MANAGING NESTING HAWSKBILL TURTLES (*Eretmochelys imbricata*) ON A SMALL TROPICAL ISLAND

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Master of Science
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PREFACE

The data described in this thesis were collected on Cousine Island, Republic of Seychelles, from September 2004 to March 2015. Experimental work was carried out while registered at the School of Life Sciences, University of KwaZulu-Natal, Pietermaritzburg, under the supervision of Professor Colleen T. Downs and Dr Mark Brown.

This thesis, submitted for the degree of Master of Science in the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, School of Life Sciences, Pietermaritzburg campus, represents original work by the author and has not otherwise been submitted in any form for any degree or diploma to any University. Where use has been made of the work of others, it is duly acknowledged in the text.

JGane

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Julie A. Gane

November 2018

I certify that the above statement is correct

Downs

…………………………..

Professor Colleen T. Downs
Supervisor
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DECLARATION 1- PLAGIARISM

I, Julie A. Gane, declare that:

1. The research reported in this thesis, except where otherwise indicated, is my original research.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other persons’ data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
    a. Their words have been re-written but the general information attributed to them has been referenced
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5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

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DECLARATION 2- PUBLICATIONS

Detail of contribution to publications that form part and/or include research presented in this thesis.

Publication 1

J A. Gane, CT Downs, and M Brown. **Nesting ecology and hatchling recruitment success of the hawksbill turtle (2004–2014) on Cousine Island, Seychelles.**

Author contributions:

JAG conceived paper with CTD. JAG collected and analysed data, and wrote the paper. CTD and MB contributed valuable comments to the manuscript.

Publication 2

J A. Gane, CT Downs, and M Brown. **The effects of nest management methods on hatchling recruitment success and predation rates of hawksbill turtles on Cousine Island, Seychelles.**

Author contributions:

JAG conceived paper with CTD. JAG collected and analysed data, and wrote the paper. CTD and MB contributed valuable comments to the manuscript.

Publication 3

J A. Gane, CT Downs, and M Brown. **Beach profiling and ghost crab densities on a hawksbill nesting beach in the Seychelles.**

Author contributions:

JAG conceived paper with CTD. JAG collected and analysed data, and wrote the paper. CTD and MB contributed valuable comments to the manuscript.

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J A. Gane

November 2018

ABSTRACT

Although human impact has caused the hawksbill turtle (*Eretmochelys imbricata*) to be on the brink of extinction, conservation efforts are on the increase and management strategies are being re-defined to manage the species towards rapid population increases. Numerous conservation measures have been applied and tested, with varying levels of success, to minimize threats and increase hatchling recruitment success rates. Conservation management is imperative for the survival of this species and has been shown to be easiest and most feasible at the nesting and hatching stages. On Cousine Island where this study took place, a turtle monitoring and management program was initiated in 1994 to protect nesting females and incubating eggs at the nesting and hatching stages of the lifecycle. Controversial conservation measures such as the handling of eggs, relocating clutches and application of crab proof barriers, have been applied on an *ad hoc* basis to minimize the high levels of mortality from natural erosion and crab predation. The merit of these practices, such as the translocation of egg clutches and the implementation of these specific barrier methods has never to our knowledge been scientifically tested using controlled experimentation. The first aim of this study was to find the most effective crab barrier method for increasing hatchling recruitment success and minimising predation rates with limited negative consequences. The second aim was to decipher crab density trends in order to offer a proxy for the number of crabs a nest might be exposed to within an area and develop beach profiles along the entire nesting beach to provide an expression of beach morphology to minimise nest loses from erosion. Finally, we analysed 10 years of nesting ecology and hatching success data with the aim of providing nesting and hatching trends to inform management decisions on Cousine Island into the future. Results across this study indicated that management measures can have both positive and negative effects on the nesting ecology and hatchling recruitment success in particular. We found that hawksbill clutches incubating without crab barriers are susceptible to losing on average a third or more eggs to crab predation than those with a crab barrier in place. Nests which were protected with netting had significantly higher hatchling recruitment success rates and nests protected with fencing had significantly lower predation rates than control nests. The use of netting, however, had a substantial cooling effect which can potentially distort natural sex ratios. Results across the entire study indicated that spatial distribution and environmental variations have an effect on embryonic development, hatchling fitness, sex determination, hatching success and the risk of predation. The hatchling recruitment success on Cousine Island was also found to be affected by nest losses each season from seasonal beach erosion. Beach dynamics were also found to be cyclical and we discovered that the nesting beach is prone to higher levels of erosion than accretion which created significant changes to beach width across the season. This study showed that when focusing turtle conservation measures at the nesting site, hatchling recruitment success can be increased by minimising mortality at the egg and hatchling stage. The aim in the long-term is to assist with the analyses of local and global population dynamics, deciphering threats and minimising the threat of extinction.

Key words: Beach morphology • conservation management • crab predation • hatchling recruitment success • hawksbill • nesting ecology

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CONTENTS

List of Figures

List of Tables

CHAPTER 1

Introduction

Sea turtles are the most conservation dependant marine taxa (Hamann *et al.* 2010). This dependency is primarily due to being susceptible to human impacts at every life stage (Hamann *et al.* 2010, Seminoff and Shanker 2008). The poaching of eggs, harvesting of adults for meat, entanglement and ingestion of marine debris and incidental deaths by artisanal and commercial fishing gear, all represent human related causes of sea turtle population declines (Antworth *et al.* 2006, Chaloupka *et al*. 2008, Erdoğan *et al*. 2004, IUCN 2008, Mazaris *et al*. 2009, Mortimer 2002). Six of the seven species of sea turtles are now listed as endangered or critically endangered by the International Union for Conservation of Nature (IUCN) (IUCN 2008). Prior to sea turtle populations being depleted by humans, they occurred in massive numbers and provided extensive benefits to marine ecosystems (Bjorndal and Jackson 2002, King 1982). The ecological role of sea turtles is substantial including roles as hosts for parasites, substrates for epibionts, landscape modifiers, consumers, prey and competitors (Bjorndal and Jackson 2002). The protection and conservation of marine turtle populations from further decline is essential in saving coastal and marine ecosystems from deteriorating into the future (Bjorndal and Jackson 2002).

Conservation measures relating to sea turtles have historically been aimed at the nesting beach (Hamann *et al.* 2010). Conservation of sea turtle nesting beaches goes back to the 1950's where a handful of turtle conservation projects began (Frazier 2002, Hamann *et al.* 2010). These projects have since expanded and today thousands are run worldwide and although most of these projects mean well, they are often not designed appropriately (Mortimer pers. comm. 2013). To develop appropriate sea turtle conservation measures they must be designed around sound information from research on both the biology of the specific turtle species and the human social and economic dynamics involved (Hamann *et al.* 2010).

Various challenges in the conservation of sea turtles relate directly to their biology. The hawksbill turtle is a long-lived species and can take up to 40 years to reach sexual maturity (Crouse 1999). The populations of long-lived species decline more rapidly and recover much slower than short-lived species (Xavier *et al*. 2006). Adding to this challenge is that this delayed sexual maturity can confuse the true status of the population and not reflect reality (Bjorndal *et al.* 1999). Sea turtles also have complex life cycles with different habitats, making them difficult to access. Hatchlings live in pelagic waters, whilst juveniles and adults live in benthic waters (Bjorndal 2017, Gerrodette and Taylor 1999). However reproductive migrations of adults between nesting beaches and feeding grounds have been well documented because of the ease of tagging adult females when they come up on beaches to nest (Antworth *et al.* 2006, Bjorndal *et al*. 1999). Eggs and hatchlings on nesting beaches are also easily available for research purposes and provide an opportunity to measure and manage hatchling recruitment success rates.

The challenge remains as to what constitutes an effective sea turtle conservation strategy. A variety of conservation frameworks and strategies can be effective for promoting population recovery (Hamann *et al*. 2010). In a species which is threatened with extinction, ensuring future success would possibly entail increasing recruitment. Most hawksbill turtle conservation activities currently focus on improving hatchling recruitment by protecting nests and nesting beaches (IUCN 2008). Although sea turtles have a high fecundity it is counterbalanced by a high mortality during the early phases of the life cycle, especially during the egg phase and directly after hatching (Xavier *et al.* 2006). These early stages represent a crucial period when considering the life history of sea turtles, especially if egg and nest mortality is high (Wyneken *et al*. 1988). These periods provide opportunity to apply conservation measures for minimizing mortality at the nest and egg stage; and for counterbalancing overall mortality by improving hatchling recruitment success. Conservation measures are also easiest and most feasible at these stages (Mazaris *et al*. 2009). As reported by Herrera *et al.* (2010) turtle hatchlings represent the future of the species and foster its success by reaching sexual maturity and reproducing. Therefore, the most important consequence of managing sea turtle nests is increased hatchling recruitment success.

Two of the biggest natural threats to sea turtle nests are predation and nest losses from beach erosion and inundation (Mortimer 1999, Whitmore and Dutton 1985). Numerous conservation measures have been applied and tested, with varying levels of success, to minimize these threats and increase hatchling recruitment success rates. Frequently applied conservation measures such as nest relocation, egg handling and hatchling releases have been reported to have adverse effects on hatching success (Eckert and Eckert 1990). However, these conservation practices have also been reported to contribute positively to population trends of sea turtles (Antworth *et al*. 2006; Mazaris *et al*. 2009; Wyneken *et al*. 1988). On Cousine Island in the Seychelles, conservation measures have been applied to minimize nest losses and increase hatchling recruitment success rates of their nesting population of hawksbill turtles, with seemingly positive results.

The hawksbill turtle (*Eretmochelys imbricata*) is listed as Critically Endangered, based on an 80% global decline over the last three generations (105 years) (Ballie *et al*. 1996, Meylan and Donnelley 1999, Ditmer and Stapelton 2012). The species has a circumglobal distribution within the tropical and subtropical Indian, Atlantic and Pacific oceans and nests on beaches in 60 different nations (Groombridge and Luxmoore 1989, Marcovaldi *et al.* 2007, Marquez 1990). Hawksbill turtles have long been considered economic and cultural resources for local communities and have endured the longest history of exploitation of any marine turtle (Meylan and Donnelly 1999). They have been heavily exploited for centuries for their carapace, meat and eggs; however, the harvesting of their shells for the tortoise-shell trade has been the leading cause in severe population declines (Groombridge and Luxmoore 1989, Meylan and Donnelly 1999). Recently hawksbill turtles have come under increasing threat due to their nesting and foraging habitats being destroyed and unregulated (Mortimer 2002). This has led to lower nesting densities throughout most of their range and resulted in the species remaining one of high conservation concern (Blumenthal *et al.* 2009, Groombridge and Luxmoore 1989, Mortimer and Bresson 1999).

The Seychelles still supports significant populations of nesting hawksbill turtles despite years of overexploitation of their raw shell which led to severe declines in the nesting population (Mortimer 2000; Mortimer and Balazs 2000). Conservation to stop this decline initially focused on a compensation and retraining program which provided artisans with financial compensation to give up their turtle shell businesses and sell their current stocks to the government. This program was very successful and led to the government passing a law which offered complete legal protection to sea turtles in the Seychelles (Mortimer 2000). This resulted in a general interest in turtle conservation throughout the Seychelles in the 1990's and therefore the attitude towards turtles changed significantly (Mortimer 2000). The focus on gathering quantitative information on the status of the Seychelles hawksbill population began with the initiation of several sea turtle conservation programs throughout the Seychelles islands. These protected nesting populations started showing signs of increase, most likely in response to protection of females and nests at the nesting beach (Mortimer pers. comm. 2013). However, many stakeholders want to further enhance hatchling recruitment success where possible by minimizing mortality of eggs and hatchlings.

In the inner islands of Seychelles, predation by ghost crabs (*Ocypode* spp. especially *O. cordimana*) and high rates of erosion during the northwest monsoon period, result in high mortality rates of incubating hawksbill egg clutches. Local stakeholders have tried a range of management techniques, including translocation of egg clutches, killing of crabs and the use of barriers to minimise the impact of crabs and increase hatchling recruitment success. However, the use of such practices is controversial, especially given that the merits of most have never been scientifically tested using controlled experimentation.

Conservation measures applied after nesting has taken place entails the manipulation and handling of eggs. This conservation strategy has been reported to be a positive conservation strategy in terms of increasing hatching success (Wyneken *et al*. 1988). Both Ratnaswamy *et al*. (1997) and Antworth *et al*. (2006) also reported that conservation measures, such as handling and moving eggs in order to screen nests from predation, is the most effective way of protecting nests from crab predation whilst also showing limited negative consequences. However, possible negative effects of these measures such as embryo detachment when handling eggs; and increased temperatures leading to the skewing of sex ratios with crab barrier netting, remains a concern.

Given how influential temperature is in determining sexual phenotype, management strategies need to be carefully considered. Thermal changes from applying protective barriers and translocating clutches can have an effect on sea turtle embryo development by disrupting the synchronising of complex physiological processes (Hawkes *et al*. 2009, Fuentes *et al*. 2010, Packard and Packard 1985). Sea turtle embryos only incubate successfully between 25 and 35°C and sex determination is dependent on temperatures during the middle third of incubation (Erdogan *et al*. 2004, Hawkes *et al.* 2007, Mrosovsky 1994). Previous studies have shown that a relatively small difference in temperature (1 – 2 °C) can have a significant effect on the hatching success and the sex ratio of a sea turtle clutch (Fuentes *et al.* 2010, Mrosovsky and Yntema 1980, Whitmore and Dutton 1985). In all sea turtle species, females develop at higher nest temperatures and males at lower nest temperatures (Hawkes *et al*. 2009, Mrosovsky 1994, Marcovaldi *et al*. 1997). With evident warming trends from climate change (Hawkes *et al.* 2009) and with sea turtle sex ratios already being skewed in favour of females (Erdogan *et al.* 2004, Mrosovsky and Provancha 1992, Hanson *et al.* 1998), thermal changes from translocation and effects from crab barrier methods require investigation.

In the process of protecting turtle nests, circumstances can arise where translocating nests is completely necessary to avoid the total loss of eggs. If the mortality of clutches left naturally situated approaches 100%, then conservation measures are necessary (Mortimer 1999). Predictable beach erosion events threaten turtle nests but are completely avoidable with informed conservation measures. Nesting beaches are critical resources for sea turtles and provide a climate space that is appropriate for embryonic development (Ackerman 2017, Antworth *et al*. 2006). Beaches are also naturally dynamic and in constant motion due to wind, tides, sea levels and storms (Adotey *et al.* 2015). However, coastal erosion is reported to be increasing globally causing coastal retreat of an estimated 70% of the world's beaches (Anthony 2005) and ocean level rise from climate change is predicted at 1ft by 2100 (Ackerman 2017, Solomon *et al*. 2007). Documenting the extent of these threats and avoiding their possible effects is obtainable through site specific research and informed management techniques. Translocating clutches to avoid egg losses is an option for management and has been used to improve hatchling recruitment success rates (Lutcavage *et al.* 2017, Mortimer 1999). This, however, entails finding the best suited variables during incubation to maximise hatchling recruitment success.

Various studies have shown that nest location influences the fitness and number of hatchlings that emerge from the nest (Horrocks and Scott 1991, Matsuzawa *et al.* 2002, Zare *et al.* 2012). Particular sites will carry higher risks than others. If clutches are placed too low on the nesting beach, they are at risk of being inundated with saline ocean water which can affect the developing embryos, or it could be washed away completely (Foley *et al.* 2006, McGehee 1990). Being placed too high or within a nesting zone that has a high occupancy of crabs will put it at a high risk of predation (Fowler 1979). All of these situations have an effect on the hatchling recruitment success rates and can limit population recovery.

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1.1 Motivation for this study

This study was motivated by the high losses of incubating hawksbill turtle hatchlings on Cousine Island, Seychelles, despite having intensive management measures in place. Both of the greatest threats to the nests are natural (crab predation and seasonal erosion), however due to the hawksbill turtle being a Critically Endangered species, high intensity management is justified. Therefore, in this study, we investigated what conservation measures and which nesting beach variables are best suited to produce the highest hatchling recruitment success rates and lowest predation rates on Cousine Island, whilst showing limited negative consequences. Additionally, we examined nesting ecology trends on Cousine over a 10-year period in relation to hatchling recruitment and predation and investigated where and to what extent incubating hawksbill nests are threatened by crab predation and seasonal beach erosion on the island.

The main aims of this study were to evaluate whether clutch translocation and crab barriers are sound conservation techniques for protecting a threatened sea turtle species and to analyse predation risk and delineate beach morphology change across the nesting beach. Our hope is to inform current and future conservation efforts and to provide baseline data with which to measure impacts of climate change on the nesting ecology and population over time on Cousine Island and other nesting sites facing similar challenges

1.2 Arrangement of thesis

The thesis is arranged as chapters prepared for publication in relevant peer-reviewed journals, and therefore some repetition in the chapters was unavoidable.

There are three experimental chapters:

Chapter 2. Nesting ecology and hatchling recruitment success of the hawksbill turtle (2004-2014) on Cousine Island, Seychelles.

Chapter 3. The effects of nest management methods on hatchling recruitment success and predation rates of hawksbill turtles on Cousine Island, Seychelles.

Chapter 4. Beach profiling and ghost crab densities on a hawksbill nesting beach in the Seychelles.

Finally, the thesis has a concluding chapter that summarises the various components of this broad study, highlighting components of the nesting ecology and outlining management implications and recommendations for minimising threats to incubating hawksbill turtle nests on Cousine Island.

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CHAPTER 2

Nesting ecology and hatchling recruitment success of the hawksbill turtle (2004 – 2014) on Cousine Island, Seychelles

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Running header: Nesting Ecology of the Hawksbill Turtle

2.1 Abstract

Hawksbill turtle *Eretmochelys imbricata* populations in the Seychelles showed significant declines in the past. They have since recovered and nesting populations are increasing due to increased protection and management intervention. Nesting ecology data on Cousine Island were collected and analysed for the breeding seasons from 2004/2005 to 2013/2014 with the aim of improving management methods. Results indicated that the number of nesting individuals was increasing; however, the clutch frequency was relatively low compared with other study areas. Night-time nesting was increasing, most likely due to increased disturbances across the study period. Clutch sizes decreased significantly across the season with a significant drop in hatchling recruitment success rate with clutch sizes exceeding 200 eggs. Predation rate and infertility rate showed an increasing trend over time. Nests incubating in full sun showed the highest mean hatchling recruitment success rate and had the shortest mean incubation duration. The present study provides insight into the nesting ecology on Cousine Island and will better inform management decisions relating to increasing hatchling recruitment success and minimising threats such as erosion and predation. The aim in the long-term is to assist with the analyses of local and global population dynamics, deciphering threats and minimising the threat of extinction.

Key words: clutch size • incubation • infertility• nest cover • nest translocation • predation

2.2 Introduction

Various challenges in the conservation of sea turtles relate directly to their biology. The hawksbill turtle is a long-lived species and can take up to 40 years to reach sexual maturity (Crouse 1999). The populations of long-lived species decline more rapidly and recover much slower than short-lived species (Xavier *et al*. 2006). Adding to this challenge is that this delayed sexual maturity can confuse the true status of the population and not reflect reality (Bjorndal *et al.* 1999). All species of sea turtles also have complex life cycles with different habitats, making them difficult to access. Hatchlings live in pelagic waters, whilst juveniles and adults live in benthic waters (Bjorndal 2017, Gerrodette and Taylor 1999). However, reproductive migrations of adults between nesting beaches and feeding grounds have been well documented because of the ease of tagging adult females when they come up on beaches to nest (Antworth *et al.* 2006, Bjorndal *et al.* 1999). Eggs and hatchlings on nesting beaches are easily available for research purposes but this makes them vulnerable to disturbances due to the lack of parental care and monitoring needs to be carefully executed (Kamel and Mrosovsky 2005, Mazaris *et al*. 2009).

The hawksbill turtle *Eretmochelys imbricata* has a circumglobal distribution within the tropical and subtropical Indian, Atlantic and Pacific oceans and nests on beaches in 60 different nations (Groombridge and Luxmoore 1989, Marcovaldi *et al.* 2007, Marquez 1990). The species has been heavily exploited for centuries for its carapace, meat and eggs. This has led to lower nesting densities throughout most of its range and is currently a species of conservation concern (Blumenthal *et al.* 2009, Groombridge and Luxmoore 1989, Llamas 2017, Mortimer and Bresson 1999)

In the Seychelles, prior to 1994 when the Government passed legislation protecting all sea turtles, hawksbill turtle populations showed significant declines in line with global trends (Mortimer 1996). However, today Seychelles still supports some of the largest sea turtle populations in the IndoPacific and nesting populations are showing signs of increase, most likely in response to the protection and monitoring of females at the nesting beach (Burt *et al.* 2015, Mortimer 1996). The monitoring of nesting female sea turtles is on-going and extensive throughout the Seychelles islands (Hitchins *et al*. 2004). This has provided opportunities for conservation exchange and regional networking which has assisted in obtaining approximate population sizes (Mortimer 2002).

On Cousin Island, one of the 115 Seychelles islands, breeding biology of the hawksbill turtle has been studied for over 40 years and it has some of the world’s most important hawksbill turtle rookeries (Burt *et al.* 2015, Mortimer 1984, Mortimer and Bresson 1994, Phillips *et al*. 2014, Wood 1986). Cousine Island, where this study was undertaken, lies < 2 km from Cousin Island and supports an annual range of 70–130 hawksbill turtle nests each nesting season (Hitchins *et al.* 2004). The sea turtle monitoring and management programme, which has been operational since 1993, has been controversial due to the relatively high levels of nest manipulation involved to protect clutches and optimise hatchling recruitment success (Mortimer pers. comm. 2014).

The intensive management and relocation of hawksbill turtle clutches has been justified by the threat of natural mortality which is generally high (Hitchens *et al*. 2004). Natural mortality of their egg clutches at Cousine Island are a consequence of a) seasonal and storm-related erosion and deposition cycles which can destroy over 50% of all egg clutches laid, and b) high levels of crab predation concentrated in preferred nesting sites which can claim 90 – 100% of eggs (Chapter 4, Hitchens *et al.,* 2004). Management techniques were increasingly used across the study period (Island staff pers. comm.) and involved the handling and relocation of clutches and the use of net barriers to protect nest sites. Embryo detachment when handling eggs (Mortimer 1999); and increased or decreased sand temperatures leading to the skewing of sex ratios with anti-predator barrier netting (Runemark 2006), are the main concerns resulting from such management interventions. However, according to Mortimer (1999), it should be considered that if mortality of clutches left naturally situated generally approaches 100%, then measures to increase survival of hatchlings is recommended. Establishing a research-based management plan is therefore a priority. This involves establishing the best protocols and factors affecting recruitment success to maximise the output of hawksbill turtle hatchlings when managing nests.

