all plots during the study duration for the two Islands was 1.4±0.2 individuals/bait. The data used in the estimations of captures, effort (no. of baits), CPUE and the amount of cumulative catch is shown in Table 8.

The initial population for Mpunguti Lower East and West was estimated at 1,018 and 555 crabs respectively. The pooled initial population size (N) of *B. latro* for both study sites was therefore estimated as 1,573 individuals. The upper and lower limits of 95% confidence, calculated for the two populations of the two Islands, estimated the populations of *B. latro* as 555-556 and 1017-1018 for Mpunguti Lower West and East Islands, respectively. Therefore, the pooled population for the two Islands was estimated at 1572- 1574 crabs. In Table 8, the CPUE is a dependent variable while cumulative catch is an independent variable. For the first sampling period, prior cumulative catch is zero. Intercept (a) and the slope (b) were determined using the generalized linear model (GLM) and an estimate of population was given by the equation:

$$N = -\frac{a}{b}$$

Table 8: Monthly catches and CPUE for each month as well as the cumulative catch for the two islands and effort expended.

Mpunguti Lower West Island					
Month	**Island**	**Catch (C)**	**Effort/No of traps**	**CPUE**	**Cumulative catch**
March	MLW	40	30	1.33	0
April	MLW	43	30	1.43	83
May	MLW	28	30	0.93	111
			q (catchability)	-0.0026	
			Intercept	1.392	
			Initial population	**555**	
Mpunguti Lower East Island					
Month	**Island**	**Catch (C)**	**Effort/No of traps**	**CPUE**	**Cumulative catch**
March	MLE	51	30	1.70	0
April	MLE	53	30	1.77	104
May	MLE	41	30	1.32	145
			q (catchability)	-0.0017	
			Intercept	1.7542	
			Initial population	**1018**	

The regression equation, given by GLM, is provided in Figures 10 and 11 for both populations of the Lower Mpunguti Islands (West and East). The linear regression equation used to calculate the estimate is also shown in the regression plot.