Various studies have shown that nest location influences the fitness and number of turtle hatchlings that emerge from the nest (Horrocks and Scott 1991, Matsuzawa *et al.* 2002, Zare *et al.* 2012). Some nest sites carry higher risks than others. If clutches are placed too low on the nesting beach, they are at risk of being inundated with saline ocean water which can affect the developing embryos (Foley *et al.* 2006, McGehee 1990). Being placed too high, or within a nesting zone that has a high occupancy of crabs will increase risk of predation (Fowler 1979). There is currently a paucity of data on nest-site characteristics, and spatial and temporal patterns in relation to turtle hatchling recruitment success in the region. There was a study on general biometric measurements of nesting turtles conducted on Cousine Island by Hitchens *et al.* (2004) prior to the implementation of management techniques. To adequately manage the risks on Cousine Island, we investigated the nesting ecology of hawksbill turtles and its relationship to their hatchling recruitment success for the breeding seasons from 2004/2005 to 2013/2014 and investigated any noticeable differences in comparative data from the previous study.

Presented in this hawksbill turtle research are data on spatial and temporal patterns, individual hawksbill turtle biometrics, number of nests oviposited, zone locations, nest characteristics, incubation times, clutch sizes, clutch frequency, development rates, hatching success, infertility, mortality and predation rates. Any significant relationship between these data and hatchling recruitment success are also presented. Collecting these data over a long period is critical to monitor the population in terms of population dynamics and to add to data on regional movements. Sea turtles are wide-ranging species, making conservation efforts complicated. Single populations can utilise various habitats for nesting and foraging, even crossing geopolitical boundaries (Antworth *et al*. 2006). We hope that these trends will inform management decisions on Cousine Island and guide turtle programmes regionally and ultimately assist in the long-term survival of the hawksbill turtle.

2.3 Materials and methods

Study site

This study took place on Cousine Island (4.3500°S, 55.6333°E), Republic of Seychelles, over a 10 year period for the annual hawksbill turtle nesting season from 2004\2005 to 2013\2014. The Seychelles is comprised of 115 islands, of which 40 are granitic islands that support 99% of the human population (Mortimer 1984, Mortimer and Bresson 1999). Cousine Island is a granitic island and one of the smallest (26 ha) of the granitic islands at just over 1 km long and 400 m at its widest point (Burt *et al*. 2016). Cousine Island lies 5 km from Praslin Island, the second largest and most populated of the main Seychelles islands (Hill *et al*. 2002) and 1.5 km from Cousin Island which is one of the most important hawksbill turtle rookeries in the world (Hitchens *et al*. 2004, Mortimer 1984, Mortimer and Bresson 1999). Cousine Island is privately owned and runs primarily as a conservation island (Gane and Burt 2016). Shortly after the present owner purchased the island in 1992, an intensive restoration project was implemented because of previous degradation by anthropogenic settlement and agricultural activities in the 1960s (Samways *et al*. 2010). The project focused on habitat restoration for the various endangered species residing or breeding on the island. Part of the project focused on improving nesting habitat for turtles (Samways *et al*. 2010). This involved the removal of exotic *Casuarina equisetifolia* from the beach crest in order to allow native *Scaevola taccada* to establish, facilitating optimal turtle nesting habitat (Samways *et al*. 2010). There is a single beach which runs along the eastern side of the island for approximately 900 m and this provides nesting habitat for female hawksbill turtles to lay their clutches (Hitchins *et al*. 2004). The beach system is highly dynamic (Hitchens *et al.* 2004), and erosion occurs at varying levels of severity across the entire beach throughout the nesting season which coincides with the northwest monsoon (Mortimer and Bresson 1999). The hawksbill turtle nesting season in Seychelles occurs during the summer, with most clutches being laid between September and March. Therefore, each nesting season was represented by a two-year code (e.g. 2004\05 nesting season). The 10-year study period therefore consisted of the nesting seasons from 2004\05 until 2013\14.

Data collection

Field surveys

In the Seychelles, hawksbill turtles emerge from the ocean during the day to nest (Mortimer and Bresson 1999). Consequently, numbers of females, and nests were obtained on daily beach patrols along the entire nesting beach during each breeding season. Based on results from pilot surveys conducted on the island which indicated that most turtles emerged between sunrise at 06h00 up until sunset at 18h00, beach patrols were conducted on an hourly basis from 06h00 until 18h00. Starting at the beginning of the 2004\05 nesting season and continuing through to the end of the 2013\14 nesting season, data were collected between September and March. The 900 m nesting beach was divided into 30 m intervals and demarcated by numerical markers into 30 separate nesting ‘zones’ (1–30).

Beach patrols also recorded all turtle activity (scouting: The process of a female turtle looking for a nest site; emergence/false crawl: A female turtle coming up onto the beach and leaving a visible track but no nest; and nesting: An actual nest with eggs laid). Any turtle which was intercepted during a patrol was processed while laying eggs or when she was returning to the sea. All untagged turtles were given identity tags and indecipherable or broken tags were replaced. Tags were positioned on the second large scale on the trailing proximal edge of each fore-flipper. For this study titanium turtle tags supplied by the Seychelles Islands Foundation were used which are part of a greater tagging project called The Turtle Action Group Seychelles (TAGS). Any additional characteristic marks or features seen on a turtle were also noted.

Any hawksbill turtle nests which were missed between patrols or where the clutches were laid before 06h00, were investigated and processed. Date, time of nesting or emergence, beach zone where the clutch was laid, track length to and from the nesting site and the mean width of female turtle tracks, were all recorded (measuring tapes used were calibrated to 0.1cm). In addition, turtle biometrics such as the curved carapace length (CCL) and curved carapace width (CCW), tag identity number and any identifying features were recorded.

Nest data

The hawksbill turtle nesting season began with the first recorded nest and continued until the last nest occurrence each season from 2004 until 2014. The nest occurrence data collected were used to determine mean nest numbers per month, per season, per time period, per zone, per beach location and per type of exposure. Nest location on the beach was classified as: lower / middle / upper / dune crest / over dune crest. Exposure of the naturally laid clutch and any relocated positions of clutches were classified as: full sun/partial/full shade. All clutches were excavated directly after or within 12 h of the nesting female returning to the sea and nesting data recorded. Eggs were carefully counted while being kept upright and were reburied in the same order as they were laid. After 50 days of incubation, clutches were carefully examined every two days until hatching by carefully digging to the top of the eggs and feeling for hatchlings. After hatching, the hatchlings were given three days to rise to the surface of the nest and were released after hatching data was recorded. Numeration of clutch sizes provided mean number of eggs per month, per nesting season and per female. Any significant changes in composition of clutch sizes over the nesting season were recorded. Distances from sand surface to the top of egg mass and from the sand surface to the bottom of the egg mass were recorded to measure the mean depth of nests. Clutches which were laid in areas in direct threat of serious and predictable erosion patterns were relocated to ‘low risk’ zones. ‘Low risk areas’ were defined from historical beach dynamic records.

Over the study period, there was an observed increase in crab predation rates of hawksbill turtle nests and an increase in actual numbers of crabs (*Ocypode cordimana* and *O. ryderi*) seen on the nesting beach (pers. obs.). If a clutch was laid in an area with a high concentration of crab holes, it was also translocated to a lower risk of predation zone. Lower risk of predation zones were defined from historical observed patterns in crab predation rates across the 30 different nesting zones. Translocation of clutches to avoid high predation areas and seasonal beach erosion was conducted on an *ad hoc* basis since the start of the project, but the use of protective netting was standard practice from 2009 - 2014.

Hatching data

After 50 days of incubation (mean hawksbill turtle incubation time) all clutches were carefully checked every two days until hatching occurred. After hatching the hatchlings were given three days to rise to the surface of the nest and were released after the relevant data were collected. Incubation period was recorded for each clutch, and mean incubation duration in relationship to clutch size analysed. Number of viable hatchlings released, infertile eggs, fertile unhatched eggs, crab predated eggs, naturally dead hatchlings, hatchlings dead from crab predation and any missing eggs were all recorded with definitions below:

1) *Viable hatchlings*: hatchlings which successfully enter the sea
2) *Infertile eggs*: egg contents contain no visible embryo of any size; however, development of the embryo may have ceased before it was visible with a naked eye.
3) *Fertile unhatched eggs*: egg contents contain a visible dead embryo

4) *Crab predated eggs*: eggs showing signs of crab predation
5) *Naturally dead hatchlings*: fully developed, dead hatchlings with no physical signs of crab predation
6) *Crab predated hatchlings*: fully developed, dead hatchlings with physical signs of crab predation

Hawksbill turtle hatchling recruitment success rates and predation rates were recorded across the entire study period. Hatchling recruitment success was defined as the proportion of eggs laid that hatched successfully and produced viable hatchlings which were released to sea (Mazaris *et al*. 2009). Predation rates were defined as the proportion of eggs and hatchlings eaten by crabs in relation to the number of eggs laid. Infertility rates (proportion of infertile eggs per nest) were also examined and significant differences in overall hatchling recruitment success rates were examined when infertile eggs were included and excluded in the equation. Any significant relationships between hatchling recruitment success and clutch size and nest cover were also analysed. Differences in incubation duration between the different nest covers were analysed.

Hawksbill turtle hatchling recruitment success rate, predation rate and infertility rate were determined using the following formulas (Eckert and Eckert 1990):

Hatching Recruitment success rate (%) = (Hatched/ Total Number of eggs)*100

Predation rate (%) = (crab predated eggs & hatchlings/ Total Number of eggs)*100

Infertility rate (%) = (infertile eggs/Total Number of eggs)*100

Data analyses

A large portion of the nesting ecology data were analysed and summarised in the form of means and proportions. All data were analysed using SigmaPlot Version 11. One-way analysis of variance (ANOVA) were used for normally distributed data. For any non-parametric data, Kruskall-Wallis post-hoc tests were run (All Pairwise Multiple Comparison Procedure's Tukey and Dunn's tests). Simple linear regressions were conducted in combination with a Pearson's Correlation Test to examine relationships.

2.4 Results

Field surveys

We recorded a total of 1039 hawksbill turtle nests during the breeding seasons from 2004 - 2014 on Cousine Island. Annual mean number of nests varied between 60 (2006\07) to 230 (2010\11) (Fig. 2.1) with a total mean number of 104 nests (n = 10) across all seasons. The annual mean number of emergences (false crawls) varied between 40 (2011\12) to 301 (2010\11) with a total mean number of 168 emergences (n = 10). The annual mean number of beachings (false crawls & crawls resulting in nests) was 272. A mean ratio of 1:2.5 nests to beachings was seen across all seasons (40% of beachings resulted in nests). The 2011\12 season showed the highest percentage of nests in relation to beachings at 71% the 2006\07 season had the lowest percentage of beachings resulting in nests at 26%.

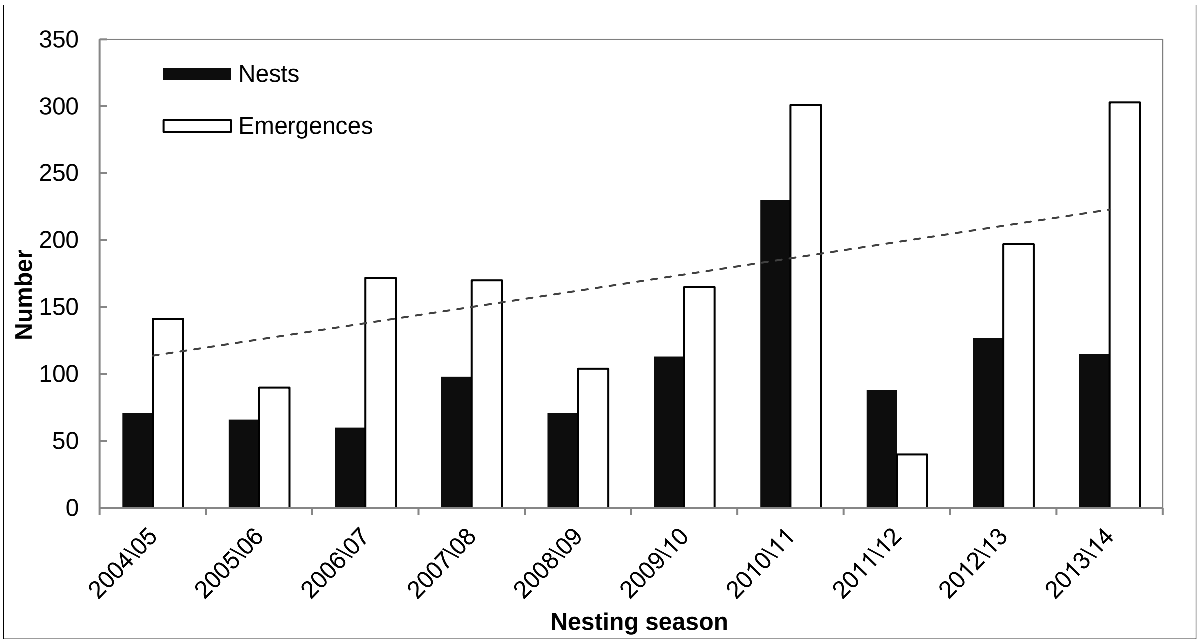

Figure 2.1 The total number of clutches laid and the total number of beach emergences by hawksbill turtles between 2004 and 2014 on Cousine Island.

The mean nesting population of hawksbill turtles per season on Cousine consisted of 60 individuals (recorded on the beach), with an annual mean of 47 actual nesters (Table 2.1). Observers encountered an average of 70.2% of the females nesting. The 2010\11 nesting season had the highest number of individuals nesting (n = 81) while 2008\09 had the lowest number of individuals nesting (n = 30). A total of 169 individuals were tagged and a further 16 individuals re-tagged (existing tags broken or indecipherable). Mean carapace length (notch-to-tip curved carapace length) of female turtles encountered on the beach was 86.4 cm (n = 535, SD = 3.59, range 67-96), and mean carapace width (curved carapace width) was 77.0 cm (n = 534, SD = 3.74, range 63.5-88). Mean track width over the study period was 74.5 cm, but varied between individuals (n = 935, SD = 5.62, range 47.7-106). Track lengths from nesting females were measured up the beach (from water line until female reached an obstacle and turned), across the beach once (track running parallel to water line) and then down track (return track after nesting). Mean track length up the beach over the study period was 28.3 m (n = 393, SD = 16.36, range 1-107), across the beach 8.2 m (n = 393, SD = 10.82, range 0-65) and the down track to water line was 29.2 (n = 393, SD = 17.24, range 1-105).

Table 2.1 Number of individual hawksbill turtles encountered on the beach between 2004 and 2014. Total number and mean number (**$\bar{x}$**) across seasons are shown on the bottom row.

Nesting Season	**Number of individuals**			
	Tagged	*Re-tagged*	*Emerged on beach*	*Nested*
2004/05	Unknown	Unknown	Unknown	Unknown
2005/06	23	1	52	36
2006/07	12	0	55	33
2007/08	Unknown	Unknown	Unknown	38
2008/09	16	1	45	30
2009/10	30	2	69	55
2010/11	34	2	Unknown	81
2011/12	15	3	52	39
2012/13	26	4	81	61
2013/14	13	3	68	41
Total ($\bar{x}$)	**169 (19)**	**16 (2)**	**422 (60)**	**414 (42)**

Nest data

Spatial and temporal patterns - Hawksbill turtle nesting on Cousine Island occurred mostly (97.9% of nests) from October to February, with the greatest number recorded (85.4%) between November and January. The highest nesting month for all 10 breeding seasons was December ($\bar{x}$ = 35.9 nests) (Fig. 2.2). The first day of season varied by 73 days over the 10-year period and seasons ranged from 102 (2006\07) to 206 (2011\12) days ($\bar{x}$ = 162 days ± 36.07) (Table 2.2).

Table 2.2 The total length (no. of days) of each of the nesting seasons including the date of the first and last nest of each season on Cousine Island over a period of 10 years (2004-2014). The 2011\12 nesting season was recorded as the longest season (n = 206 days) and the 2006\07 nesting season as the shortest (n = 102 days).

Year	**First Nest of the season**	**Last nest of the season**	**Total length of season (days)**
2004\05	06-Oct-04	11-Feb-05	**128**
2005\06	30-Sep-05	26-Jan-06	**118**
2006\07	16-Oct-06	26-Jan-07	**102**
2007\08	22-Sep-07	16-Feb-08	**147**
2008\09	13-Sep-08	13-Mar-09	**181**
2009\10	30-Aug-09	03-Mar-10	**185**
2010\11	24-Sep-10	16-Mar-11	**173**
2011\12	04-Aug-11	26-Feb-12	**206**
2012\13	23-Aug-12	26-Feb-13	**187**
2013\14	06-Oct-13	21-Apr-14	**197**

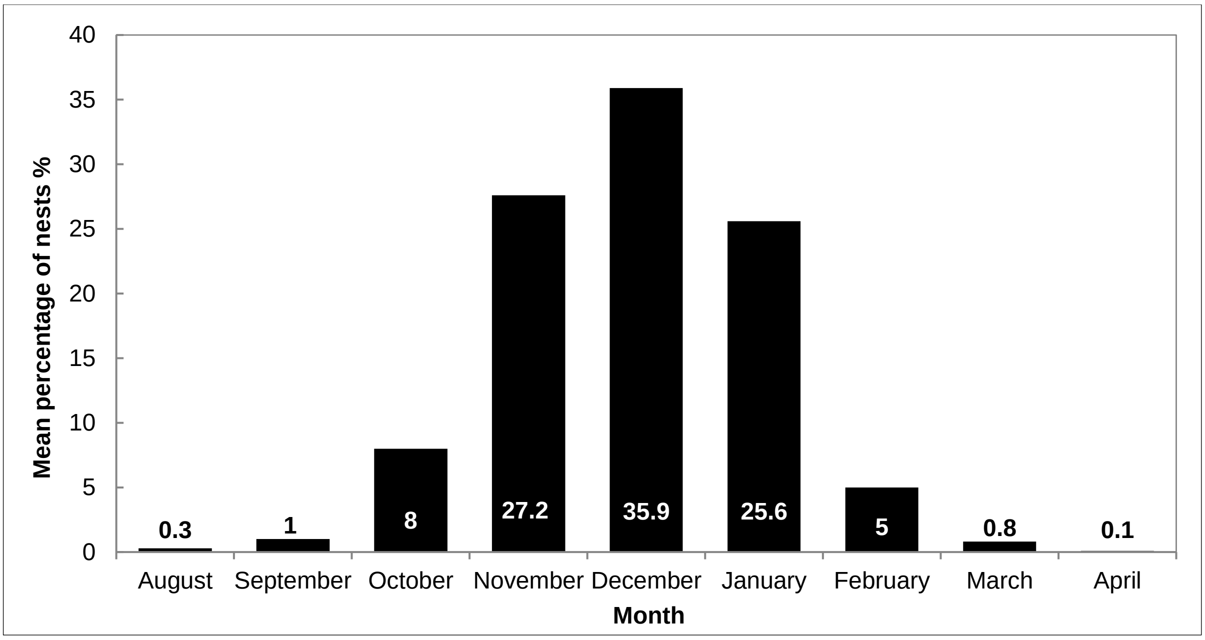

Figure 2.2 Mean percentages of hawksbill turtle nests per month 2004-2014 on Cousine.

Nesting time data from the 2005\06 nesting season to the 2013\14 nesting seasons was analysed. Peak nesting times were found to occur between 06h00 - 09h00 (n = 250, 26%) and 15h00 - 18h00 (n = 248, 25.6%), followed by 09h00 - 12h00 (n = 188, 19.4%) and 12h00 - 15h00 (n = 177, 18.3%). The lowest nesting period occurred at night between 18h00 - 6h00 (n = 105, 10.9%), however an increase in night time nesting was observed over time. A Simple linear regression was carried out to investigate whether there was an increasingly higher number of a turtle clutches being laid after sunset between 6pm and 06h00 over the 10-year study period. A strong positive linear relationship between an increasing number of night nesters and the more recent nesting seasons was seen ($r^2 = 0.56$; $p < 0.05$), which was confirmed with a Pearson’s correlation coefficient of 0.749 (Fig. 2.3).

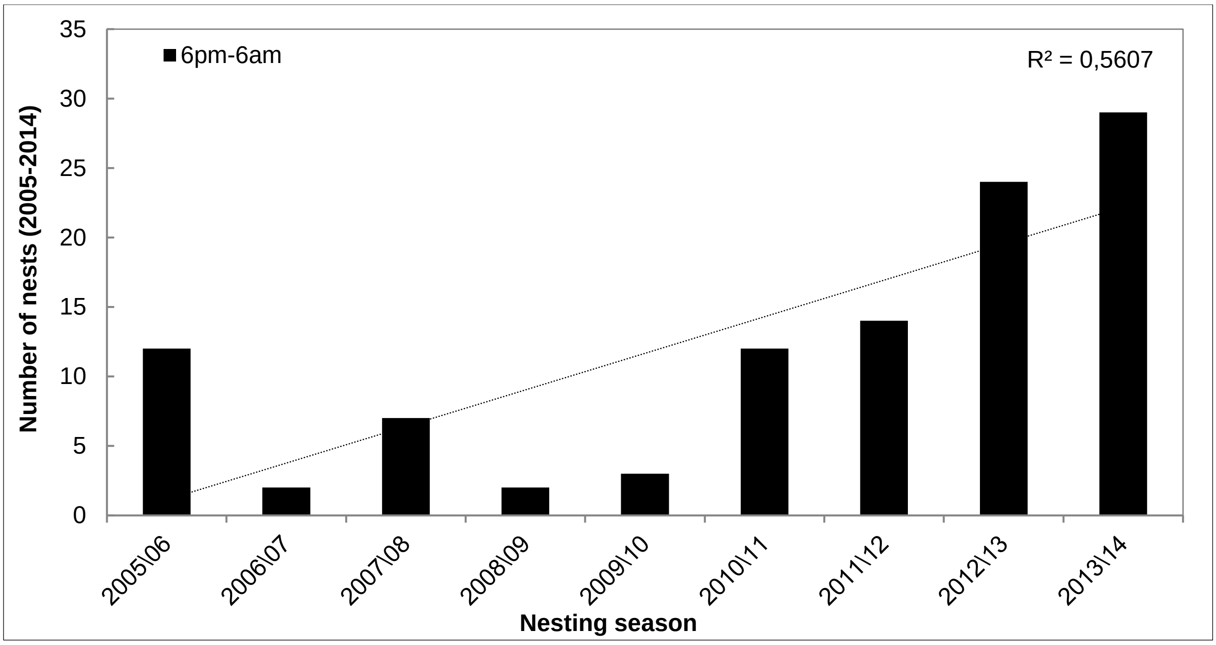

Figure 2.3 Nesting numbers during the 18h00-06h00 time period with the more recent nesting seasons showing a significant positive linear regression ($p = 0.02$). Included is the associated r^2 value of 0.5607 from 2005-2014

Distribution of hawksbill turtle nesting activity along the Cousine Island nesting beach varied between the designated beach zones (zones 0-28). Beach zone 28 was selected most frequently by nesting females ($n = 138$, 13.3% of all nests), followed by beach zone 29 ($n = 118$, 11.4% of all nests). Beach zones two and three had the lowest overall number of nests ($n = 5$ for both) over the 10 year period. When selecting a nesting site, nesting hawksbill turtle females selected the upper beach reaches most frequently during the study period ($n = 326$, 33.8% of all nests) followed by the dune crest ($n = 300$, 31.1% of all nests); over dune crest ($n = 246$, 25.5% of all nests); middle reaches ($n = 81$, 8.4% of all nests) and lower reaches ($n = 13$, 1.4% of all nests). No significant differences in selected beach reaches between the different nesting seasons was seen (ANOVA, $df = 8$, $F = 1.28$, $p = 0.281$).