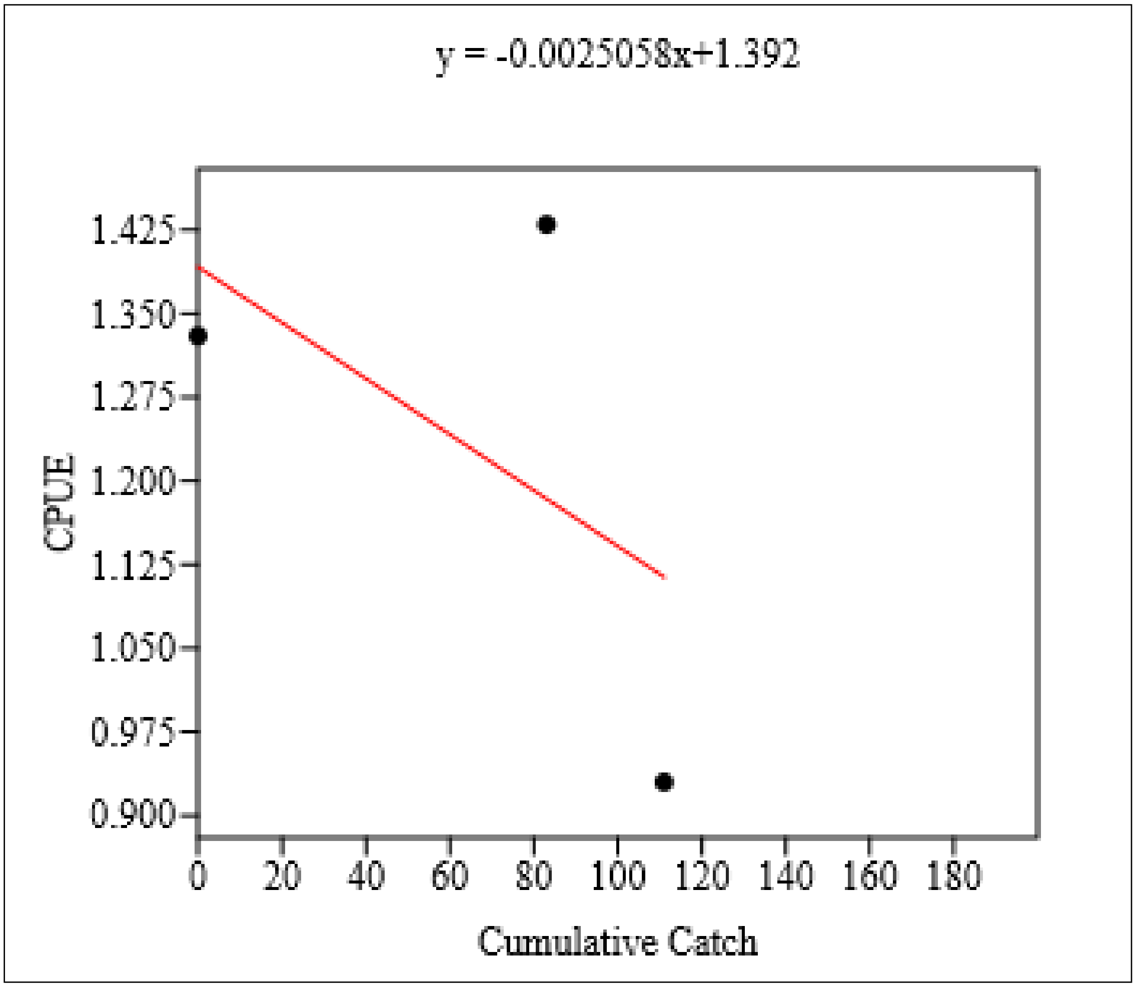

Figure 10: Cumulative catch and CPUE relationship for a series of successive field samples for Mpunguti Lower West (MLW), during March-May 2016.

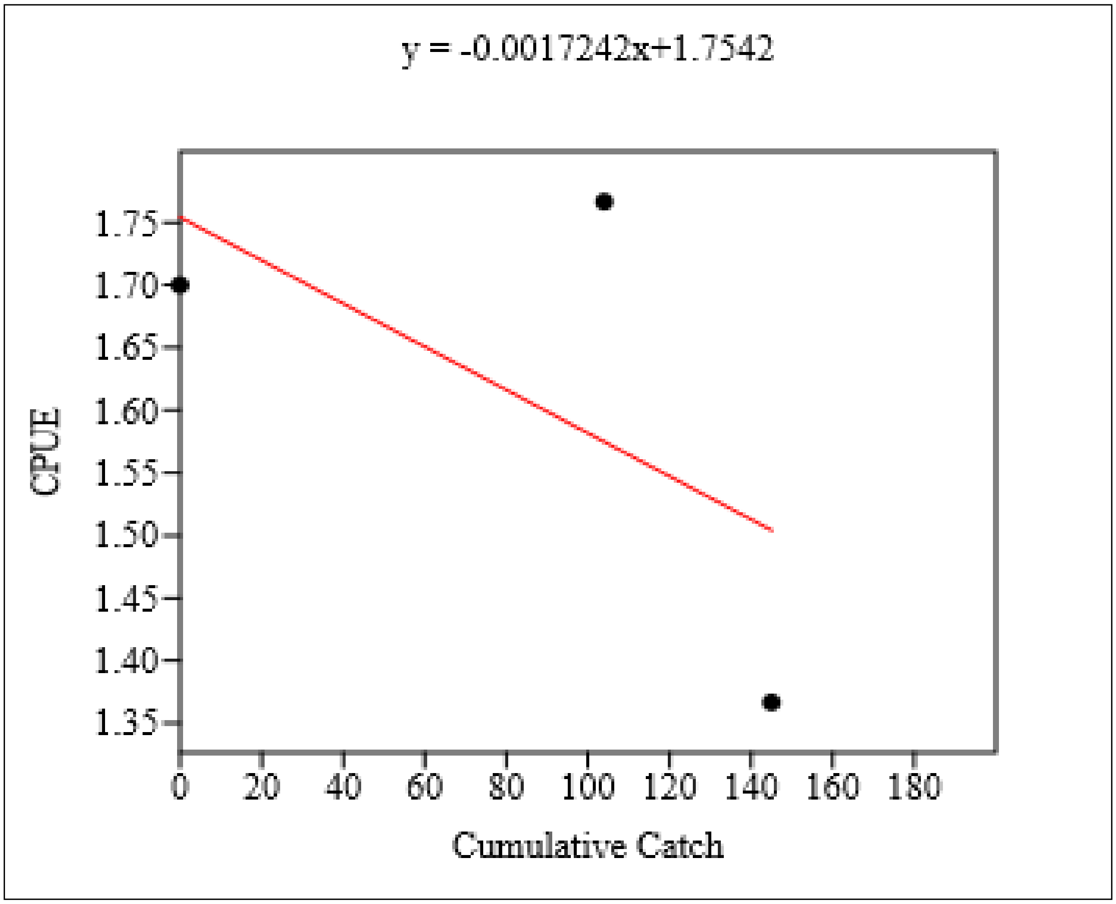

Figure 11: Cumulative catch and CPUE relationship for a series of successive field samples for Mpunguti Lower West (MLW), during March-May 2016.

The generalized linear model (GLM) was applied to study the interaction of different months and islands on CPUE. Seasonal confounding factors were considered as random factors in the calculation since sampling was not uniform across all seasons for the two study sites, and therefore, eliminated from the analysis.

The average CPUE across both Islands was 1.4±0.3 crabs per bait. The highest average CPUE values of 1.8±0.3 and 1.6±0.3 per bait were recorded for Mpunguti East in April and Mpunguti West in February. However, since Mpunguti East was not sampled during February it is hard to compare catch between months. The overall CPUE for females was 0.8±0.1 and for males 0.7±0.2 (Figure 12).

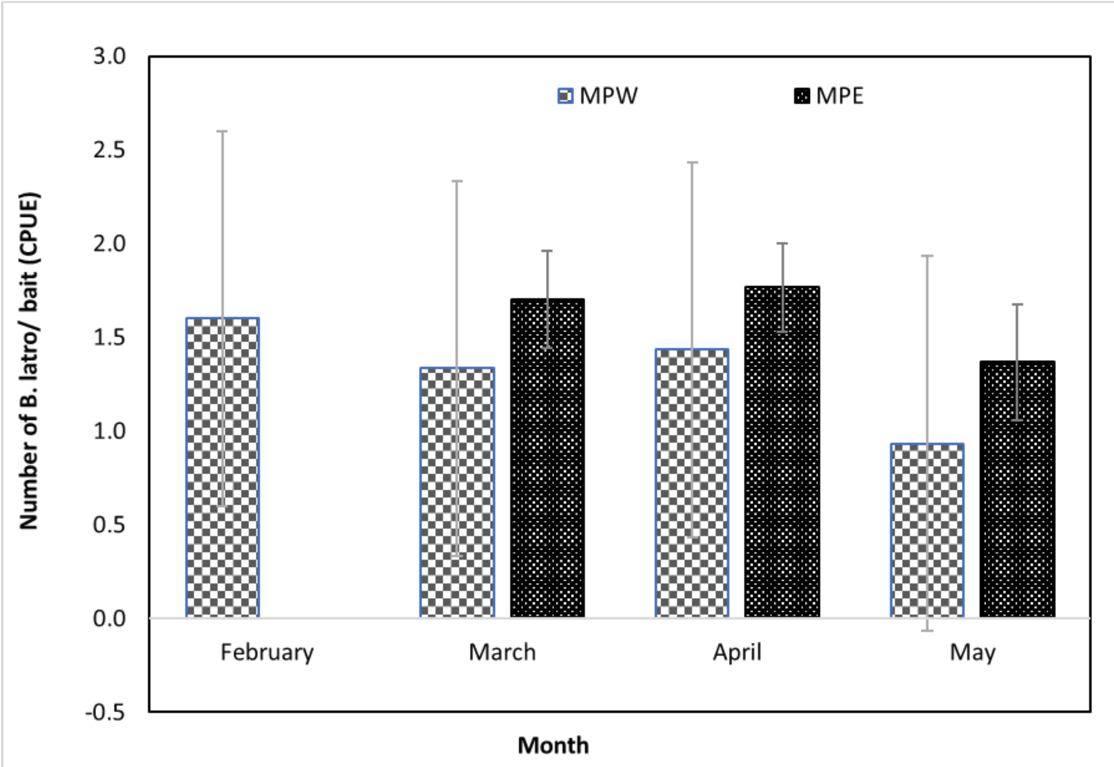

Figure 12**:** Monthly variation of CPUE for Mpunguti Lower East (MLE) and Mpunguti Lower West (MLW).