When selecting a nest site, hawksbill turtle females selected to nest most frequently in full sun ($n = 394$, 41% of all nests) then in partial sun ($n = 296$, 30% of all nests) and then in full shade (n = 280, 29% of all nests) (Fig. 2.4). No significant differences were seen between the different nesting seasons (post-hoc Tukey Test, p > 0.050) except for season 2010\11, which was found to be statistically different from all the other nesting seasons (post-hoc Tukey Test, p < 0.050). The 2010\11 season had the highest number of nests at 230 which would explain the significant difference in numbers with the other seasons.

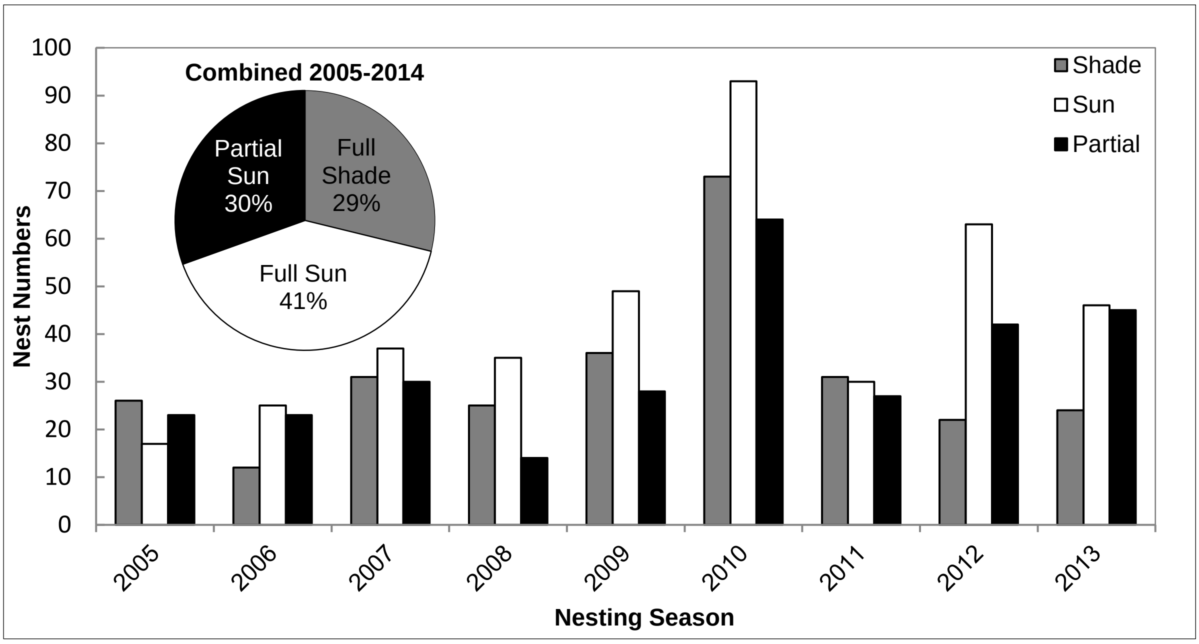

Figure 2.4 The number of clutches per season (2005-2014) which were laid in full shade, full sun or partial sun on Cousine Island. Included is a pie chart showing data of nest cover over the entire 10-year study period. Most clutches were laid in full sun (41%) then partial sun (30%) and then full shade (29%).

Nest characteristics - Distances from sand surface to the top of the egg mass and from the sand surface to the bottom of the egg mass were examined. The mean distance from the sand surface to the top of the egg mass across the entire study period (n = 554) was 31.0 cm (SE ± 0.3) and from the sand surface to the bottom of the egg mass (n = 544) was 50.3 cm (SE ± 0.3). When examining clutch size, the largest and smallest recorded clutch size was seen during the 2004\05 nesting season (n = 276 and n = 12 eggs respectively). The 2006\07 nesting season had the highest mean number of eggs per clutch ($\bar{x}$ = 178.4) and the 2004\05 nesting season had the lowest mean number of eggs per clutch ($\bar{x}$ = 164). The mean clutch size per nest across the entire study period was 169.6 eggs. The largest clutch found over the entire study period was 301 eggs. A Simple linear regression was carried out to investigate whether clutch size decreases as the season progressed. A strong negative linear relationship between clutch size and nesting season progression was seen (r^2 = 0.89; p = < 0.001) which was confirmed with a Pearson's correlation coefficient of -0.943 (Fig. 2.5).

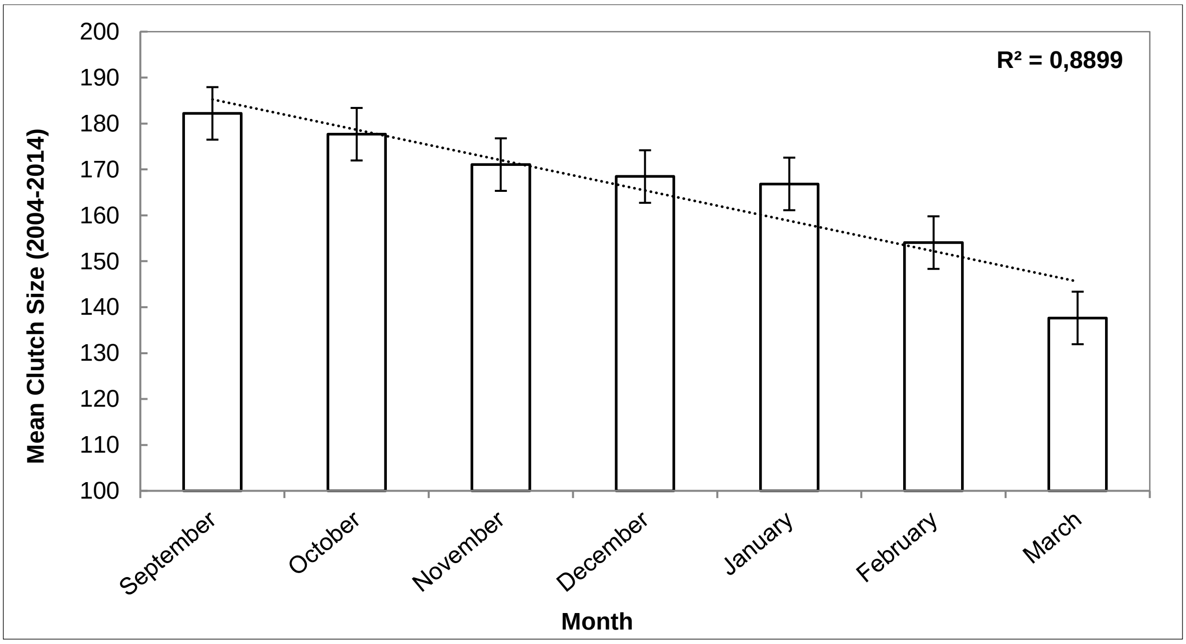

Figure 2.5 The relationship between clutch size and season progression (r^2 = 0.89, p < 0.001).

A total of 427 identifiable (tagged) females came to nest on Cousine Island between the 2005\06 and 2013\14 nesting season giving a mean of 47.4 individuals nesting each season (Table 2.3). When examining nesting frequency across the entire study period, 275 (64.4%) of the 427 females nested once in a season; 90 (21.1%) nested twice in a season, 37 (8.7%) nested three times in a season, 19 (4.5%) nested four times in a season and six (1.4%) nested five times in a season.

Incubation duration in relation to clutch size was examined by dividing clutch sizes into size classes of <1 50 eggs, 150-200eggs and > 200 eggs. Clutches with more than 200 eggs incubated for the longest period ($\bar{x}$ = 58.1 days), followed by 150-200 eggs ($\bar{x}$ = 57.7 days) and clutches with less than 150 eggs ($\bar{x}$ = 57.5) (Fig. 2.6). However, when a Kruskal-Wallis One Way Analysis of Variance on Ranks was run, no significant difference was seen between incubation duration and the three different clutch size classes (Tukey Test post hoc, p = 0.677).

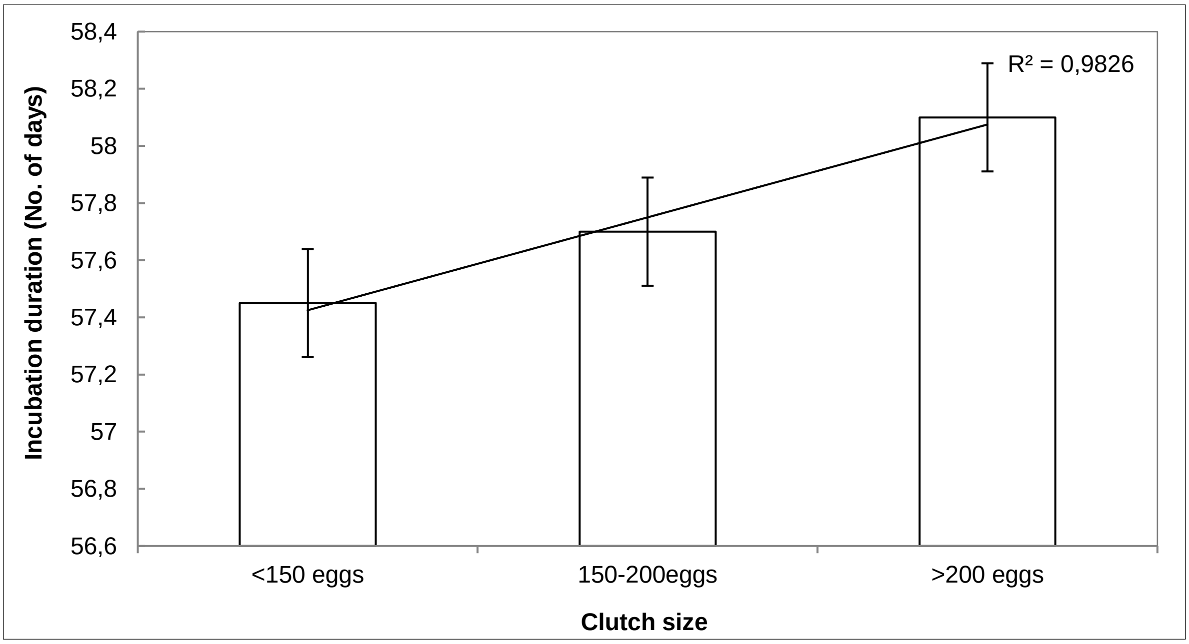

Figure 2.6 Incubation duration in relation to clutch size. Larger clutches (>200 eggs) required on average 1 extra day to incubate fully. A positive linear regression can be seen between an increase in incubation days with larger clutches (r^2 = 0, 98).

Table 2.3 Individual females and nesting frequency during each nesting season on Cousine Island over the study period (2005-2014). A mean of 47.4 individuals nested each season on Cousine Island, with the mean majority of 64.40 % of individuals only nesting once.

Nesting Season	**Nesting frequency**					**Total no. of individuals**
	5 times	4 times	3 times	2 times	1 time	
2004\05	unknown	unknown	unknown	unknown	unknown	unknown
2005\06	0	2	3	8	24	**37**
2006\07	0	1	3	7	26	**37**
2007\08	2	2	5	7	19	**35**
2008\09	0	0	1	7	22	**30**
2009\10	0	4	1	12	37	**54**
2010\11	1	8	6	22	44	**81**
2011\12	1	0	5	6	36	**48**
2012\13	1	0	7	13	40	**61**
2013\14	1	2	6	8	27	**44**
Total no.	**6**	**19**	**37**	**90**	**275**	**427**
Mean ($\bar{x}$)	**0.7**	**2.1**	**4.1**	**10.0**	**30.6**	**47.4**
Percentage (%)	**1.4**	**4.5**	**8.7**	**21.1**	**64.4**	**100**

Hatching data

Hatching data from all hawksbill turtle nests examined on Cousine Island from 2004 - 2014 were recorded and summarised (Table 2.4). An increase of naturally dead hatchlings, hatchlings eaten by crabs, fertile unhatched eggs, infertile eggs and eggs eaten by crabs can be seen over the study period (Appendix 2.1). An increase in the number of hatchlings to sea can be seen from 2004\05 (6935) to 2013\2014 (11124). However, between 2004\05 and 2013\14 on Cousine Island, the hatchling recruitment success rate differed significantly between the nesting seasons (Kruskal-Wallis test, $p < 0.001$). Annual mean hatchling recruitment success rate varied between 46.7% in 2012\13 (n = 127) and 74.5% in 2005\06 (n = 61) (Fig. 2.7a). Mean annual hatchling recruitment success rate from 2004 - 2014 was 60.1% (n = 1031).

Infertility rates and the hatchling recruitment success rates with the exclusion of infertile eggs were examined. Infertility rates differed significantly between the 10 nesting seasons (Kruskal-Wallis test, $p < 0.001$). The annual mean infertility rate varied between 4.9% in 2005\06 (number of eggs = 485) and 30.2% in 2008\09 (number of eggs = 3581) with a total mean infertility rate of 16.8% (SE ± 2.6) across all seasons (Fig. 2.7b). The hatchling recruitment success rate across all seasons including infertility rates (60.1%) differed significantly from the hatchling recruitment success rate when infertility rates were excluded (76.9%) (Kruskal-Wallis test, $p < 0.001$).

Table 2.4 Table of hatching and egg data from 2004-2014 on Cousine Island. The mean hatchling recruitment success rates (HRSR) and predation rates (PR) per season as percentages are included and the total mean for all hatchling and egg data are shown in the bottom row.

		Hatchlings			**Eggs**					
Season	**Total no. of eggs**	**To sea**	**Dead natural**	**Dead crabs**	**Fertile unhatched**	**Infertile**	**Eaten by crabs**	**Missing eggs**	**HRSR**	**PR**
2004\05	12326	6935	228	118	262	747	144	3892	56.2	2.3
2005\06	9840	8092	424	66	169	485	30	574	74.5	1.0
2006\06	9097	2979	340	16	18	340	165	5239	70.5	5.3
2007\08	16283	8486	569	193	578	4426	219	1812	52.3	2.1
2008\09	11878	6400	257	51	419	3851	1	899	53.5	0.4
2009\10	18776	12680	916	253	484	4200	0	243	67.4	1.7
2010\11	37867	25044	1766	611	1133	7217	1606	490	66.3	6.1
2011\12	14314	7845	759	1652	285	1781	898	1094	55.5	17.6
2012\13	21861	10073	595	1068	**448**	2928	4159	2590	46.7	25.0
2013\14	19032	11124	738	457	547	3741	912	1513	58.0	7.6
Mean ($\bar{x}$)	**17127.4**	**9965.8**	**659.2**	**448.5**	**434.3**	**2971.6**	**813.4**	**1834.6**	**60.1**	**6.9**

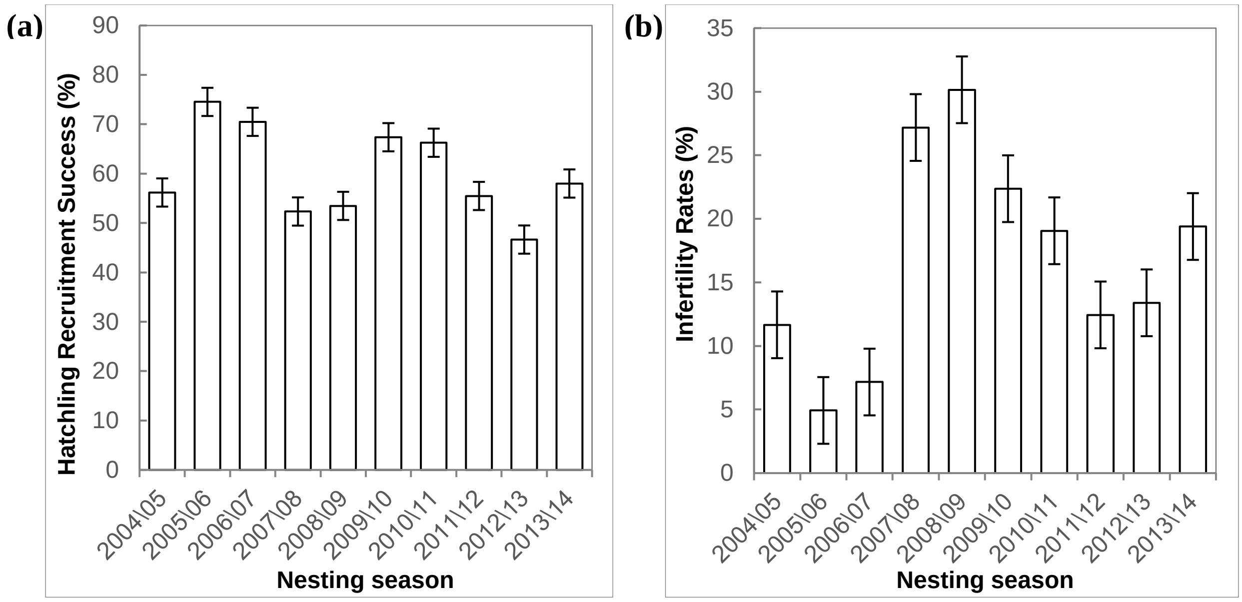

Figure 2.7 The mean annual **(a)** hatchling recruitment success rate from 2004-2014 and **(b)** infertility rate from 2004-2014.

Hawksbill turtle hatchling recruitment success rate in relation to clutch size was examined by dividing clutch sizes into size classes of < 150 eggs, 150-200 eggs and > 200 eggs. Clutches of 150-200 eggs showed the highest hatchling recruitment success rate (n = 576), then clutches of > 150 eggs at 60.4% (n = 265) and clutches with > 200 eggs (n = 115) showed the lowest hatchling recruitment success rate at 56.5%. Size classes had a significant difference on hatchling recruitment success rate (ANOVA, H = 6,641, df = 2, p = 0.036). It was found that only the clutch size classes of 150-200 eggs and > 200 eggs were statistically different from one another (post-hoc Dunn's Test, p = < 0.05). No significant difference was seen between 150-200 eggs and < 150 eggs and between >200 eggs and < 150 eggs (post-hoc Dunn's Test, p = > 0.05).

Hawksbill turtle hatchling recruitment success and incubation duration were examined in relation to the different nest vegetation cover (full sun, partial sun and full shade) (Table 2.5). Annual mean hatchling recruitment success rate for nests incubating in full sun varied between 52.4% (2007\08) and 85.0% (2004\05); in partial sun between 34.6% (2012\13) and

84.0% (2005\06) and in full shade between 34.3% (2008\09) and 80.4% (2005\06). Across the entire study period, hatchling recruitment success rates were significantly different between the different covers (Kruskal-Wallis test, $p = < 0.05$). Hatchling recruitment success in full sun showed the highest mean of 65.1% ($n = 403$), then full shade at 58.0% ($n = 262$) and partial sun at 56.9% ($n = 245$). Annual mean incubation duration for clutches incubating in full sun varied between 54.7 days (2012\13) and 61.2 days (2005\06); in partial sun between 56 days (2006\07) and 65.1 days (2008\09) and in full shade between 56.9 days (2009\10) and 66.1 days (2005\06). Across the entire study period, incubation duration was significantly different between the different nest covers (Kruskal-Wallis test, $p = < 0.05$). Clutches incubating in full shade incubated for the longest period with a mean of 59.8 days ($n = 228$, SE ± 0.8), followed by clutches in partial sun with a mean incubation period of 59.2 days ($n = 244$, SE ± 0.9) and clutches in full sun with a mean incubation period of 57.8 days ($n = 379$, SE ± 0.6).

Between 2004\05 and 2013\14, the predation rates of hawksbill turtle nests differed significantly between the respective nesting seasons (Dunn's post-hoc Test, $p < 0.001$). Mean annual predation rate varied between 0.4% in 2008\09 ($n = 98$) and 25.0% in 2012\13 ($n = 128$) (Fig. 2.8). Mean annual predation rate from 2005-2014 was 6.9% ($n = 986$, SE ± 0.7). A positive linear regression showed that predation rate was increasing over time ($r^2 = 0.4296$).

Table 2.5 The mean hatchling recruitment success rate and incubation duration in clutches which incubated in the different covers (full sun, partial sun and full shade) across the entire study period on Cousine Island (2004-2014). Hatchling recruitment success rate values are represented as a mean percentage and incubation duration values are represented as a mean number of days. Both include the associated sample sizes (n).

	Hatchling recruitment success rates% (n)				**Incubation Duration, days (n)**			
Season	Full Sun	Partial Sun	Full Shade	p-value	Full Sun	Partial Sun	Full Shade	p-value
2004\05	-	-	-	-	-	-	-	-
2005\06	85.0 (39)	84.0 (7)	80.4 (8)	0.901	61.4 (40)	62.9 (9)	66.1 (8)	0.142
2006\07	76.7 (14)	62.0 (6)	58.6 (3)	0.58	57.1 (13)	56.0 (7)	57.8 (6)	0.829
2007\08	52.4 (37)	53.3 (30)	51.3 (30)	0.759	60.2 (35)	58.8 (30)	59.1 (29)	0.247
2008\09	68.5 (34)	47.2 (14)	34.3 (22)	**<0.001**	59.7 (34)	65.1 (12)	63.4 (17)	**<0.001**
2009\10	65.9 (49)	64.6 (28)	71.6 (36)	0.611	56.2 (47)	58.3 (27)	56.9 (36)	0.032
2010\11	65.7 (93)	62.3 (65)	70.7 (73)	0.245	58.7 (91)	58.8 (60)	58.4 (70)	0.417
2011\12	54.0 (28)	49.5 (26)	54.0 (28)	0.686	56.9 (21)	58.7 (23)	59.5 (22)	0.951
2012\13	[a] 54.2 (63)	[a]34.6 (41)	46.9 (22)	[a]**<0.05**	54.7 (52)	56.9 (31)	58.1 (17)	0.203
2013\14	[a]63.6 (46)	[a]54,27 (45)	54,32 (23)	0.341	55.7 (46)	57.2 (45)	58.8 (23)	**0.031**
Mean	[a]**65.1**	[a]**56.9**	**58.0**	[a]**<0.05**	*57.8	**59.2**	*59.8	*<0.05

[a] Significantly different between full sun & partial sun, * Significantly different between full sun and full shade according to non-parametric post-hoc Dunn's Comparison Procedure

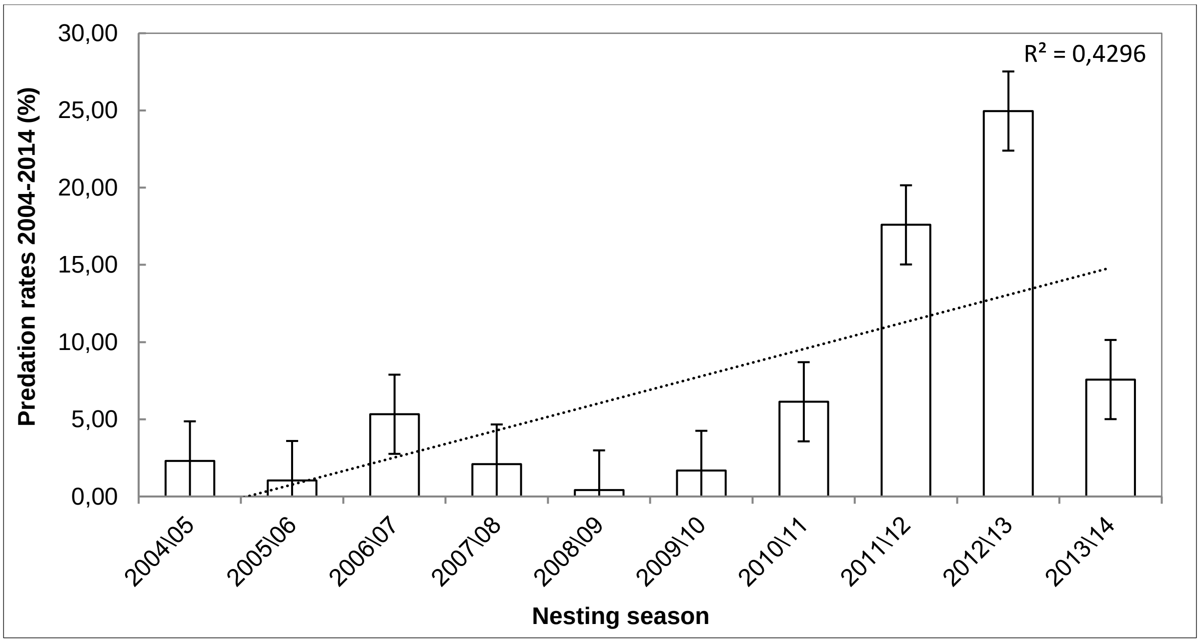

Figure 2.8 The predation rate (%) per season on Cousine Island from 2004-2014.

2.5 Discussion

The length of the nesting season on Cousine Island runs on average for 162.4 days. The season is consistent from year to year with 98% of clutches being laid between October and February, with a peak 85% of clutches between November and January. These results correspond to the nesting season on the neighbouring island of Cousin (Mortimer and Bresson 1999); however nesting peaks were slightly less condensed than on Cousine which showed that 88.0% of nesting occurred between October and February and 75.8% from the end of October to the end of January. The hawksbill turtle nesting season of the inner islands in Seychelles coincides with the northwest monsoon rainy season. According to a study done by Garnett in 1978 on Cousin Island, successful nest construction correlated positively to rainfall which could explain the consistent nest peaks during the monsoon period. Any periodic changes in nesting can therefore indicate changes in climate which could affect hatchling recruitment success on Cousine.

When investigating field data, results showed that the mean number of hawksbill turtle nests and beach emergences varied across all seasons. However, it should be noted that both showed a general increase across the entire study period. Since the number of nests and emergences are linked to the number of individual nesting females (Schroeder *et al*. 2003), we can conclude that the number of nesting hawksbill turtles coming to nest on Cousine Island is increasing. Our results showed that currently the mean nesting population on Cousine is ~60 individuals compared with 36 individuals in the study done by Hitchens *et al.* (2004) showing the nesting population has increased significantly. Emerging females nested on average 40% of the time. These results however, varied substantially across all seasons from as low 26% to a high of 71%. Nesting success has been connected to the skill of the individual and if the individual is a neophyte or a first-time nester to the island, nesting success would be less likely (Hitchens *et al.* 2006). Many environmental factors or anthropogenic disturbances can also influence nesting behaviour (Horrocks and Scott 1991) and further studies are recommended on Cousine to better explain the high variability which was seen across seasons.

Across the entire study period, 89.2% of hawksbill turtle clutches were laid during daylight hours which was similar to results on daylight nesting recorded on the neighbouring island of Cousin at 85% (Mortimer and Bresson 1999). However, our study showed that there was a significant increase in night time nesting as the study progressed. By the last nesting season in the study (2013\14) a total of 25% of clutches were being laid at night-time between 18h00-06h00. Day time nesting for hawksbill turtles is most prevalent in the western Indian Ocean, especially in the Seychelles (Mortimer and Bresson 1999). Hawksbill turtles in other parts of the world typically nest at night (Witzell 1983). An increase in nocturnal nesting could be an indication of increasing disturbances during the daytime possibly by predators or anthropogenic disturbances. The construction of two large buildings close to the nesting beach on Cousine began in 2011 and could have influenced this change of behaviour. Results could also be an indication of the impacts of climate change and changing conditions which have been shown to change emergence patterns (Adam *et al*. 2007).

Hawksbill turtles selected the upper reaches on the beach most frequently to nest in the present study. Horrocks and Scott (1991) reported that the length of beach crawl would be an important factor influencing where a turtle would nest. Cousine has a relatively narrow beach in comparison with other nesting beaches and would be easier for a smaller sized turtle like the hawksbill turtle to reach. The energy expenditure to get to the upper reaches would therefore be minimal in comparison with leatherback turtles (which are substantially larger) which nest predominantly in the lower reaches (Caut *et al.* 2006). Various biological, chemical and physical factors have been reported to influence a successful nesting site (Mortimer 1990). The different beach reaches exude different factors and must be considered when managing nest translocations. Moisture (Mortimer 1990); oxygen and salinity (Ackerman 1980); sand texture (Mortimer 1990) and ambient temperature (Mrosovsky *et al.* 1995) can influence the success of a turtle nest. Further research is recommended on these variables in relation to hawksbill turtle hatchling recruitment success to better inform management on Cousine Island.

In terms of clutch frequency, hawksbill turtles on the granitic islands are reported to deposit between four and five egg clutches a season (Mortimer and Bresson 1999). Clutch frequency on Cousine was found to be substantially lower than this with one to two clutches a season. It was also lower than the two to three nestings reported for hawksbill turtles in Oman (Ross 1981) and in Costa Rica (Bjorndal *et al.* 1985). Females could be selecting Cousin as their primary nesting site and using Cousine as a secondary nesting site when conditions are unfavourable. Although Cousin is less than 1 km away, at least four times more hawksbill turtle nests are recorded there each season (Mortimer pers. comms. 2013), which indicates that nesting conditions are more favourable on Cousin. However, the lower average clutch frequencies on Cousine could be an indication of increased levels of recruitment, which in other recovering populations are reported to show similar low clutch frequencies (Beggs *et al.* 2007).

We examined hawksbill turtles’ natural nest dimensions for nest translocations. When translocating nests, original nests microhabitat should be resembled as closely as possible (Mortimer 1999). Mean nest depth from the surface of the sand to the bottom of the nest cavity was 50.3 cm which resembles other mean nest depths from similar studies (Frazier 1984, Hitchens *et al.* 2004). It is important for managers to mimic mean nests depths on Cousine and adjust for clutch size and the inclusion of netting if applied. Clutch size varied within and across seasons with an overall annual mean of 169.6 eggs. Similar variations in hawksbill clutch sizes have been reported in other studies (Antworth *et al.* 2006, Wood 1986). Variations could be a result of variations in body size (Gibbons *et al.* 1982) or resource availability (Broderick *et al.* 2003). According to Wood (1986) and Garnett (1978) clutch size will vary within-season and generally decreases from a female's first clutch to her last clutch. Our results showed significant decreases in clutch size from the beginning of the season to the end of the season with an annual mean clutch size in September of 182.2 eggs and then in March 137.7 eggs.

Hawksbill turtle incubation time in relation to clutch size showed no statistically significant differences in the present study. Incubation time is an important consideration on Cousine as nests are generally under threat from beach erosion and inundation. The movement of beach erosion and deposition from south beach in the beginning of the season to north beach nearing the end of the season is predictable (Hitchens pers. comm. 2013). The area where threatened nests are translocated to should therefore not become under threat from erosion later in the incubation period and adjustments should be made according to erosion trends.

Hawksbill turtle hatchling recruitment success rate varied among seasons in the present study. The 2005\06 nesting season had an unusually high hatchling recruitment success rate of 74.5%, and so it was the only season which differed significantly from the other seasons in terms of hatchling recruitment success rate. Overall annual hatchling recruitment success rate (60.1%) showed a slight decrease from previously reported hatching success on Cousine of

64.3% (Hitchens *et al*. 2004). Management techniques, such as the *ad hoc* translocation and netting of nests which were implemented during the study period, have therefore had no positive affect on the hatchling recruitment success rate overall. However, the annual mean predation rate of 6.9% was significantly lower than predation losses of 33.9% which were reported on Cousine between 1995 and 1999 (Hitchens *et al*. 2004). There was an observed increase in crab numbers over the study period which is why management started using techniques such as netting nests and translocating to perceived ‘low risk’ of predation areas/zones. If the decline in predation rate occurred whilst crab numbers increased, then the use of netting and translocation is considered extremely effective. However, without evidence to show that predator numbers have increased whilst predation rate decreased, it cannot be assumed that netting and translocation were the reasons for a decreased predation rate.

When examining hawksbill turtle hatchling recruitment success rate in comparison to the reported hatchling recruitment success in the study done by Hitchens *et al.* (2004), increased infertility rates could possibly account for the decrease. Results from this study showed that infertile egg numbers increased across the study period. Additionally, results showed that when the hatchling recruitment success included infertile eggs it differed significantly from when infertile eggs were excluded, emphasising how infertility can affect hatchling recruitment success rate figures. When examining hawksbill turtle clutch size in relation to their hatchling recruitment success, a significant drop in the hatchling recruitment success rate was seen when clutch sizes exceeded 200 eggs. Before reaching the 200-egg mark, size had no effect on success. Ditmer and Stapleton (2012), however, found a positive effect of clutch size on hatch success on clutches no larger than 185 eggs, while Mortimer (1990) found no significant relationship between clutch size and hatch success. The significant drop in hatchling recruitment success rate in the largest clutches on Cousine could be an effect of predator netting used which was standard in size and could have limited the movement of hatchlings and caused mortalities from compaction which would have resembled natural deaths. When examining hatching data, an increase in the proportion of naturally dead hatchlings over the entire study period was seen. There was also an increase in the proportion of hatchlings eaten by crabs, infertile eggs, eggs eaten by crabs and fertile unhatched eggs in relation to the recorded number of 'missing eggs'. The number of 'missing eggs' decreased over the study period which could be the result of data collection techniques and hatching classifications improving.

We examined nest cover in relation to hatchling recruitment success and incubation duration. Hawksbill turtles are unique in that they are one of the only turtle species which nests near or under vegetation (Ditmer and Stapleton 2012). Studies have shown than vegetation plays an important role in turtle nest site selection (Ditmer and Stapleton 2012, Ficetola 2007), and influences hatching success and the sex ratio of a clutch (Godley *et al.* 2002, Wibbels 2003). Results showed that both hatchling recruitment success and incubation duration were significantly affected by cover in the present study. The hatchling recruitment success rate was highest in full sun which was consistent with a study done by Ditmer and Stapleton (2012) where they reported that hatching success increased with less vegetative cover and that full sun nests resulted in a 7.2% higher hatching success. In the present study the majority of clutches were laid in full sun which was contrary to other studies which showed a nesting preference for vegetation cover (Horrocks and Scott 1991), and just below vegetation (Schoefield 1996). Incubation duration is the shortest in full sun and was significantly shorter than nests incubating in partial shade and full shade. Incubation durations are directly related to ambient temperature (Mrosovsky *et al*. 1995) with higher temperatures increasing metabolic rates of embryos which decreases incubation time (Lima *et al.* 2012). In terms of managing the movement of clutches to the best possible sites, climate change will need to be considered when translocating nests as it has been reported to affect incubation periods (Marcovaldi and Laurent 1996).

In conclusion, our results provide valuable insight into the hawksbill turtles nesting ecology on Cousine Island and illustrate the complexities of hatchling recruitment and conservation management. Their nesting ecology on Cousine showed unique spatial and temporal patterns and was variable from season to season. Hatchling recruitment success was affected by several environmental and ecological factors and was positively influenced by management techniques, especially if the main objective of the management protocol is to maximise the output of hatchlings. The nesting population is not isolated to just one island and increasing communication between islands is advised to assist with analysing population dynamics, deciphering threats and minimising the threat of extinction in the long term.

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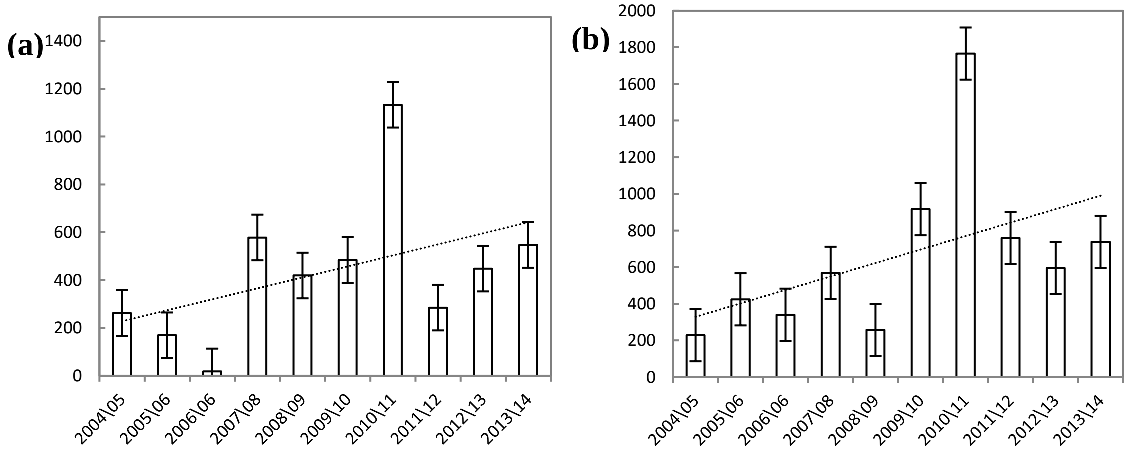
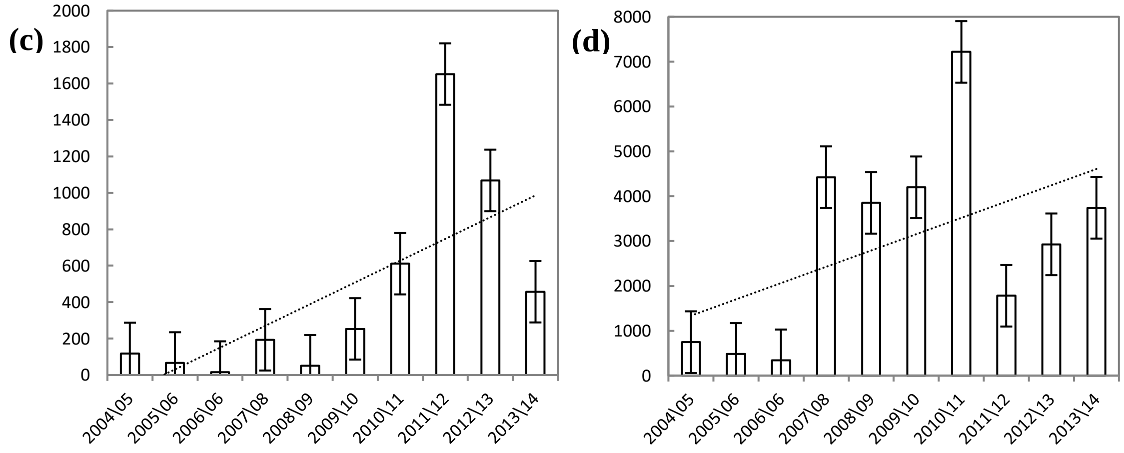
2.8 Appendix

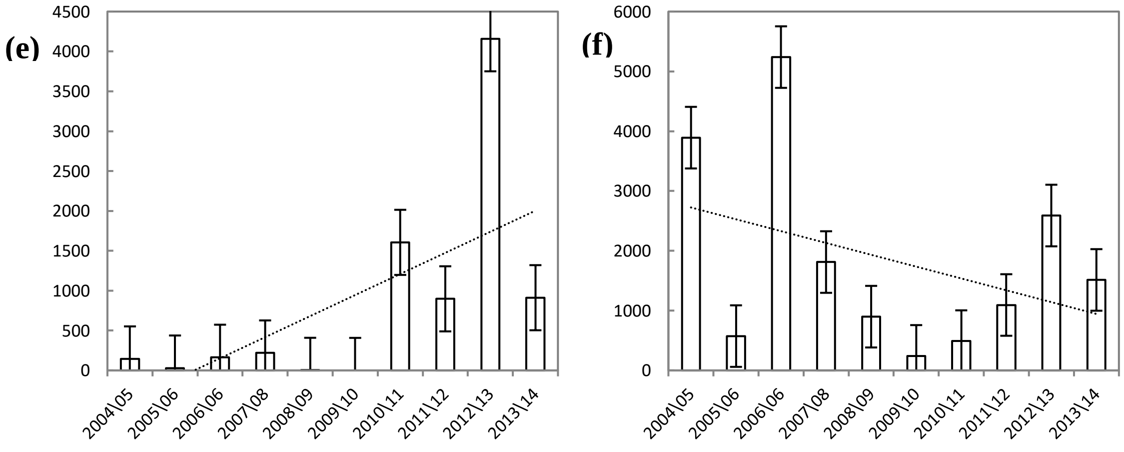
Appendix 2.1: Summaries of all hatching data collected over the 10-year study period (2004-2014) on Cousine Island. Graphs a, b, c, d and e show increasing trends towards the end of the study period. Graph f. (number of missing eggs) is the only graph with a slight decreasing trend from the beginning of the study period to the end of the study period.



Number of fertile unhatched eggs **Number of dead hatchlings in nest**



Number of crab eaten hatchlings **Number infertile eggs**



Number of eggs eaten by crabs **Number of missing eggs**

CHAPTER 3

The effects of nest management methods on hatchling recruitment success and predation rates of hawksbill turtles on Cousine Island, Seychelles

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Running header: Nest management methods effects on hatchling recruitment success

3.1 Abstract

Globally sea turtle populations have declined and are of conservation concern. We investigated the effects of nest management methods on hatchling recruitment success and predation rates of hawksbill turtles *Eretmochelys imbricata* on Cousine Island, Seychelles. We determined the effectiveness of two different crab barrier methods on hatchling recruitment success and predation rates and examined the relative influence of nest site cover (full sun, partial sun and full shade) and location ('high risk' or 'low risk' of predation zone). We also examined temperature disparity between netted and control nests to estimate potential effects on sex ratios and measured typical incubating medium temperatures in different nesting habitats. We compared data from 40 netted, 40 fenced and 40 control nests during the 2014\2015 breeding season. Nests protected with netting had significantly higher hatchling recruitment success rates and nests protected with fencing had significantly lowest predation rates than control nests. Clutches which incubated in full sun displayed the highest hatchling recruitment success rates (netted - 72.0%, fenced - 66.6%, control - 49.8%) while clutches which incubated in full shade had the highest predation rates (netted - 21.6%, fenced - 18.3%, control - 31.8%). Nest temperatures significantly differed between netted and control nests with netting used to protect nests having a substantial cooling effect. Nestling sex ratios of natural nests were skewed towards females and netted nests skewed towards males. With climate change and increasing ambient temperatures imminent, conservation actions involving the manipulation of nests and the use of crab barriers will need to be carefully considered and managed to increase the future success of nesting sea turtle populations.

Key words: ghost crab • hawksbill turtle • hatchling recruitment success • predation barrier • pivotal temperature • sex ratio

3.2 Introduction

Hawksbill sea turtle (*Eretmochelys imbricata*) populations have declined globally by 80% during the past three generations (105 years) (Ditmer and Stapleton, 2012; Meylan and Donnelly, 1999). This led to the species being listed as Critically Endangered in 1996 by the IUCN (International Union for the Conservation of Nature) and becoming dependant on conservation management for their survival (Baillie and Groombridge, 1996). Population declines can be attributed to: nesting and foraging habitats being destroyed and unregulated (Mortimer, 2002; Wyneken *et al*., 1988); incidental deaths by artisanal and commercial fishing gear (Erdogan *et al*., 2004; Mortimer, 2002); human exploitation of eggs and meat (Chaloupka *et al*., 2008, Mazaris *et al*., 2009; Mortimer, 2002) and an increase in egg predation rates caused by human disturbance on nesting beaches (Antworth *et al*., 2006; Mrosovsky *et al.*, 1995).

Numerous conservation methods have been applied, with varying levels of success, to minimise threats and increase population numbers of sea turtles. Conservation actions which are undertaken at the nest level and at the nesting site have generally led to an increase in hatchling recruitment success and increased nesting populations of sea turtles (Bjorndal *et al*., 1999; Marcovaldi and Chaloupka, 2007; Mazaris *et al*., 2009; Chaloupka *et al*., 2008; Wyneken *et al.*, 1988). Although sea turtles have a high fecundity it is counterbalanced by a high mortality during the early phases of the life cycle, especially during the egg phase and directly after hatching (Xavier *et al.,* 2006). These early stages represent a crucial period when considering the life history of sea turtles, especially if egg predation is high (Wyneken *et al*., 1988). This presents an opportunity to apply conservation actions to minimise mortality at the egg stage and counterbalance overall mortality by ultimately improving hatchling recruitment success. Conservation actions are also easiest and most feasible at these stages (Mazaris *et al*., 2009).