A two-sample Wilcoxon rank sum test (the Mann-Whitney test) of the mean equality of the male and female population in terms of catch per unit effort was performed and calculated the corresponding point estimate and confidence interval to determine whether there a significant difference between mean male and female CPUE. Sample medians of the ordered data were 0.80 for female and 0.70 for male. The 95.9% confidence interval for the difference in population medians (ETA1-ETA2) was (-0.1000 - 0.2999). The test statistic W = 61.0 has a p = 0.4433 or 0.4271 when adjusted for ties. Since the p-value is greater than the chosen p-level of 0.05, it is concluded that there was insufficient evidence to reject the hypothesis of equal mean CPUE for male and female population for the two Mpunguti Lower East and West Islands.

The highest CPUE was recorded for females (0.78±0.02) followed by males (0.67±0.08) Figure 13. However, paired t-test after the transformation of data to normal distribution (t = -1.62; p = 0.156) showed no significant difference between the sexes mean CPUE for both male and female *B. latro.*

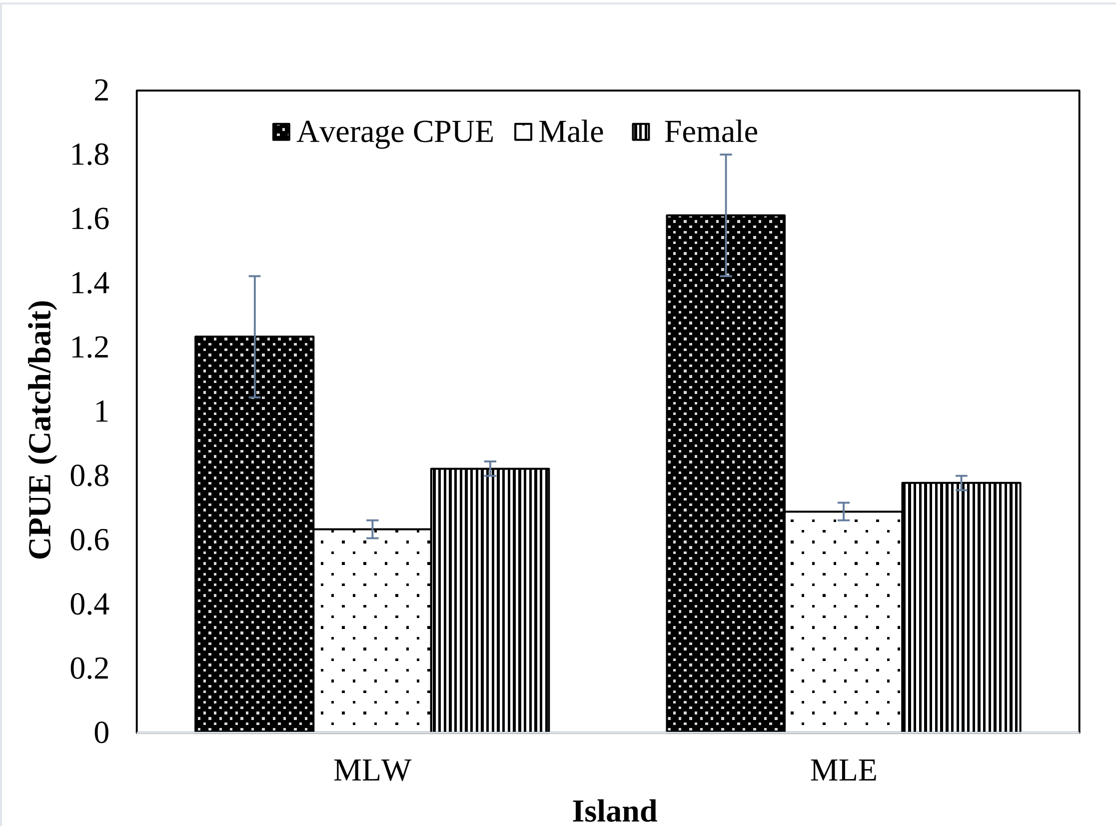

Figure 13**:** Three months population overall mean (Mean ± SE) of CPUE for the two Islands of Mpunguti Lower West (MLW) and East (MLE), South Coast Kenya.