High levels of predation at the egg stage can affect an entire sea turtle population and can slow down the recovery of a threatened population (Barton and Roth, 2008; Leighton *et al.*, 2011). Predation caused by ghost crabs *Ocypode* spp. is one of the most serious observed threats to incubating sea turtle nests on small oceanic islands (Marco *et al.*, 2015). The translocation of egg clutches, the use of crab-proof barriers, hatcheries and the controlled release of hatchlings are a few of the techniques that have been used to minimise crab predation rates and increase hatchling recruitment success of incubating sea turtle eggs (Barton and Roth, 2008; Bjorndal, 1995; Ehrenfeld, 1995; Hitchins *et al.*, 2004). Turtle management programmes faced with high levels of predation would need to rely on clutch translocation as their main management tool or use some barrier method (Bjorndal, 1995; Boulon, 1999). The use of these management techniques is controversial, especially given that the merits of most have not been tested using controlled experimentation.

Thermal changes from applying protective barriers and moving clutches can have an effect on sea turtle embryo development by disrupting the synchronising of complex physiological processes (Hawkes *et al.*, 2009; Fuentes *et al.*, 2010; Packard and Packard, 1985). Sea turtle embryos only incubate successfully between 25 and 35°C and sex determination is dependent on temperatures during the middle third of incubation (Erdogan *et al.*, 2004; Hawkes *et al.*, 2007; Mrosovsky, 1994). Previous studies have shown that a relatively small difference in temperature (1 – 2 °C) can have a significant effect on the hatching success and the sex ratio of a sea turtle clutch (Fuentes *et al.*, 2010; Mrosovsky and Yntema, 1980; Whitmore and Dutton, 1985). In all sea turtle species, females develop at higher nest temperatures and males at lower nest temperatures (Hawkes *et al.*, 2009; Mrosovsky *et al.*, 1994; Marcovaldi *et al.*, 2007). With evident warming trends from climate change (Hawkes *et al.*, 2009) and with sea turtle sex ratios already being skewed in favour of females (Erdogan *et al.*, 2004; Mrosovsky and Provancha, 1992; Hanson *et al.,* 1998), thermal changes from translocation and effects from crab barrier methods require investigation.

Relatively few studies have compared the effectiveness of different crab barrier methods effects on sea turtle hatchling recruitment success, predation rates and sex ratios, and none have been conducted in the Seychelles. The nesting population of hawksbill sea turtles on Cousine Island, Seychelles have crab predation rates of 90 - 100% in preferred nesting areas so clutches are frequently translocated to avoid crab predation and seasonal beach erosion (Chapter 4, Hitchens *et al.,* 2004). A turtle monitoring and management programme started on Cousine in 1991 (Hitchens *et al.,* 2004) and continues annually. Translocation of clutches to avoid high predation areas and seasonal beach erosion was conducted on an *ad hoc* basis since the start of the programme, but the use of protective netting became standard practice from 2009 - 2014. The nature and length of the turtle monitoring programme on Cousine provided us with an opportunity to test the effects of two different crab barrier methods (netted and fenced) on sea turtle hatchling recruitment success and predation rates in the present study. We also examined temperature disparity between netted and non-netted nests and between the incubating mediums of typical nesting habitats (full sun, partial sun and shade) to estimate potential effects on sex ratios. This research was conducted to inform future conservation actions involving translocating nests and mitigating climate change effects on sex ratios. Our main aim was to evaluate whether nest translocation and crab barriers are sound conservation techniques for protecting a threatened sea turtle species such as the hawksbill turtle. It was hoped that this would inform current and future conservation efforts at Cousine Island and other nesting sites facing similar challenges. We predicted that sea turtle nests surrounded by crab barriers would yield higher rates of hatchling recruitment and minimize predation. We also predicted that crab barriers will increase or decrease incubation temperatures, but not to the extent that sex ratios are affected.

3.3 Methods

3.3.1 Study site

This study was conducted on Cousine Island, Seychelles (longitude 04°21′ 41″ S, latitude 55°38′ 51 ″ E) during the 2014/2015 hawksbill turtle nesting season (Fig. 3.1). Cousine Island (26 ha) is one of the smallest granitic islands in the Seychelles Archipelago. It is just over 1 km long, 400 m wide and 70 m at its highest point (Samways *et al.,* 2010). The island is privately owned and runs primarily as a conservation island (Gane and Burt, 2016). The single beach on the island is approximately 900 m in length and supports an average of 70 - 130 hawksbill turtle nests each nesting season (Hitchens *et al.,* 2006). The back-shore nesting habitat is variable along the entire length of the beach, with dense to sparse areas of *Scaevola sericea*, to areas shaded entirely by *Hernandia nymphaeifolia* forest and to areas with steep, un-vegetated sand banks. The extremes of nesting habitat can be attributed to the nesting season coinciding with the northwest monsoon (Mortimer and Bresson, 1999). The northwest monsoon has predictable heavy rains and storms, which create a highly dynamic beach system on Cousine. The beach also experiences predictable erosion on South Beach from the start of the nesting season which slowly gets deposited in a northward direction as the season progresses (Chapter 4). During the peak hawksbill turtle nesting season, the northern beach is the most highly exposed and from this point to the end of north beach there is the highest concentration of crabs (De Bruyn, 2002).

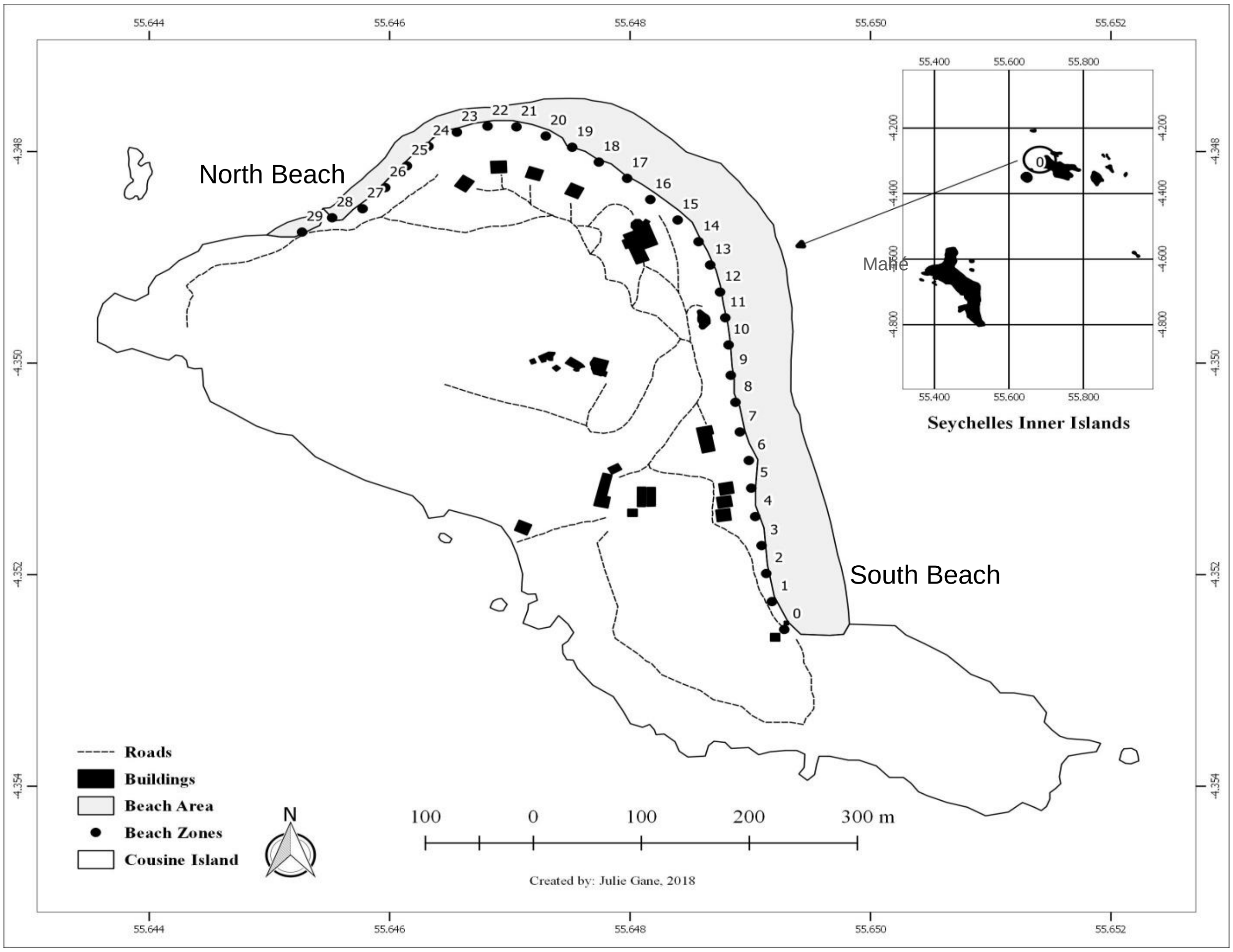

Figure 3.1 Locational map of Cousine Island within the Seychelles Inner Islands. Included are beach zones 0-29 running from South Beach to North Beach.

3.3.2 Hatchling recruitment success and predation rates

Data were collected from the 10th October 2014, with the first hawksbill turtle nest for the season and continued until the 90th nest on the 30th January 2015. Hawksbill turtles typically nest at night in other parts of the world (Witzell, 1983); however, they nest predominantly during the day in the western Indian Ocean, especially in the Seychelles (Mortimer and Bresson, 1999). Beach patrols, which covered the entire length of the beach, were therefore done on the hour from 06h00 until 18h00. The

900 m beach was divided into 30 nesting zones, each 30 m in length and designated with a visible beach marker. Each of the 30 zones were distinguished into either ‘a high risk of predation zone’ (zones: 18 and 25 - 29) or ‘a low risk of predation zone’ (zones: 1 - 17, 19 - 24) based on historic hatching success data from the previous 10 years (Cousine Island, unpublished data; high risk of predation zones - mean hatching success of 55% or lower; low risk of predation zones - mean hatching success of 56% or higher). Zone 0 was excluded from the experiment because of predictable annual flooding of the zone which occurs half way through the nesting season.

Protective netting (black nursery 40 % shade cloth) and protective fencing (black plastic fencing with 1 cm x 1 cm openings) were used as barrier methods against nest predation around selected hawksbill turtle nests. Fencing with small openings was selected to minimise the chance of hatchlings getting stuck in the openings after hatching. Two experiments were conducted; one which used entire clutches and one which used split clutches. Clutches were split in half to eliminate some of the variability relating to biological differences between individual females (J. Mortimer pers. comm., 2014). Nests 1-30 were split, equalling 60 half clutches of which 20 were protected with netting, 20 with fencing and 20 without either. All 60 half clutches were translocated and split equally among the ‘high predation risk zones’. Nests 31-90 were kept whole and translocated evenly among the high and low predation risk zones. Therefore 10 netted, 10 fenced and 10 control nests were placed in each predation risk zone equalling a total of 60 full clutch nests. Of the 40 fenced nests, 19 incubated in full sun, 13 in partial sun and eight in full shade. Of the 40 control nests, 15 incubated in full sun, 13 in partial sun and 12 in full shade. All nests in this experiment were translocated on or over the dune crest to avoid tidal inundation or erosion.

Relocation of hawksbill turtle nests took place directly after or within 12 h of the nesting female returning to sea. Eggs were carefully removed from the natural nest site into a bucket carrier. A mean egg chamber depth (46.5 cm) was used based on previous research from Cousine (Hitchins *et al.,* 2004) and all the relocated, control and experimental clutches were re-buried at this depth. Oviposition order was maintained by having the first eggs laid being placed at the bottom of the new nest site. After 50 days of incubation, all hawksbill turtle nests were carefully examined every two days until hatching by carefully digging to the top of the eggs and feeling for hatchlings. After hatching, the hatchlings were given three days to rise to the surface of the nest and were released after being counted. After excavation the number of hatchlings to sea; infertile eggs; fertile unhatched; dead natural; dead from crab predation and missing eggs were recorded. Predation rates and hatchling recruitment success were then calculated and correlated between variables. Hawksbill turtle hatchling recruitment success was defined as the proportion of eggs laid that hatched successfully and produced viable hatchlings which left the nest (Mazaris *et al*., 2009). Predation rates were defined as the proportion of eggs and hatchlings that were killed by crabs.

3.3.3 Nest temperature

Temperature data loggers (Hygrochron iButtons DS1923) were used to measure the hawksbill turtle nest temperatures of typical nesting habitat mediums (shade, partial sun and full sun) and clutch temperatures of netted and non-netted nests. The data loggers were calibrated and then programmed to record temperatures on a half-hourly basis. Sex ratios were estimated using the mean temperature during the middle third of the incubation period and the formula from Chevalier *et al.* (1999) which is based on the best fit curve of the sex ratio applied. The pivotal temperature (the temperature at which 50% of each sex is produced) for hawksbill turtles has been estimated to be 29.2 °C (Mrososky *et al.,* 1992). Predominantly females are produced above this temperature and males below this temperature. The data collected on clutch temperatures of netted and non-netted nests were collected from a previous nesting season to ensure no impact was caused to the hatching success of the 90 experimental nests.

Nest temperatures and sex ratios - The data loggers used to measure actual hawksbill turtle incubating temperatures were placed in sets of three within the clutch, one logger at each level (bottom, middle and top of nest). Three netted and three non-netted nests were used in the experiment. Each of these three treatments was repeated along the exposure gradient described above, i.e. one netted nest and one non-netted nest in the shade, in partial sun and in full sun. The loggers were deployed for the entire incubation period. The average sex ratios for netted and non-netted nests in shade, partial sun and shade were estimated and any significant differences between the netted and non-netted nests were recorded.

Incubating medium temperatures - The data loggers (Hygrochron iButtons DS1923) used to measure hawksbill turtle incubating medium temperature were deployed in sand in sets of three in the bottom (50.3 cm), middle (40.7 cm) and top (31.0 cm) level of a hawksbill turtle nest depth (mean depths based on 10 year data from Cousine). Loggers were deployed at sites that appeared typical of the nesting habitat and where nests could be translocated in the future. Three nesting areas used by hawksbill turtles were identified in both a ‘high risk of predation zone’ and a ‘low risk of predation zone’. Three sets of three loggers were placed in each zone: deep inside *Scaevola sericea* shrub in the shade, on the edge of *Scaevola sericea* shrub in partial shade and in open sand in full sun for a period of 60 days. Mean temperatures during the middle third period between each of the covers were tested for significant differences.

3.3.4 Data analyses

All data were analysed using SigmaPlot Version 11. One-way ANOVAs were used to determine if any significant difference in hawksbill turtle hatchling recruitment success rate and predation rate was seen between the different treatments. If any significant results were obtained a post-hoc Tukey HSD test was conducted to determine which covers and which treatments were significantly different. In addition, a Kruskal-Wallis one way analysis of ranks was run to see whether there were significant differences in hatchling recruitment success rate and predation rate between the low and high risk zones within treatments and which combination had the most significant difference in hatchling recruitment success rate and predation rate. When comparing the netted nests and control (open) nests for significant temperature differences during the critical middle third period, an all Pairwise Multiple Comparison Procedure (Tukey Test) was run.

Hawksbill turtle hatchling recruitment success rate and predation rate were determined using the following formulas:

Hatchling Recruitment success rate (%) = (Hatched/ Total Number of eggs) X 100

Predation rate (%) = (crab predated eggs & hatchlings/ Total Number of eggs) X 100

When estimating sex ratios the following formula was used estimate the proportion of females:

Proportion of females =

$$\frac{1.0}{1+\exp\left(\frac{-(T-28.8)}{0.6}\right)}$$

3.4 Results

3.4.1 Hatchling recruitment success and predation rates

Results showed that the combinations of treatment, risk zone placement and cover produced varying rates of hatchling recruitment and predation (Table 3.1). We further examined hatchling recruitment success rates and predation rates against the different treatments (netted, fenced and control) (Fig. 3.2). Overall, treatment did not affect hawksbill turtle hatchling recruitment success rate significantly (ANOVA, $F = 2.671$, $df = 2$, $p = 0.07$), but hatchling recruitment success rate was significantly higher in netted than control nests (Tukey post hoc, $p = < 0.05$). The predation rate differed significantly between all three treatments (ANOVA, $F = 6.441$, $df = 2$, $p = 0.002$), with the highest significant difference between fenced and control nests (Tukey post hoc 1, $p = < 0.05$) followed by netted and control nests (Tukey post hoc, $p = < 0.05$). There was no significant difference in predation rate between netted and fenced nests (Tukey post hoc, $p = > 0.05$). Overall the netted nests ($n = 40$, $\bar{x} = 60.1$, SE ± 4.76) had the highest mean hatchling recruitment success rate of 60.1% and the second highest predation rate of 10.3%. Fenced nests ($n = 40$, $\bar{x} = 54.2$, SE ± 4.67) had the second highest mean hatchling recruitment success rate of 54.2% and the lowest predation rate of 9.0% followed by the control nests ($n = 40$, $\bar{x} = 27.6$, SE ± 4.61) with lowest mean hatchling recruitment success rate of 45.0% and highest predation rate of 27.6%.

Hawksbill turtle mean total predation rate and hatchling recruitment success rate across all nests were 15.6% (SE ± 2.48) and 53.1% (SE ± 2.73) respectively. Predation rate and hatchling recruitment success rate had a negative linear relationship using a simple linear regression (Pearson’s correlation coefficient of 0.672). There was a significant negative relationship between an increasing predation rate and a decreasing hatchling recruitment success rate ($p < 0.05$, r^2 value was 0.452) (Fig. 3.3).

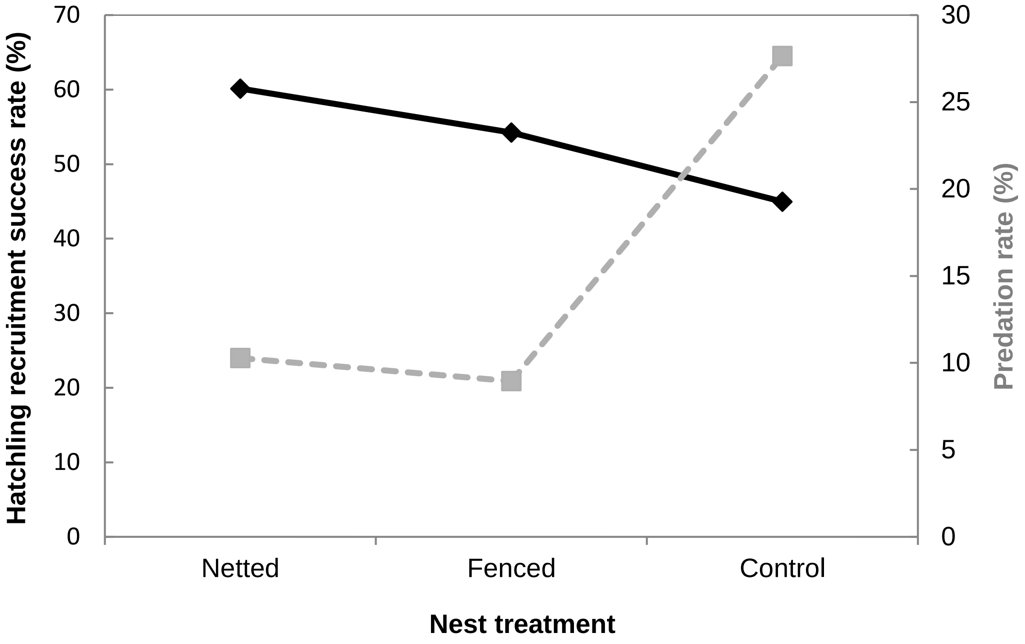

Figure 3.2 Mean hawksbill turtle hatchling recruitment success and predation rate between treatments in the present study.

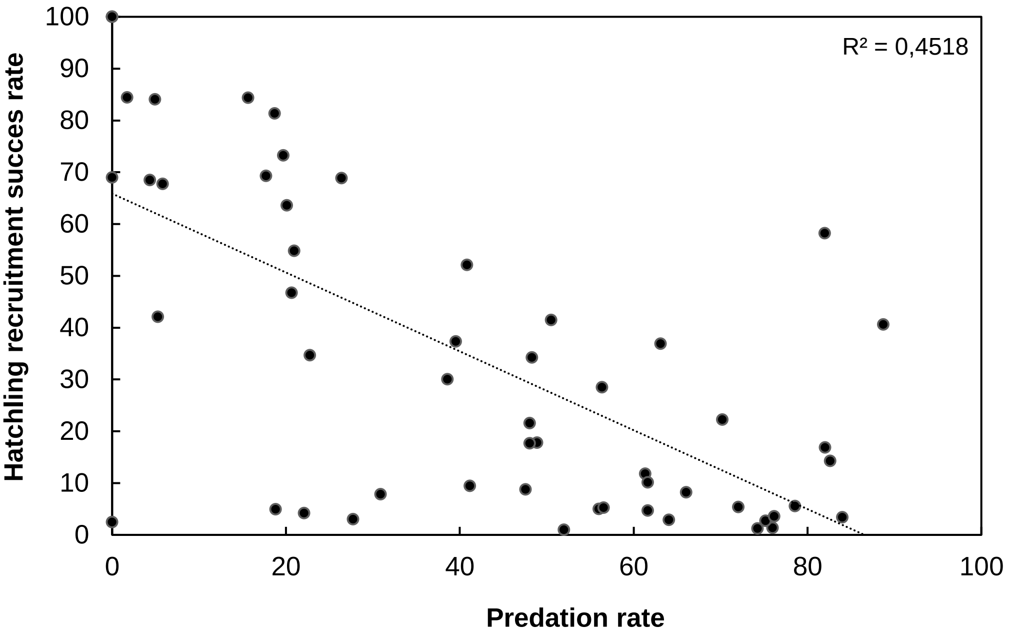

Figure 3.3 Hawksbill turtle hatchling recruitment success rate in relation to predation rate in the present study.

Table 3.3. Summary of hawksbill turtle hatchling recruitment success rates and predation of the entire data set within the collective variations / combinations of treatments cover and position ('high or low risk' of predation zone). The various combinations are listed in descending order from the highest hatchling recruitment success rates to the lowest hatchling recruitment success rates.

Treatment / area / cover	**$\bar{x}$ HRSR %**	SE $\bar{x}$	**$\bar{x}$ PR %**	SE $\bar{x}$
Netted / low risk zone / sun	76.38	16.443	0.00	15.10
Netted / low risk zone / partial	74.49	12.737	0.24	11.69
Netted / high risk zone / sun	70.98	7.899	8.67	13.07
Fenced / high risk zone / sun	70.60	7.612	2.21	6.99
Netted / low risk zone / shade	68.14	20.139	0.00	18.49
Control / low risk zone / sun	65.36	20.139	0.67	18.49
Fenced / low risk zone / shade	56.55	28.48	5.24	26.15
Fenced / low risk zone / sun	55.47	12.737	21.33	11.69
Fenced / high risk zone / partial	48.00	9.493	2.77	8.72
Control / high risk zone / sun	47.423	7.899	27.08	7.25
Control / high risk zone / partial	46.13	9.493	30.03	8.72
Fenced / low risk zone / partial	45.27	14.24	12.36	13.07
Netted / high risk zone / shade	44.39	10.069	26.99	9.24
Netted / high risk zone / partial	43.33	9.493	9.03	8.72
Control / low risk zone / partial	34.22	14.24	24.98	13.07
Fenced / high risk zone / shade	33.42	10.765	20.13	9.88
Control / high risk zone / shade	30.92	10.069	39.88	9.24

Hawksbill turtle nests placed in full sun had the highest mean hatchling recruitment success rate of 62.8% (SE ± 3.71), compared with partial sun with 48.0% (SE ± 5.20) and full shade with 42.4% (SE ± 5.02). The highest significant difference in hatchling recruitment success rate was seen between nests incubating in full sun and nests incubating in full shade ($p < 0.001$), then between full sun and partial sun ($p = 0.005$). Hatchling recruitment success rate of nests incubating in partial sun and full shade did not differ significantly ($p = 0.454$). Nests in full sun had on average a 20.5% higher hatchling recruitment success rate than nests placed in full shade and a 14. 8% higher hatchling recruitment success rate than nests in partial sun. Nests in partial sun had on average a 5.7% higher hatchling recruitment success rate than nests in full shade.

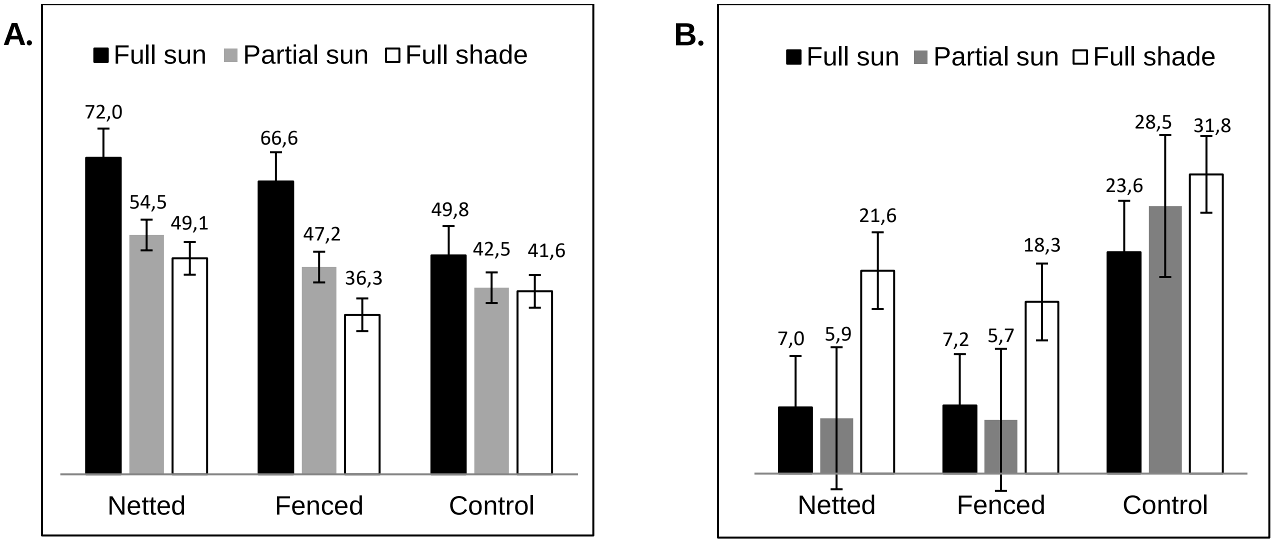

Figure 3.4. Hawksbill turtle a. hatchling recruitment success rate (%) between treatments and cover and b. predation rate between treatments and cover in the present study.

Across the individual treatments the highest hawksbill turtle hatchling recruitment success rate was all incubating in full sun (netted in full sun = 72.0%, fenced in full sun = 66.6%, control in full sun = 48.8%) (Fig. 3.4A). A significant difference in hatchling recruitment success rate was seen between control and netted nests when they incubated in full sun (ANOVA, H = 5.994, df = 0.2, $p = 0.05$), but not when incubating in full shade (ANOVA, F = 0.480, df = 2, $p = 0.624$) and not when incubating in partial sun (ANOVA, H = 0.984, df = 2, $p = 0.611$). The greatest difference in hatchling recruitment success rate was seen between full sun nests and partial sun nests which were fenced (full sun 19.5% higher hatchling recruitment success rate than partial sun nests) and the smallest difference was seen between partial sun control nests and full shade control nests (partial sun 0.8% higher than full shade nests).

When looking specifically at cover in relation to hawksbill turtle hatchling recruitment success rate, there was no significant difference in hatchling recruitment success rate between the different covers in netted nests (ANOVA, $F = 2.299$, $df = 2$, $p = 0.114$) or control nests ($H = 0.883$, $df = 2$, $p = 0.643$). Hatchling recruitment success rate did, however, differ significantly between the three covers in the fenced nests ($H = 6.518$, $df = 2$, $p = 0.038$), with the biggest difference seen between full shade and full sun ($p = 0.005$).

Hawksbill turtle nests placed in full shade had the highest mean predation rate (24.8%), then partial sun (13.8%) and full sun (12.1%). The highest significant difference was seen between nests incubating in full sun compared with those in full shade ($H = 8.629$, $df = 1$, $p = 0.003$), then between partial sun and full shade ($H = 7.580$, $df = 1$, $p = 0.006$). Predation rate of nests incubating in full sun and partial sun did not differ significantly ($H = 0.00789$, $df = 1$, $p = 0.928$). Nests in full shade had on average 11.3% higher predation rate than those in full sun and 10.5% higher predation rate than those in partial sun. Nests in partial sun had on average a 0.8% higher predation rate than nests in full sun.

Across the individual treatments the highest hawksbill turtle predation rate was incubating in full shade (netted in full shade = 21.6%, fenced in full shade = 18.3%, control in full shade = 31.8%) (Fig. 3.4B). A significant difference in predation rate was seen between netted and control nests when they incubated in partial sun ($H = 6.350$, $df = 1$, $p = 0.012$), but not when incubating in full sun ($H = 2.930$, $df = 1$, $p = 0.087$) and not when incubating in full shade ($H = 2.555$, $df = 1$, $p = 0.110$). No other significant differences in predation rate were seen between the different treatments when incubating in a specific cover. The greatest difference in predation rate when looking at percentage difference alone was seen between full shade nests and partial sun nests which were netted (full shade 15.7% higher predation rate than partial sun nests) and the smallest difference was seen between full sun netted nests and partial sun netted nests (full sun 1.2% higher predation rate than partial sun nests).

Hawksbill turtle nests which were incubating in the high risk of predation zones had an overall mean hatchling recruitment success rate of 51.1% and predation rate% of 17.2% (Fig. 3.5). Nests incubating in the low risk predation zones had an overall mean hatchling recruitment success rate of 59.1% and predation rate 0f 10.9%. Netted nests which were placed in high risk zones had a mean hatchling recruitment success rate of 55.6% and a mean predation rate of 13.7%. Netted nests which were placed in the low risk zones had a mean hatchling recruitment success rate of 73.8% and a mean predation rate of 0.12%. Fenced nests placed in high risk zones had a mean hatchling recruitment success rate of 55.1% and a mean predation rate 6.6% and in low risk zones a mean hatchling recruitment success rate of 51.1% and mean predation rate of 16.1%. Control nests placed in high risk zones had a mean hatchling recruitment success rate of 42.6% and a mean predation rate of 31.4% and in low risk zones a mean hatchling recruitment success rate of 52.0% and a mean predation rate of 16.4%.

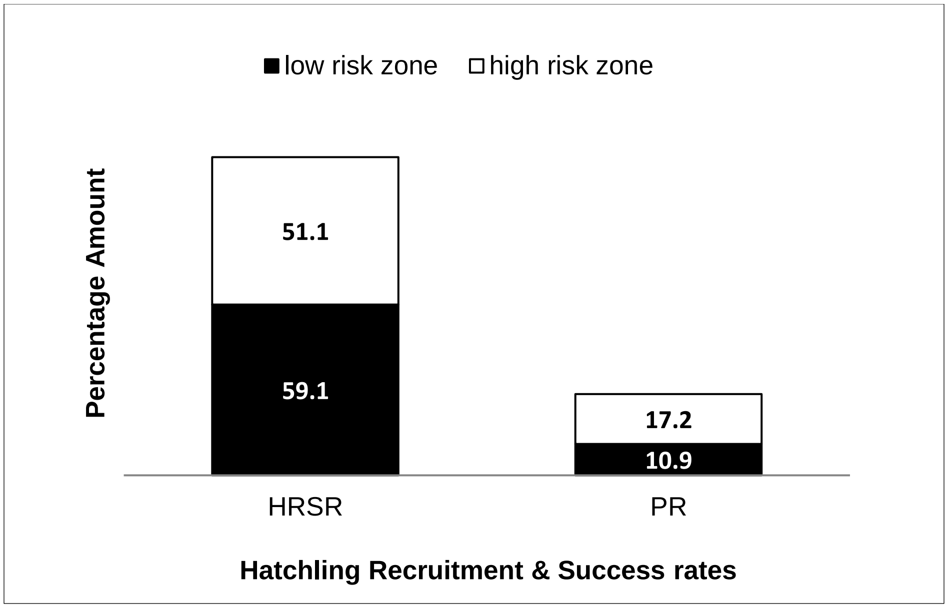

Figure 3.5 Hawksbill turtle hatchling recruitment success and predation rate (%) in the different risk zones in the present study.

No significant differences in hawksbill turtle hatchling recruitment success rate were seen between the low- and high-risk zones when fenced (H = 0.282, df = 1, p = 0.595), when netted (H = 1.889, df = 1, p = 0.169), nor with the control nests (H = 0.881, df = 1, p = 0.348). When examining predation rate, fenced nests were the only nests to show a significant difference in predation rate between the high and low risk zones (H = 3.913, df = 1, p = 0.048), not netted nests (H = 2.008, df = 1, p = 0.156) nor control nests (H = 0.401, df = 1, p = 0.526).

Differences in hawksbill turtle hatchling recruitment success rate and predation rate between the three different treatments were also measured for significance. No significant differences in hatchling recruitment success rate were seen between the three different treatments in the high-risk zones (p = 0.141) nor in the low risk zones (p = 0.075). However, significant differences in predation rates were seen between the three different treatments in the high-risk zones (F = 6.482, df = 2, p = 0.002), with the greatest difference between fenced and control nests

(H = 9.695, df = 1, p = 0.002) than between netted and control nests (H = 7.156, df = 1, p = 0.007). No significant difference in predation rate was found between netted and fenced nests (p = 0.943). Significant differences in predation rate were found between the three different treatments in the low risk zones (H = 11.324, df = 2, p = 0.003), with the greatest difference between fenced and control nests (H = 10.414, df = 1, p = 0.001) than between netted and fenced nests (H = 8.170, df = 1, p = 0.004). No significant difference was seen between fenced and control nests (p = 0.761).

3.4.2 Temperature

The mean nest temperature of all hawksbill turtle incubation periods (actual nests and typical incubation mediums) measured on Cousine Island was 29.65° C in the present study. Combined mean temperature of full sun nests and full sun incubation medium was 30.06° C; partial sun nests and partial sun incubation medium combined mean was 29.57° C and shade nests and shade incubation medium combined mean was 29.32° C.

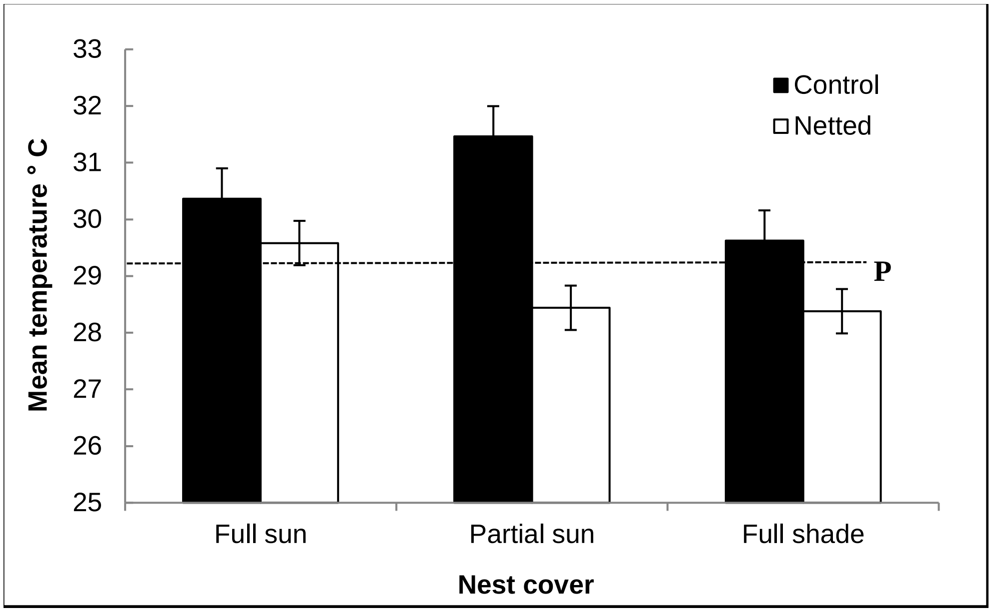

Figure 3.6 Mean temperatures of control and netted hawksbill turtle nests under different covers in the present study. Included is the hawksbill pivotal temperature of 29.2° C.

Nest temperatures and sex ratios – Results showed that there was a statistically significant difference in hawksbill turtle nest temperature between netted and control nests ($p < 0.05$). Control nests were on average 1.68°C higher than netted nests. The highest mean critical middle third temperature was seen in the control nests incubating in partial sun (31.46°C) followed by control nests incubating in full sun (30.46°C) and control nests in full shade (29.62°C). The netted nests mean critical middle third temperatures were all lower than the control nests with full sun being the highest at 29.58°C, then partial sun at 28.44°C and then full shade at 28.38°C (Fig. 3.6). The highest nest temperature recorded during the critical middle third period was seen in a control nest incubating in partial sun over a period of 23 h (34.87 - 34.94°C). The lowest recorded nest temperature was during the critical middle third period in a netted nest incubating in full shade (26.07°C).

In using the pivotal temperature of 29.2°C for hawksbill turtles, it was estimated that control nests incubating in full sun had the highest percentage of females comprising 70% females and 30% males; control nests incubating in partial sun comprised 69% females and 31% males; control nests incubating in full shade comprised 51% females and 49% males; netted nests incubating in full sun also comprised 51% females and 49% males and netted nests incubating in partial sun comprised 46% females and 54% males. Netted nests incubating in the shade had the lowest percentage of females comprising 36% females and 64% males (Table 3.2). As predicted the number of females increased with increasing nest temperature (°C) (Pearson's correlation coefficient of 0.918, $p < 0.001$, $r^2 = 0.828$, Fig. 3.7).

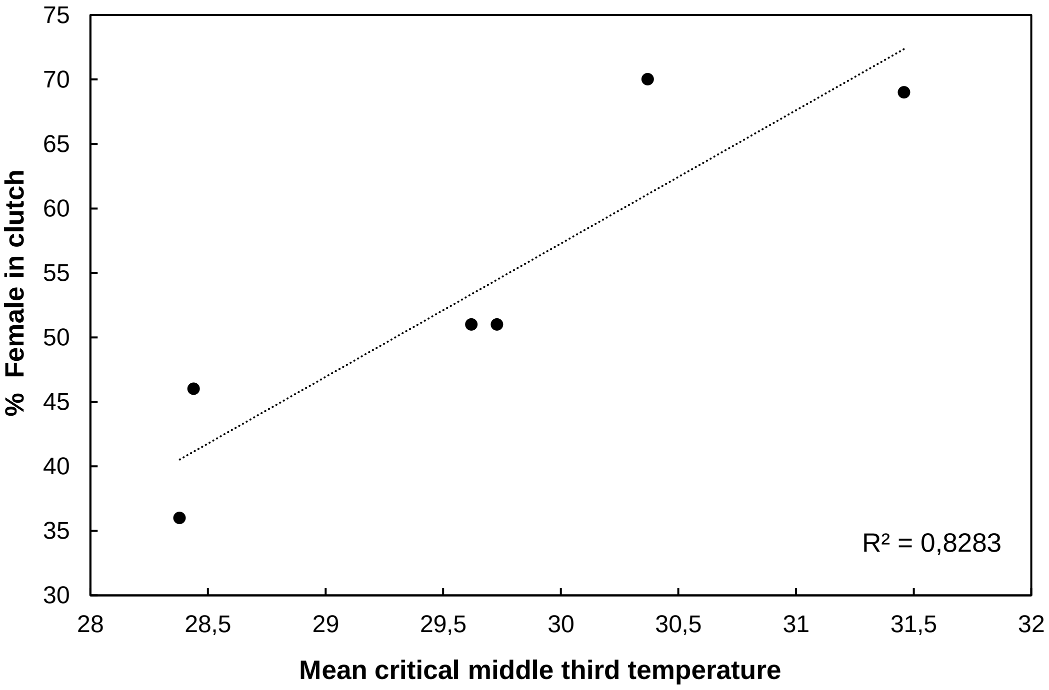

Figure 3.7 The percentage of hawksbill turtle females in relation to middle third temperatures in the present study.

Table 3.2 Summary of hawksbill turtle mean incubation temperatures across the entire incubation duration (Total ID) and during the critical middle third incubation duration (CMTID) of the six nests planted with temperature data loggers. Each row shows the associated treatment and cover for each nest; each nests incubation duration in days and then the estimated proportion of females represented as a percentage in each nest.

Nest	**Cover**	**Treatment**	**ID (d)**	**Total ID**				**Critical Middle third**				**F%**
				Mean	SD	Min.	Max.	Mean	SD	Min	Max	
1	full sun	netted	53	30.17	1.04	28.56	33.30	29.73	0.48	28.87	31.22	**51**
2	partial sun	netted	58	29.34	1.78	19.70	33.20	28.44	0.77	26.60	30.70	**46**
3	full shade	netted	59	29.39	1.33	24.38	33.62	28.38	0.90	26.07	30.25	**36**
4	full sun	control	54	31.11	1.40	27.69	34.43	30.37	0.73	28.25	31.94	**70**
5	partial sun	control	51	29.34	1.78	19.70	33.20	31.46	0.90	29.07	34.94	**69**
6	full shade	control	55	30.50	2.06	25.57	34.37	29.62	0.4	28.81	31.37	**51**

Incubating medium temperatures - The mean nest temperatures of typical hawksbill turtle incubating mediums were measured for a period of 60 days. Incubating medium in full sun had a mean temperature of 29.55°C, in partial sun a mean temperature of 28.65°C and in full shade a mean temperature of 28.85°C. During the critical middle third period the incubating medium in full sun had a mean temperature of 29.78°C, in partial sun 28.49°C and in full shade 28.57°C (Table 3.3). There was a significant difference in nest temperature between full sun, partial sun and full shade incubation ($p < 0.05$). The difference in nest temperature was most significant between full sun and full shade (H = 5834.108, df = 1, p < 0.001), and between full sun and partial sun (H = 7204.409, df=1, p < 0.001). No significant difference was seen between the full shade and partial sun incubation mediums (H = 0.203, df = 1, p = 0.652).

When comparing nest temperature differences between the low risk and high-risk zones, a significant difference was seen overall (H = 1378.701, df = 1, p < 0.001) with the high risk zones having a higher mean temperature of 0.43°C than the low risk zones. The mean nest temperature in the high risk zones over all three covers was 29.16°C and in the low risk zones 28.73°C. Nest temperature differed significantly between the low and high risk zones when they were in partial sun (H = 794.656, df = 1, p < 0.001) and in full shade (H = 2754.567, df = 1, p < 0.001), but not in full sun (H = 3.066, df = 1, p = 0.080).

Table 3.3 Summary of mean incubation medium temperatures across the entire duration of a typical nest (Total ID) and during the critical middle third incubation (CMT). Each row shows the associated cover and location within either a 'high risk' or 'low risk' of predation zone.

Zone	**Total T°C mean**			**CMT T°C mean**		
	Full sun	Partial sun	Full shade	Full sun	Partial sun	Full shade
High risk	29.33	28.90	29.48	29.71	28.72	29.05
Low risk	29.78	28.40	28.22	29.84	28.25	28.09
Total	29.55	28.65	28.85	29.78	28.49	28.57

3.5 Discussion

When managing a threatened population of sea turtles, strategic intervention should ideally aim at minimising impact whilst maximising benefits. In this study we looked at nest management techniques and associated variables for minimising ecological or biological impacts. Sea turtle nest management on Cousine Island aims at having the highest hatchling recruitment success rate and the lowest predation rate as possible. The results from this study clearly demonstrated that the overall hawksbill turtle hatchling recruitment success of nests protected with a crab barrier method of either netting or fencing, is significantly increased and the predation significantly decreased. Hawksbill turtle clutches incubating without crab barriers are susceptible to losing on average a third or more eggs to crab predation than those with a crab barrier in place.

Hawksbill turtle nests protected with netting had the highest hatchling recruitment success rates and nests protected with fencing had the greatest effect on minimising predation. Although predation rates and hatchling recruitment success rates were negatively correlated, the hatchling recruitment success will be additionally affected by variables not related to predation such as infertility (Hitchins *et al.*, 2004) and environmental factors (Ditmer and Stapleton, 2012; Miller, 2017). Overall results suggested that predation rate is a better indicator on the successful use of a crab barrier method.

We further investigated how cover affects hawksbill turtle hatchling recruitment rates and predation when crab barriers were applied. Nest placement in relation to cover appears to be of particular importance. Nests incubating in full sun displayed the highest rates of success and nests incubating in full shade displayed the highest rates of predation. With temperature playing a vital role in the ecology and biology of the offending ghost crabs, the sun could be setting distributional limits that protect nests in full sun (Hughes *et al*., 2014). Alternatively, the full shade areas, where predation rates were on average 10.9% higher than full sun and partial sun nests, are providing optimal burrow and air temperatures for crabs to thrive. Results further indicate that the crab barrier methods influence the hatchling recruitment success rate positively when turtle nests are incubating in full sun, other than just assisting in decreasing predation rate. A netted or fenced nest could be assumed to increase the humidity within a nest, which when considering full sun incubation, it could influence the hatchling recruitment success rate. This was seen in studies done by Mortimer (1990) and Huerta (1995) who found positive correlations between sand moisture and turtle hatching success.