Mann-Whitney test was applied to establish the difference between the CPUE for Mpunguti Lower West (MLW) and East (MLE) populations by determining corresponding point estimate and confidence interval to establish whether there was significant difference between CPUE of the two Mpunguti Lower Islands. Sample medians of the ordered data were 1.7 for MLE and 1.3 for MLW. The 91.9% confidence interval for the difference in population medians (ETA1-ETA2) was (0.0601, 0.8401).

The test statistic was W = 14.0 (p= 0.1904) and indicating that there was no significant deviation from the hypothesis of equal mean CPUEs for the populations of *B. latro* on the two Mpunguti Lower Islands.

The generalized linear model (GLM) was applied to the catch data to study the effects of variables on the number of crabs to test which variables influenced the population means. Setting the number of crabs caught as a dependent variable, the study tested for interaction with other factors. The interaction of the factors was explained by (F (21) = 5.6365) with p-values for the various factors shown in Table 9.

Table 9: Significance of factors in influencing the number of *B. latro* captured on the Mpunguti Lower East and West Islands. The bolded p-value indicates a significant value.

	Coeff.	**Std. err.**	**T**	**p**	**R^2**
Months	-1.8	1.2	-1.5	0.200	0.040
Islands	3.8	2.6	1.5	0.200	0.040
Plots	-5.5	1.5	-3.7	**0.002**	0.400

CHAPTER 5: DISCUSSION

5.5.2Biological Aspects of *Birgus latro*

In the present study results showed that the carapace colour of Coconut crab *B. latro* in the Mpunguti Lower East and West Islands varied from orange, red, and brown, to purple, blue and black colours. Out of the 304 crabs sampled from Feb to May on Mpunguti Lower East and West Islands about 69% had a reddish morph, 23% with bluish and the remaining 8% had varied intermediate colours. It wasn't possible to compare colours by sampling sites but it was clear that the intermediate colours such as orange morph and dark bluish-black were found on both Islands. While studying *B. latro* on Cook island, McCormack (2007) noted that the species occurred in two different colour morphs; blue and red, but the colours were not related to age or sex. On the contrary, other studies found that colour of the carapace varied between regions and among individuals within same area (Amesbury, 1980; Brown & Fielder, 1991; Fletcher, 1993). In this study the red morph was noted as the most frequent colour in the Mpunguti Lower Islands.

The smallest female recorded in this study was 25.1 mm thoracic length (TL) compared to 27.11 mm for males while the largest females was 50.2 mm TL compared to 70.3 mm TL for males sampled on Mpunguti Lower West. Therefore, the male *B. latro* caught during this study had, on average, a larger body size compared to females. Majority of the males were >50mm TL. Comparison of male and female size classes clearly indicates that the male *B. latro* have larger size classes than do the females. The majority of female and male crabs have a TL between 31 mm- 40 mm. In majority of the morphological studies conducted on this species (Fletcher, 1993; Drew *et al.*, 2010; Anagnostou & Schubart, 2014) results indicate that *B. latro* exhibit sexual dimorphism with males attaining larger body size than females. Sato *et al.* (2008) determined the size of males at sexual maturity by histological methods and found that at 22.2 mm TL, 50% of the individuals were sexually mature, indicating the size at massive maturity (L_{50}) as 22.2 mm TL with all males >25 mm TL confirmed as sexually mature. On the other hand, the size at functional maturity in females was estimated as 24.5 mm TL. Drew *et al.* (2010) similarly observed that variation in size between sexes is not unusual in crustaceans and is potentially associated with the energetic costs of reproduction and/or sexual selection processes associated with the selecting of mates. Sexual size dimorphism in this species has been recorded throughout its range**.** Studies have also found differences in the size structures of the sexes, with males attaining much larger sizes than females (Amesbury, 1980; Fletcher, 1993; Anagnostou & Schubart, 2014). Consequently, our findings are in line with all other studies.

The differences of *B. latro* growth among regions have been attributed to availability of food sources, both in number and type (Drew *et al.*, 2010). All *B. latro* sampled during this study had TL> 25mm and therefore, according to Sato *et al.* (2008), all the male and female *B. latro* sampled on the Mpunguti Lower Islands were considered as physiologically mature. This is a good example of a population which has been protected from human exploitation yet lack recruits with overall absence of juveniles samples on both Mpunguti Lower West and East populations. However, Hamasaki *et al.* (2009) stated that *B. latro* megalopae and juveniles prefer a humid environment as this stimulates emigration from the sea. This emphasizes the importance of nearness to the ocean, such as the periphery of islands, as important habitat for supporting recruits of this species. Most of the Mpunguti Islands peripheral habitats are cliffs and pinnacles of very sharp rock which are overgrown by impenetrable coastal scrubland. Therefore, it was not possible for investigators to access this area for data collection. This could explain the general absence of small crabs in the sample. Many other studies reported an overall lack of small crabs and a population which is skewed toward adults (Fletcher & Amos, 1994; Chauvet & Kadiri-Jan, 1999; Wang *et al.,* 2007; Williams *et al.*, 2008; Kessler, 2011; Drew *et al.,* 2013). Kadiri-Jan & Chauvet (1998) observed that the mature crabs (>25mm TL) commonly migrated between the coastal region and higher elevations. This could possibly explain why juveniles were not captured in the sampling area on the Islands of Mpunguti Lower East and West. It also clearly indicates the puzzling nature of juvenile crabs, provoking further studies to demystify this gap in the data.

Previous studies on Coconut crabs have estimated age from body weight and thoracic length (Fletcher *et al.*, 1990a). Some studies predicted that it takes up to five (5) years for *B. latro* to attain 1.0 kg of weight. Reese (1968) in his study concluded that large crabs of >1.0 kg may be 30 to 40 years of age. Fletcher *et al.* (1990a) established a growth curve model in Vanuatu in the South Pacific through an experiment, which indicated that a male crab weighing 1.0 kg was likely to be >10 years old. The study noted that the maximum size is not attained until >30 years of age. Therefore, following the premise of this study, if it takes up to 10 years to attain 1.0 kg weight, majority of the Mpunguti Islands *B. latro* which weighed 1.0-2.4 kg were estimated to be aged between 10-20 years.

Comparing the populations of the two Islands in terms of mean body size, significant differences between the populations were found. The population of Mpunguti Lower West, recorded larger body sizes compared to the Mpunguti Lower East Island. Studies have attributed the larger body weight and thoracic length to the age (Fletcher *et al.*, 1990a). Therefore, the larger body sizes of Mpunguti Lower West crabs could be attributed to the crabs evolutionary and ecological possibility, that the MLW Island was the first island to be colonized before the population spread to Mpunguti Lower East Island.

The present study documented similar sex ratios for the population of *B. latro* on the Mpunguti Lower East and West Islands indicating a balanced, viable population. Similarly, the sex ratios were not significantly different across sampled plots for Mpunguti Lower East Island, but Mpunguti Lower West revealed a deviation from the overall expected 1:1 sex ratio in favour of females. Similar finding was reported by Drew *et.al*. (2014), on Charismas Islands in Indian Ocean coasts of Australia. The study observed considerable variation of each sex both spatially and temporally between and within the sampling grids.

Morphometric characteristics are important biological aspects in estimating the population of a crustacean species. Length-weight relationships are important as they provide information useful for management and conservation of a fishery (Amesbury, 1980; Froese, 1998). In this study, the growth parameter "*b"* values of the sampled *B. latro* body parameters did not differ significantly from the isometric value of b=3. Thoracic length-weight and thoracic width-weight showed negative allometric growth (b<3). Therefore, the body weight for both male and female *B. latro* does not proportionally increase with increasing body dimensions. Only after the crabs reach a certain age and length does the growth in dimensions become proportional to the weight. A study on *B. latro* by Widiyanti *et al*. (2015) on Sayafi Islands, North of Maluku Indonesia , showed that growth pattern of *B. latro* was negative allometric (b < 3). The study indicated that the increase in body weight of female *B. latro* was faster than that in males, although the growth pattern of the male *B. latro* indicated a positive allometry (*b*> 3). The differences in the growth patterns (negative vs. positive allometric growth), in the male and female *B. latro* were attributed to sexual dimorphism, sizes and food availability.