To further advance on existing management practices, previously identified high risk and low risk of predation zones were analysed for relevance and significance by using hawksbill turtle hatchling recruitment success rate and predation rate as indicators. It must be noted that these zones were distinguished into ‘high’ and ‘low’ risk from previous hatchling recruitment success rates and not from predation rates. A certain degree of discrepancy in hatchling recruitment success rate and predation rate was seen between the low and high-risk zones. Lower levels of predation and higher hatchling success were seen in turtle nests incubating in the low risk zones. In contrast, turtle nests that were fenced showed the opposite trend and showed higher levels of predation and lower success in the low risk zones and lower levels of predation and higher success in the high-risk zones. Predation rate was seen to be more greatly affected by zone placement than hatchling recruitment success rate, which was most evident in fenced nests and nests without crab barriers. Overall, there were no statistically significant results to justify placing nests according to zone criteria.

The use of temperature loggers provided useful insight into actual hawksbill turtle incubation temperatures within a clutch and typical incubation medium / sand temperatures. For hawksbill turtles, the pivotal temperature for sex determination is 29.2 ° C (Mrosovsky *et al.*, 1992). Recorded turtle nest temperatures varied between the actual nest recordings and the incubation medium recordings, but when combined the mean temperature recordings were all above the pivotal temperature. However, we focused only on the mean middle third temperatures which determine sex ratios in turtles and which can affect the operational sex ratio. The operational sex ratio (the available ratio of males to females in a breeding population) of sea turtles is vulnerable to disturbances with management intervention because of temperature-dependant sex determination (Mrosovsky *et al*., 1999; Stewart and Dutton, 2014).

When netting was used to protect hawksbill turtle nests, it had a substantial cooling effect which could potentially distort natural sex ratios. These cooling effects from netting were seen in nests incubating across all covers during the critical middle third period. Netted turtle nests incubating in partial sun and shade displayed temperatures substantially lower than the pivotal temperature, which contrasted dissimilarly to temperatures of the control nests which were above the pivotal temperature and would therefore produce a greater number of females. These results were similar to other studies done on the sex ratios of sea turtles where natural ratios were highly skewed towards females due to mean incubating temperatures being above the pivotal temperature (Mrosovsky and Provancha, 1992; Marcovaldi *et al*., 1997; Hanson *et al*., 1998). When examining the estimated sex ratios, the natural nests sex ratios were skewed towards female, even when incubating in full shade. The netted nests were skewed towards male except for when in full sun where the ratio was estimated at 49% male and 51% female.

With climate change and increasing temperatures imminent, management strategies involving the manipulation of sea turtle nests need to be carefully considered (Erdoğan *et al*., 2004; Hanson *et al*., 1998). The application of netting could possibly be used to counteract the effects of climate change and increasing temperatures in the future. An increase of 1 or 2° C could be reversed using netting and the current natural operational sex ratio simulated. As temperature data in this study were limited, further extensive sampling is recommended.

When looking at typical turtle nest incubating medium temperatures, only the loggers recording in nests in full sun displayed temperatures above the pivotal temperature. The partial sun and full shade incubating medium mean temperatures were both below the pivotal temperature.

However, when considering effects on possible hawksbill turtle sex ratios, these temperatures do not make consideration for metabolic heating. Heat is produced by the developing eggs and increases as the eggs develop. During the middle third of incubation, temperatures can increase by 1.1° C and increase to over 3° C in the final third of incubation (Glen and Mrosovsky, 2004). If these readings were to be used for predicting sex ratios, a correction for metabolic heating would need to be used, as can be seen in studies was done by Fuentes et al (2010) and Hawkes et al 2007). Without looking specifically at pivotal temperature, but at differences between sites, middle third temperatures differed significantly when incubating under different covers. A difference of 1.29° C between full sun and partial sun, and then 1.21° C between full sun and full shade was seen. These results substantiate how the location of a hawksbill turtle nest can differ in condition and which, according to Mazaris *et al*. (2009); can significantly affect embryonic development, fitness, sex determination, hatching success and the risk of predation.

We further investigated the difference in hawksbill turtle incubating medium temperatures between the high risk and low risk or predation zones. The high-risk areas overall had higher temperatures than the low risk areas, but only differed significantly when incubating in partial sun and in full shade. Rates of predation were found to be lower in full sun nests which does not correspond to these higher temperature results in high risk zones. Further sampling between predation rates, nest temperatures and beach zonation would be necessary to justify managing turtle nests according to zone risk.

Focusing turtle conservation actions at the nesting site can increase output and increase the nesting population in the long term (Bjorndal *et al.*, 1999; Marcovaldi and Chaloupka, 2007; Mazaris et al., 2009). This is a crucial period where the opportunity to minimise mortality and increase output exists. The natural mortality of hawksbill turtle incubating eggs and hatchlings on Cousine is high and hatchling recruitment success rates are lower than in other areas where research studies have been conducted on hawksbill turtle hatch success (Ditmer and Stapelton, 2012; Horrocks and Scott, 1991; Wyneken *et al.*, 1988). Results from this study have provided an opportunity for managers to minimise mortality at the egg stage and counterbalance overall mortality by increasing output. Both Ratnaswamy *et al.* (1997) and Antworth *et al*. (2006) have demonstrated that managing nests is the most effective way of protecting nests from crab predation while also showing limited negative consequences.

In conclusion, our results provide insights about how spatial distribution and environmental variations influence hawksbill turtle hatchling recruitment success rates and levels of predation. We clearly demonstrate that management measures have both positive and negative consequences on hatchling recruitment success rate and predation rate. These conservation measures need to be carefully considered and applied if the objective is to maximise hatchling recruitment success rate and minimise predation rate and natural nest temperatures will also need to be maintained in order to ensure an operational sex ratio occurs. Further research is needed into the hatchling recruitment success rate of hawksbill turtle nests to develop a deeper understanding of hatchling recruitment success rate drivers and their relationship to predation rate. With the use of crab barrier methods, monitoring of turtle nests will be a conservation priority, as these measures could play an increasingly important role in protecting turtle nesting populations into a future of increasing human populations and predicted climate change.

3.6 Acknowledgments

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CHAPTER 4

Beach profiling and ghost crab densities on a hawksbill nesting beach in the Seychelles

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Running header: Beach profiling and ghost crab densities of hawksbill nesting beach

4.1 Abstract

The 900 m long beach on Cousine Island, Seychelles, supports a nesting population of approximately 70 - 130 hawksbill turtle *Eretmochelys imbricata* nests each season. Increasing beach sediment loss from erosion, and high levels of crab *Ocypode* spp. predation are threatening nests and nesting habitat which has resulted in intensive management measures to minimise egg and nest losses. Seasonal and storm-related erosion and accretion cycles on Cousine Island have the potential of destroying 50% or more of all egg clutches on the island in a single nesting season and observed crab predation rates have reached 90-100% in preferred nesting beach zones in previous years. We investigated the distribution and population density of ghost crabs, and the morphology of the beach across the different beach area zones and across the nesting season during 2014 - 2015. Crab burrow numbers varied between beach zone areas and across the season and were highest on the backshore. Crab density correlated negatively with available beach area and we found that in the presence of turtle nests crab density increased. When examining beach dynamics, we found them to be cyclical and found the nesting beach to be prone to higher levels of erosion than accretion with significant changes in beach width throughout the season. The mean vertical beach elevation drop on Cousine Island was higher than what hawksbill turtles have been reported to prefer. We suggest the continuation of beach elevation monitoring and for management to use the beach morphology data to assist with hawksbill turtle nest translocations to minimise nest losses and maximise hatchling recruitment success.

Key words: crab density • beach morphology • beach profile • hatchling recruitment • hawksbill • predation

4.2 Introduction

Nesting beaches are critical resources for sea turtles and provide a climate space that is appropriate for embryonic development (Ackerman, 2017; Antworth *et al*., 2006). Beaches are naturally dynamic and in constant motion due to wind, tides, sea levels and storms (Adotey *et al.*, 2015). Beach material naturally moves during periods of erosion and accumulates in other areas during periods of accretion (Pilkey, 2013). Longshore currents and storms can permanently remove sediment from a beach causing coastal retreat (Marchand, 2010). Coastal erosion is reported to be increasing globally, causing coastal retreat of an estimated 70% of the world's beaches (Anthony, 2005) and ocean level rise from climate change is predicted at ~30 cm by 2100 (Ackerman, 2017; Solomon *et al*., 2007). All of which can be considered a threat to turtle nesting beaches.

The hawksbill turtle *Eretmochelys imbricata* is listed as Critically Endangered by the 1996 IUCN Red List of Endangered species and is based on an 80% global decline during the last three generations (105 years) (Ballie *et al*., 1996; Meylan and Donnelley, 1999; Ditmer and Stapelton, 2012). This has led to the species becoming one of conservation concern and priority has been given to protecting nesting habitats which are currently restricted to relatively few beaches (Bass *et al.*, 1996).

Hawksbill turtle nesting behaviour and the density of nests can be affected by changes in beach morphology (Lamont and Carthy, 2007). However, hawksbill turtles show relatively high fidelity to nesting areas, returning to the same nesting beach and shoreline location within and among nesting seasons even after changes occur in beach topography (Bass *et al.*, 1996; Kamel and Mrosovsky, 2005). It is unknown at what point females will discontinue with these high levels of fidelity if a nesting beach experiences high levels of microclimate change or permanent sediment loss. Due to a lack of parental care in sea turtles, egg clutches become vulnerable to microclimate change and predation after nesting takes place (Kamel and

Mrosovsky, 2005). In order for incubation to be successful, an interaction between physical characteristics such as beach structure, beach sand, climate and the actual eggs occurs to create an adequate incubating microclimate (Ackerman, 2017; Mortimer, 1990). The microclimate is naturally dynamic, however if the physical characteristics experience extreme disturbances, hatchling recruitment will be affected (Ackerman, 2017). A disturbance such as increased predation can be managed to improve hatchling recruitment rates. However, beach erosion and inundation from seasonal storms cannot be controlled or managed. Translocating nests to prevent losses from seasonal storms, is an option for management and has been used to improve hatchling recruitment success rates because of increased control over the nesting habitat and predation (Lutcavage *et al.,* 2017; Mortimer, 1999).

The hawksbill turtle nesting beach on Cousine Island, Seychelles, is highly dynamic and experiences high levels of erosion and accretion due to the nesting season coinciding with the northwest monsoon season when periods of erosion and accretion are enhanced (Mortimer and Bresson 1999). What is concerning is there has been an increase in beach sediment loss since the beginning of the turtle management program in 1991 and that its cause is unknown (Hitchens pers. comm., 2013). There is a predictable pattern of erosion on the south beach and accretion to the north beach in the beginning of the nesting season and a slow exchange in the opposite direction as the season progresses. However, this movement has not been formally documented on Cousine to date. The translocation of nests to avoid nest losses from erosion and predation is currently being used as a management technique on the island (Island staff pers. comm. 2014). These seasonal and storm-related erosion and accretion cycles can destroy 50% or more of all egg clutches on the island and observed crab predation rates are reaching a maximum of 90-100% in preferred nesting zones in some years (Island staff pers. comm. 2014).

Ocypode ceratophthalmus and *Ocypode cordimana* are two species of ghost crab recorded on Cousine Island (De Bruyn, 2002). Ghost crabs are the only actual active predators of turtle hatchlings and eggs on the island and are responsible for the high predation rates recorded each year. Predation caused by ghost crabs is one of the most serious observed threats to incubating turtle nests on small oceanic islands (Marco *et al.,* 2015) and high levels of predation at the egg stage can affect an entire turtle population and can slow down the recovery of a threatened population (Barton and Roth, 2008; Leighton *et al.,* 2011). Although ghost crabs are an important component of sandy beach ecosystems as an apex invertebrate predator (Tureli *et al.*, 2014), predation rates and risk on turtle nests need to be documented in order to inform turtle management programs.

In this study we investigated the distribution and population density of ghost crabs across the nesting beach on Cousine Island and across the nesting season to obtain a proxy for the number of crabs a nest might be exposed to. The morphology across the nesting beach zones and across the season was also investigated using beach profiling methodology. Our main aim was to analyse the hawksbill turtle predation risk and to the delineate beach morphology change across their nesting beach. We predicted that ghost crab density would increase according to locality in relation to cover and food provision. We also predicted that changes in beach morphology would be greatest on either ends of beach (north beach and South Beach), and the change in beach width and elevation would be greatest from October to December. It is hoped that results could inform current and future conservation efforts on Cousine Island and provide baseline data with which to measure impacts of climate change on the nesting ecology and population over time.

4.3 Methods

4.3.1 Study Site

This study took place on the 900 m long hawksbill turtle nesting beach on Cousine Island (4.3500°S, 55.6333°E), Republic of Seychelles. The beach is exposed to minimal human impact and supports an average of 70 – 130 hawksbill turtle nests each nesting season (Hitchins *et al.*, 2004). The hawksbill turtle nesting season on Cousine Island occurs during the summer months and runs approximately from September to February each year. The beach system is highly dynamic, and erosion occurs at varying levels of severity across the entire beach throughout the nesting season. The 900 m beach has previously been divided into 30 nesting zones, each 30 m in length and designated with a visible beach marker. The South Beach (zones 0 - 4) is at its widest at the end of the nesting season and North Beach (zones 25 - 29) is at its widest at the beginning and middle of the nesting season (Hitchens pers. comm., 2013). Erosion gradually increases southwards and accretion northwards and then switches back again as the season progresses (Hitchens pers. comm., 2013). A previous study confirmed that two species of ghost crab (*Ocypode cordimana* and *O. ryderi*) are present on the beach at Cousine Island, with the highest densities occurring on North Beach (De Bruyn, 2002).

4.3.2 Data collection

4.3.2a. Crab density and distribution

Data on burrow counts were collected during the 2014\15 hawksbill turtle nesting season on Cousine Island. The number of burrows was used as an estimate of crab density (Turra *et al.*, 2005; Rosa and Borzone, 2008). Crab densities were quantified by counting the number of active burrow openings within quadrats along a belt transect. Distribution patterns of crab burrows were also assessed using a dispersion index. In each of the 30 zones, a 30 m wide belt transect was used and extended from the water line to the base of the dune crest. Each transect was divided into sequential 1 m wide quadrats placed continuously from the dune crest to the water line. Quadrats were distinguished into a foreshore (lower and middle beach reach) quadrat or a backshore (upper and front of dune crest) quadrat to measure where crab densities were higher. Quadrats lying within the area where the tideline had reached its highest point within the last 12 h were defined as foreshore quadrats. Quadrats lying above any sign of a recent tideline were defined as backshore quadrats. Thus, the sampling units measured were 1 x 30m quadrats and the number of burrows in a quadrat was expressed as the number of crab burrows per 30 m^2 then further divided into per m^2. Additionally, the 30 beach zones were sub-divided into six beach area zones (zones 0-4, 5-9, 10-14, 15-19, 20-24 and 25-29) (Figure 4.1). Zones 0 - 4 are ‘South Beach’ and zones 25 - 29 the ‘North Beach’. Fresh tracks around the burrow indicated an active burrow and only burrows larger than 3 cm wide were counted to represent individuals big enough to predate on turtle nests. The first count was conducted at the start of the hawksbill turtle nesting season in October (beginning of season) and replicated in December (middle of season) and in February (end of the season). All counts were done over a period of 2 h and were always done during low tide.

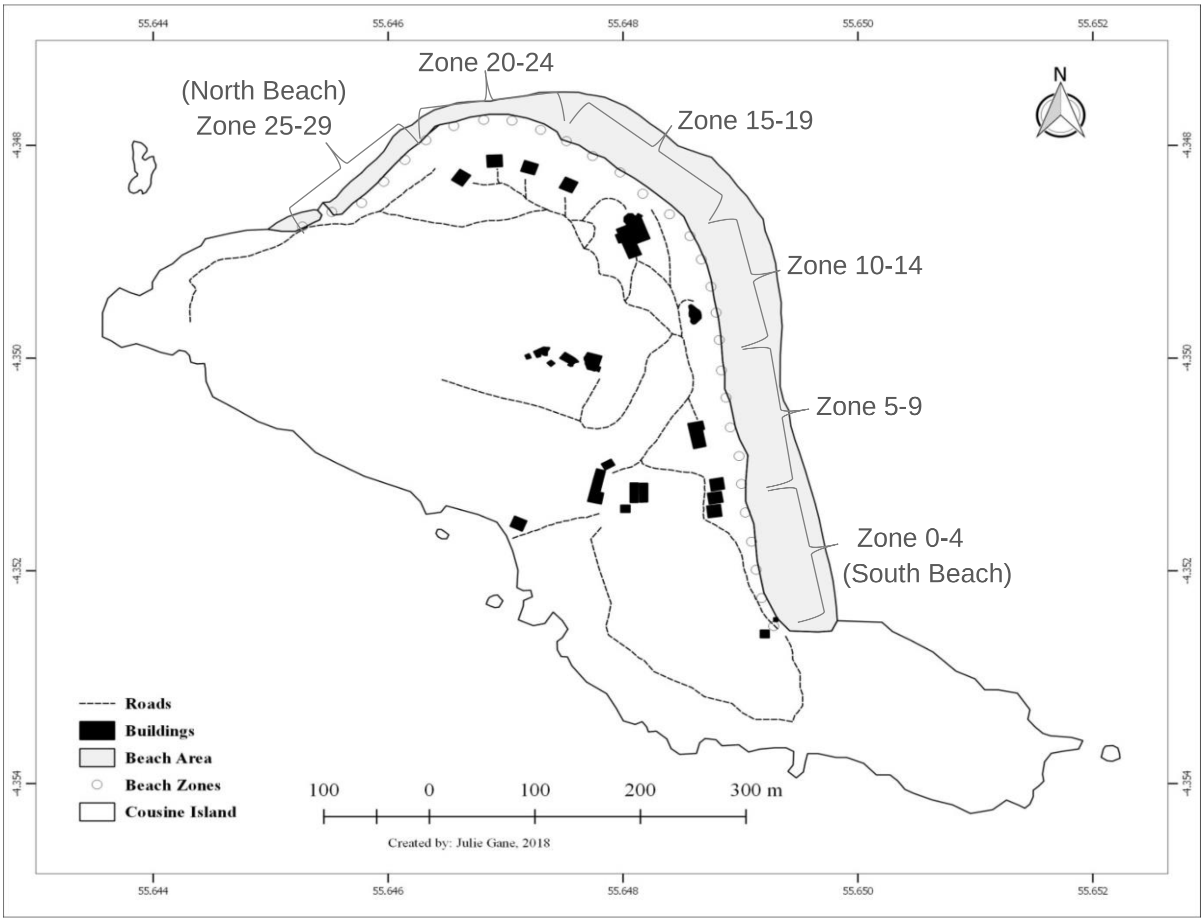


Figure 4.1 Map of the Cousine Island designated beach area zones from South to North Beach.

4.3.2b. Beach morphology

Each of the 30 beach zones were profiled (measure of a beach cross section) every two months in order to obtain an expression of beach morphology across the entire nesting season. The first profile was measured at the start of the hawksbill turtle nesting season in October and replicated in December and in February. The existing zone markers which are permanently fixed at the back of the beach were used as reference markers. The profile was measured directly perpendicularly to the water line and started from each of the 30 reference markers. A ranging pole was used to lay the individual profiles into segments at each visual break of slope and ended at the low tide mark. An Abney Level (CST/berger 5.25') was used to measure the distance and slope of each segment which ultimately provided the beach profile from the elevation measurements. The segment slope was recorded in degrees and minutes and to the nearest 10 min with either a plus or minus sign indicating an upslope or a downslope. The ground distance was measured along the slope and was recorded in metres. All 30 zones were divided into six areas made up of six beach zone areas (zones 0 - 4, 5 - 9, 10 - 14, 15 - 19, 20 - 24 and 25 - 29). A mean profile was established for each of the six areas and compared across the season.

4.3.3 Data analyses

The mean number of burrows / m^2 was obtained by dividing the number of burrows per transect by 30 m^2. Density was examined during the beginning, middle and end of season for each of the beach zone areas. A one-way analysis of variance (ANOVA) and Tukey Post-Hoc tests were used to determine significant differences in density of burrow counts between foreshore and backshore areas and between the beginning, middle and end of season months. Dispersion patterns of crab burrows in the different beach zone areas at the beginning, middle and end of the season, were estimated using a dispersion index (DI). The DI is equivalent to the ratio between the variance and the mean number of burrows per beach zone area (Elliott, 1977). The distribution pattern was analysed with a DI which indicates whether distribution is clumped (values above 1), uniform (value equal to 1) or random (value below 1) (Krebs, 1989).

Beach Profiles were determined by calculating the total elevation and total beach width. By plotting the cumulative vertical elevations (y-axis) as a function of the cumulative horizontal (x-axis) positions we determined the beach profiles of six beach zone areas on Cousine's nesting beach. We used Beach Profile Analysis Version 3.2 (2000) to plot and create visual profile graphs of the six zone areas. All statistics were done using SigmaPlot Version 11. A one-way analysis of variance (ANOVA) and Tukey Post-Hoc tests were used to determine the significant differences in vertical drops between seasons and profile lengths between seasons and beach zone areas.

4.4 Results

4.4.1 Crab density and distribution

A significantly higher crab burrow density was found on the backshore (n = 1147) than on the foreshore (n = 775) across the whole nesting season (Kruskall Wallis Tukey test; H = 20.825, df = 1, p<0.05). However, there was no significant difference in density of crab burrow counts between the backshore and the foreshore at the beginning of the season (October) (H= 0.903, df = 1, p = 0.342), only in the middle of the season (December) (H = 9.994, df = 1, p = 0.002) and at the end of the season (February) (H = 12.431, df = 1, p < 0.05) (Figure 4.2).