5.2 Ecological Aspects of *Birgus latro*

The population of Coconut crabs in the Mpunguti Lower East and West Islands was found to be markedly higher in areas where there was an abundance of rocky crevices and holes, in comparison to areas which still had good forest cover but had fewer rocky microhabitats and crevices. While the crabs can and do take shelter under logs and fallen tree trunks, in burrows in soil or sand, or even high in the trees, they show an obvious preference for rocky refuges in the Mpunguti Lower East and West Islands. Plots with a high abundance of crevices and holes recorded a higher catch compared to those forested areas with few crevices and holes. Previous studies (Amesbury, 1980; Wells *et al.*, 1983; Fletcher *et al.*, 1991) also documented that *B. latro* inhabit rock crevices and sand burrows along the coastline, although preferences vary between Islands and their choice may depend on the habitat available. Therefore, forest areas with no rocky holes and crevices are less preferred, even if there is an understorey.

In this study, tree climbing was noted as strategy to escape predators. The individuals quickly climbed trees to avoid being caught during sampling. The crabs seemed to detect and react more to vibration and/or sound than to visual stimuli. However, further studies are needed to confirm this observation. During the study, it was observed crabs moved faster backwards and quickly retreated into a hole or crevices. Slow sideways movement was also observed when there was no apparent disturbance. Peter Greenaway (2003) noted that *B. latro* climb vertical or overhanging surfaces with long needle-like terminations of the dactyls of the walking legs, which also used these to grip bark on large tree trunks or irregular surfaces on rock.

The eastern end of the Mpunguti Lower West Island, which hosts a base for the KWS rangers recorded a higher abundance of crabs in the plot (MPW-1) located near the rangers' post compared to the other plots located further away in the interior of the forest. The presence of human population on the island appears to greatly influence the crab distribution due to the availability of leftover maize meal, fish and other food scraps which provide food for the crabs. Additionally, MPW-1 is close to the shore and therefore it's also part of the preferred microhabitat for the crabs. The population of *B. latro* on Mpunguti Lower West Island showed a clump distribution, compared to a more even distribution on the Mpunguti Lower East Island, where CPUE among sampling plots and monthly plots averages did not show any significant difference.

The pooled mean CPUE for both Islands was 1.4±0.3 crabs/bait. The highest average CPUE recorded were 1.8±0.3 and 1.6±0.26 crabs/bait for Mpunguti Lower East and West Island, respectively. Therefore, although Mpunguti Lower East had a higher *B. latro* population than Mpunguti Lower West Island, the CPUEs for the two Islands were fairly similar. Analysis of the CPUE by sex also indicated no differences between the CPUEs for male and female *B. latro.*

A low rate of recapture was experienced in almost all the six (6) of the study plots. It was speculated that *B. latro* may be sensitive to being handled and may avoid recapture by moving away from the study area or by going into burrows and crevices, and remaining there when there was some disturbance. In similar studies, Fletcher (Fletcher *et al.*, 1990a, 1990b) also experienced low rates of recapture, and attributed this to the likelihood that most of the marked individuals migrated away from the study area.

Grouping of sexes was evidently detected on the two Mpunguti Lower Islands studied. Sexual preference for specific area of the island was clear after sampling using randomly distributed baits; Males *B. latro* appeared to aggregate on one part of the Island while females migrated to the other side of same Island forming some sort of spatial sexual segregation. Choice of an area by sex and excluding of the opposite sex has also been observed in previous study (Drew *et.al*. , 2014). While studying the Christmas Islands on the Australia Indian Ocean coast, Drew *et.al*. (2012) observed that large males often actively excluded females and potentially smaller males from desirable feeding locations, and hence this may explain some of the sexual variation between sites. However, Schiller (1993) observed that most females moved to moist places such as coastal caves during incubation to prevent desiccation of the egg mass and this could probably be the reason for male and female temporary separation of the sexes during some stages of breeding activities.

During this study, rats were observed competing for food with Coconut crabs at some of the bait stations. It is noted that the numbers of rats on Mpunguti Lower West Islands was quite high compared to the populations on the Mpunguti Lower East Island. Further studies should be conducted to establish recruitment behaviors and patterns of the rats (*Rattus* spp.) and how they're likely to influence. Although data was not collected to describe the rat population in the two Islands, it is important to note that the rodents, which are often invasive, are known to predate on the *B. latro* (Eldredge, 1996). Consequently, the invasive rodents, especially *Rattus* spp., are a significant contributor to loss of biodiversity in island ecosystems, affecting over 80 % of all islands or island chains worldwide (Atkinson 1985).

Rats have also been documented to cause ecological damage which includes destruction of native flora and fauna, including threatened and endangered species (Towns *et al*., 2006), possibly threatening the survival of the *B. latro* on these Islands in the future.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

This study presents the first contribution to knowledge on the biology and ecology of *B. latro* on Mpunguti Islands in the Kisite-Mpunguti Marine Park and Reserve, Kenya**.** The rocky terrain and coastal coral rag forests of the Mpunguti Islands provide suitable habitats for the *B. latro* particularly the holes and crevices formed in the sharp coral limestone rocks which as well form the substrate for a coral rag forest. Although some authors noted that the distribution of *B. latro* follows that of coconut palms, coconut palm are virtually absent on the two Islands. It was observed that some wild fruits such as baobab fruits are consumed by the crabs, although the abundance of food resources was not quantified in this study.

This study provides useful information on the *B. latro* populations on both Mpunguti Lower West and East Islands of the MPA presenting some substantial information on the population size, density and the body size structure of *B. latro* on Islands of Mpunguti. Overall, the sex ratios and CPUEs for the populations of Mpunguti Lower West and East were fairly similar. Nonetheless, considerable differences between sexual size structures as well significant differences in body size between Islands were evident in this study.

The *B. latro* population for the two Islands in the study was estimated to be between 1572 and 1574 individuals. This study established that the two Islands of Mpunguti Lower in South coast Kenya are an important home and habitats to this data-deficient species. The higher crab population in the sampled areas of the two Islands was not expected for an area which was initially considered as out of the home range for the *B. latro* species. Furthermore, no studies had been conducted on the *B. latro* population of wider Kisite-Mpunguti ecosystem. Therefore, this study provides baseline information on the populations of this species, and also re-defines the *B. latro* range extension into Kenya from the previous boundary of Zanzibar Island, off mainland Tanzania.

Based on the findings of the current study, the following recommendations are made:

- This study has provided vital information on biology and ecology of Viable *B. latro* population on Islands of Mpunguti, which should be used by management when conservation decisions are made about this MPA now and into the future.
- The Mpunguti Lower East and West Islands is infested with the invasive domestic rat (*Rattus* spp.) and therefore studies are needed to assess the impact of these invasive species on the B. latro populations, as well as on the general biodiversity of the Mpunguti Islands ecosystems, with recommendation for control of the rat populations depending on the results of the studies to reduced competing for food resources and possible predation of *B. latro* recruits.
- A higher aggregation of crabs was observed around the KWS base on Mpunguti Lower West Island where food remains from the base camp were are scavenged by *B. latro* with higher aggregations around base camp. This study recommends proper waste disposal procedures to reduce the “artificial” feeding of the *B. latro* population on human food left overs, therefore likely driving the population distribution.
- Comprehensive studies into the genetics of the *B. latro* population on the Mpunguti Lower Islands is needed to confirm whether it was the same genetic population with linkages to the Zanzibar and other Indian Ocean populations, or whether it was a completely separate population, as well as unravel the mystery of source recruitment.

- Studies of ecological aspects such as distribution, food and feeding habits of the species should be undertaken to generate information to safeguard the populations in events of future developments of the Mpunguti Islands.

- Movement, migration and breeding studies would add further knowledge about recruitment and add insight into the dynamics of mating, spawning and recruitment of the juveniles to the Islands to enable the protection of critical habitats to be protected especially to improve recruitment levels, which were notably low in the *B. latro* population of the two Islands.

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APPENDICES

Appendix 1: Bait preparation process: (A) Baits were prepared off site. (B) The baits were secured to trees or rocks on site. (C) The Coconut crabs emerged to feed on the baits. (D) The crabs were **caught,** and their data **recorded. (**Photos: J. Katello and the fieldwork team, 2016)

Appendix 2: Field data collection: (A) Crabs are drawn to the baits by the Coconut scent. (B) As the team catches the first ones to arrive, others continue to arrive and even fight over the baits (C). (D) The crabs' data is recorded. (Photos: M.Simba and the fieldwork team, 2016)

Appendix 3: Crabs climb trees with ease. (Photos: J. Katello and the fieldwork team, 2016)

Appendix 4: Sexing Coconut Crabs: The arrows show the female Coconut crab's pleopods (limbs that hold her eggs in place against her abdomen). Males lack pleopods, as shown on the right. (Photos: Jillo Katello, 2016)