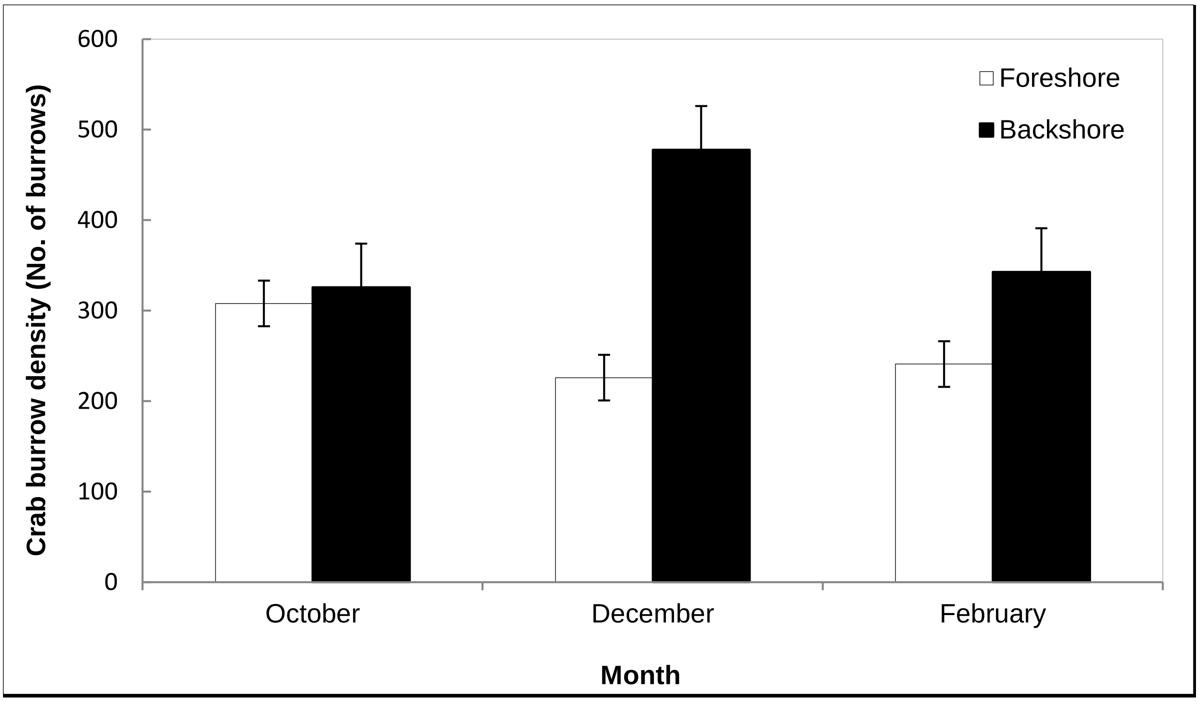


Figure 4.2 Mean (± SD) foreshore and backshore crab burrow counts across the nesting season on Cousine Island in 2014 - 2015.

Table 4.1 Crab burrow density data collected on Cousine Island beach during the 2014\2015 nesting season. Included is the total size of sandy beach present (m^2) over the nesting period and between the different beach zone areas.

Date	**Zone**	**Mean burrows / m^2**	**No. of burrows**	**No. 30m^2 transects**	**Total sandy beach (m^2)**
October	(0 - 4)	0.14	84	31	930
	(5 - 9)	0.11	70	34	1020
	(10 - 14)	0.09	59	51	1530
	(15 - 19)	0.03	84	106	3180
	(20 - 24)	0.03	108	124	3720
	(25 - 29)	0.08	229	108	324
	Total	**0.08**	**634**	**454**	13620
December	(0 - 4)	0.09	95	44	1320
	(5 - 9)	0.03	113	120	3600
	(10 - 14)	0.02	55	109	3270
	(15 - 19)	0.04	91	79	2370
	(20 - 24)	0.04	85	82	2460
	(25 - 29)	0.10	265	89	2670
	Total	**0.05**	**704**	**523**	15690
February	(0 - 4)	0.06	359	157	4710
	(5 - 9)	0.04	97	104	3120
	(10 - 14)	0.07	63	41	1230
	(15 - 19)	0.17	58	29	870
	(20 - 24)	0.19	57	29	870
	(25 - 29)	0.11	193	63	1890
	Total	**0.11**	**827**	**423**	12690
	$\bar{x}$ **Mean**	**0.08**	**722**	**467**	14000

The total mean number of crab burrows / m^2 recorded on Cousine Island during the study period was 0.08 m^2 (Table 4.1). The mean number of crab burrows was at its lowest in the middle of the season at 0.05/m^2 and at its highest at the end of the season at 0.11/m^2. The total amount of sandy beach available for measuring burrow counts was at its highest in the middle of the season at 15690 m^2, then 13620 m^2 at the beginning of the season and at its smallest at the end of the season at 12690 m^2. The mean size of sandy beach throughout the season was 14000 m^2. We also examined crab burrow density in relation to the width of beach area (m) between the different months of the season (Figure 4.3) and then looked for any significant relationships between crab burrow density and beach area size over the entire season. When using a Pearson's Correlation coefficient, we found that there was a significant negative correlation between the two variables ($r = - 0.707$, $p = < 0.001$, $n = 18$).

on Cousine Island in 2014 – 2015 and in relation to beach width (m).

South beach (zones 0-4) and north beach (zones 25-29) had the highest counts over the whole season with 538 and 687 burrow counts respectively. The number of crab burrow counts on South beach was highly varied across the season, with 84 burrows found at the beginning of the season and 359 at the end of the season. Therefore, the end of season counts (359) on South beach differed significantly from the beginning of the season counts ($n = 84$) and from the middle of the season counts ($n = 95$; $p < 0.05$ for both). The number of burrow counts on North beach showed less variation across the season, with 229 counts at the beginning of the season and 193 at the end of the season. The beginning and end of season counts did however still differ significantly with the middle of the season count ($n = 265$; $p < 0.05$ for both).

Simple linear regressions were run to investigate relationships between the beach zones and burrow numbers throughout the season. In the beginning of the season (October) a positive relationship between burrow numbers and increasing zone numbers (increasing towards North Beach) was seen ($r^2 = 0.54$; $p < 0.001$) which was confirmed with a Pearson's correlation coefficient of 0,657 (Figure 4.4A). During the middle of the season (December) a similar positive relationship between burrow numbers and increasing zone numbers (increasing towards North Beach) was seen ($r^2 = 0.33$; $p < 0.01$), which was confirmed with a Pearson's correlation coefficient of 0,498 (Figure 4.4B). At the end of the season a negative relationship between burrow numbers and increasing zone numbers (increasing towards North Beach) was seen, however it was not statistically significant ($r^2 = 0.18$; $p < 0.1$). The Pearson's correlation coefficient was -0.345 (Figure 4.4C).

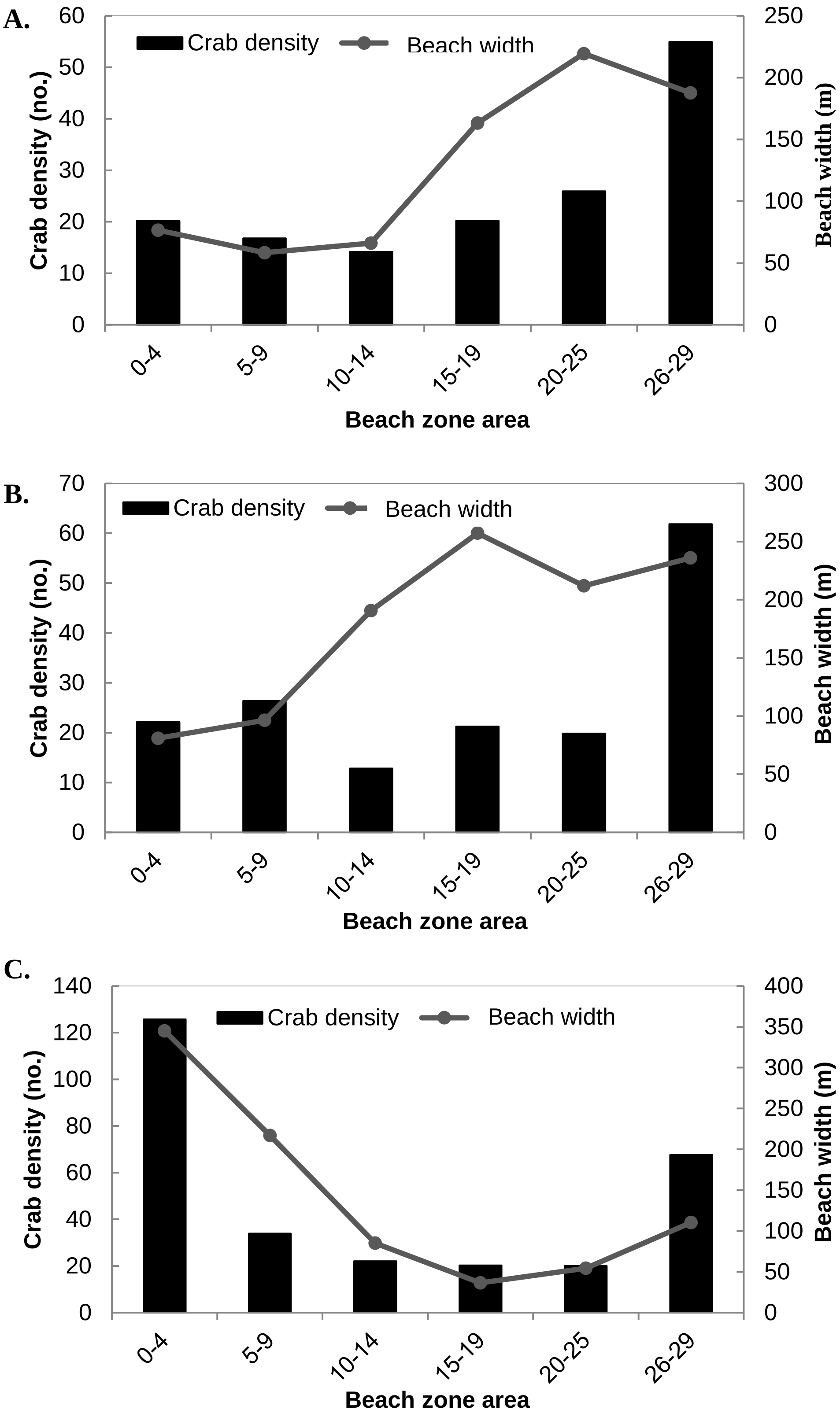


Figure 4.3 Crab burrow density across beach zone areas during **A**. Oct, **B**. Dec and **C**. Feb.

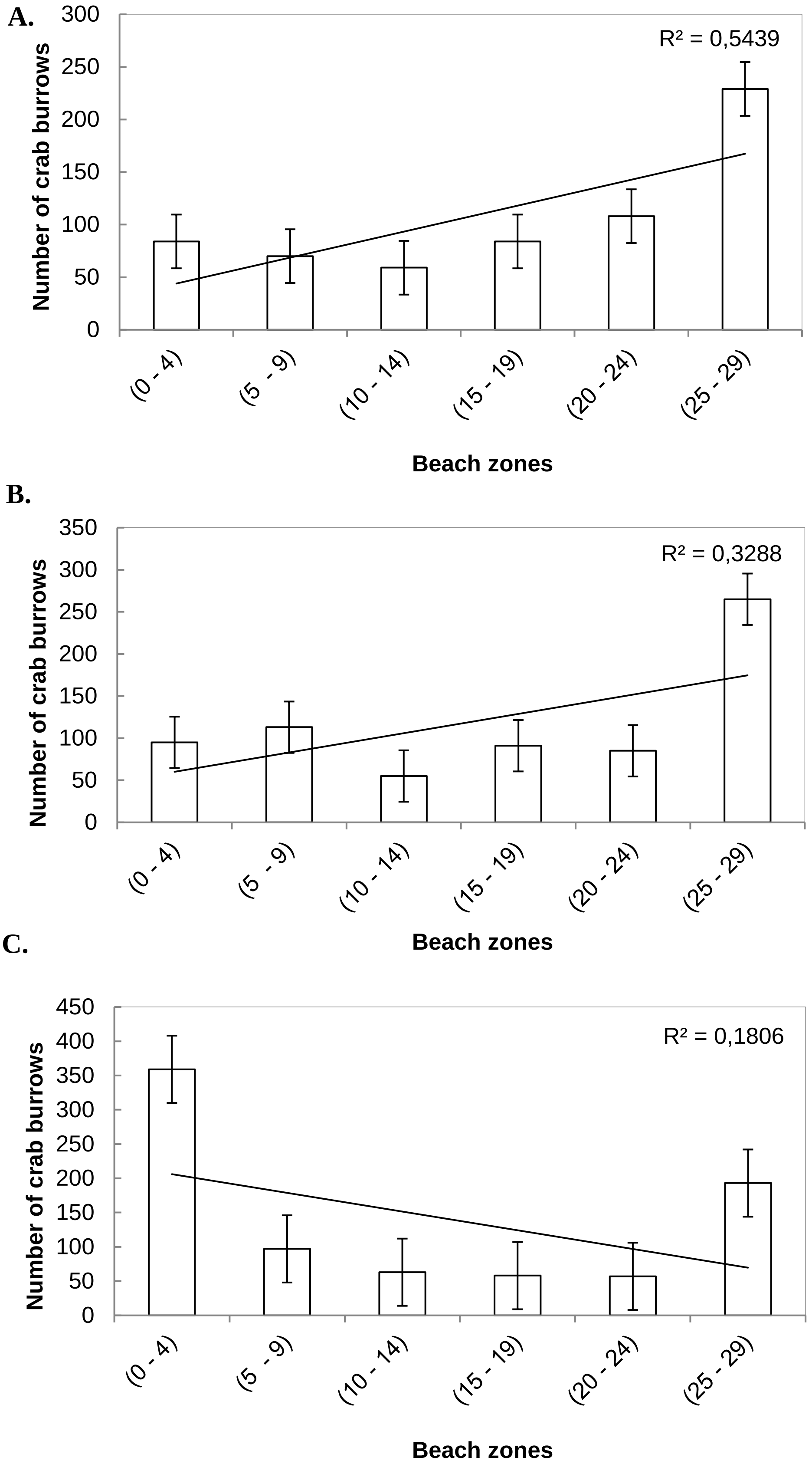


Figure 4.4 Crab burrow density across beach zone areas during **A**. Oct. **B.** Dec. & **C**. Feb. on Cousine Island.

When examining the distribution of crab burrows on Cousine Island, we used a Dispersion Index (DI). The DI values across all beach area zones and sampling months (October, December and February) were all above 1 therefore indicating clumped distribution of crab burrows across the whole of Cousine Islands beach (Table 4.2).

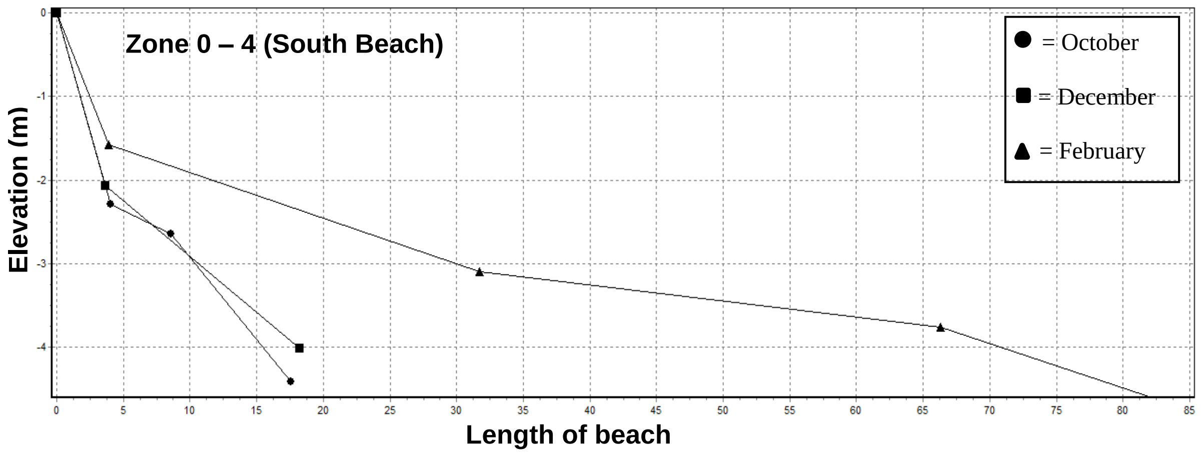
Table 4.2 The dispersion pattern of ghost crab burrows in relation to the month (beginning, middle and end of nesting season) and beach zone on Cousine Island during the 2014\2015 nesting season. Dispersion Index (DI) is based on the relationship between the variance and number of burrows. The higher the dispersion index, the more clumped the burrows will be.

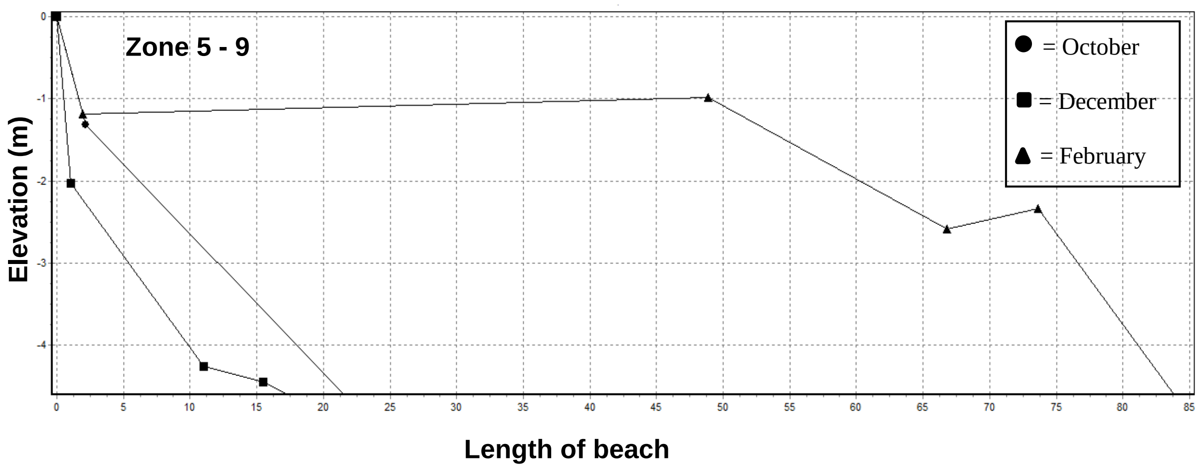
Date	Zone	Total no. of burrows	Dispersion Index	Type of distribution
October	(0 - 4)	84	**5.96**	clumped
	(5 - 9)	70	**4.48**	clumped
	(10 - 14)	59	**3.14**	clumped
	(15 - 19)	84	**1.99**	clumped
	(20 - 24)	108	**3.02**	clumped
	(25 - 29)	229	**2.38**	clumped
December	(0 - 4)	95	**1.62**	clumped
	(5 - 9)	113	**1.20**	clumped
	(10 - 14)	55	**3.16**	clumped
	(15 - 19)	91	**8.97**	clumped
	(20 - 24)	85	**2.67**	clumped
	(25 - 29)	265	**12.71**	clumped
February	(0 - 4)	359	**35.23**	clumped
	(5 - 9)	97	**5.64**	clumped
	(10 - 14)	63	**4.45**	clumped
	(15 - 19)	58	**7.30**	clumped
	(20 - 24)	57	**4.52**	clumped
	(25 - 29)	193	**23.09**	clumped

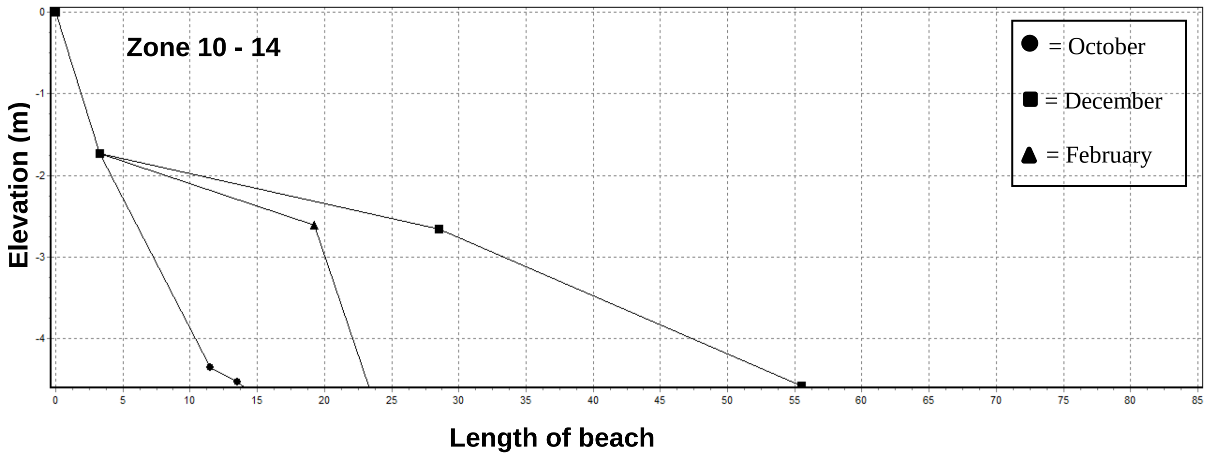
4.4.2 Beach Morphology

The beach on Cousine Island comprised of two different profile types, namely an erosional profile and an accretional profile. A visual representation of beach profile change across the nesting season and across the six beach zone areas is shown in Figure 4.5. Vertical elevations varied between beach zone areas and over the season. The smallest mean vertical drop was -16°78´ in zones 15 - 19 during October and the highest was - 81°38´ in zones 4 - 9 during December. The biggest difference in mean vertical drop over all beach zone areas was seen between October and December with an increase of 9°68´. A mean decrease of 4°32´ was seen between December and February across all beach zones areas. Zones 4 - 9 showed the greatest difference in vertical drop with an increase of 40°80´ between October and December and then a decrease of 37°32´ between December and February. Mean vertical drops between the different beach zone areas did not differ significantly in October (ANOVA, F = 1,637, p = 0.20), December (Kruskal-Wallis ANOVA, H = 1,416, p = 0.92) nor in February (Kruskal-Wallis ANOVA H = 5,114, p = 0.40).

The mean vertical elevation drop of all the profiles was 537 cm (measured from the position of the reference marker which is located on the top of the dune crest). The overall mean profile length was the shortest in October at 32.2 m, then 40.4 m in December and then 49.5 m in February. The overall mean beach width across all zones and across the season was 40.7 m. Profile lengths or beach widths varied between beach area zones and across the season. Mean beach widths of beach zone areas varied between 120.8 m in zones 0 - 4 and 12.8 m in zones 15 - 19, both during February. The biggest and smallest difference in mean beach width was seen in zones 0 - 4. The biggest difference was seen between December and February with 101.9 m, and then a difference of only of 0.5 m was found between October and December.


Zone 0 – 4 (South Beach)
● = October
■ = December
▲ = February
Elevation (m)
0
-1
-2
-3
-4
Length of beach
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85


Zone 5 - 9
● = October
■ = December
▲ = February
Elevation (m)
0
-1
-2
-3
-4
Length of beach
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85


Zone 10 - 14
● = October
■ = December
▲ = February
Elevation (m)
0
-1
-2
-3
-4
Length of beach
0
5
10
15
20
25
30
35
40
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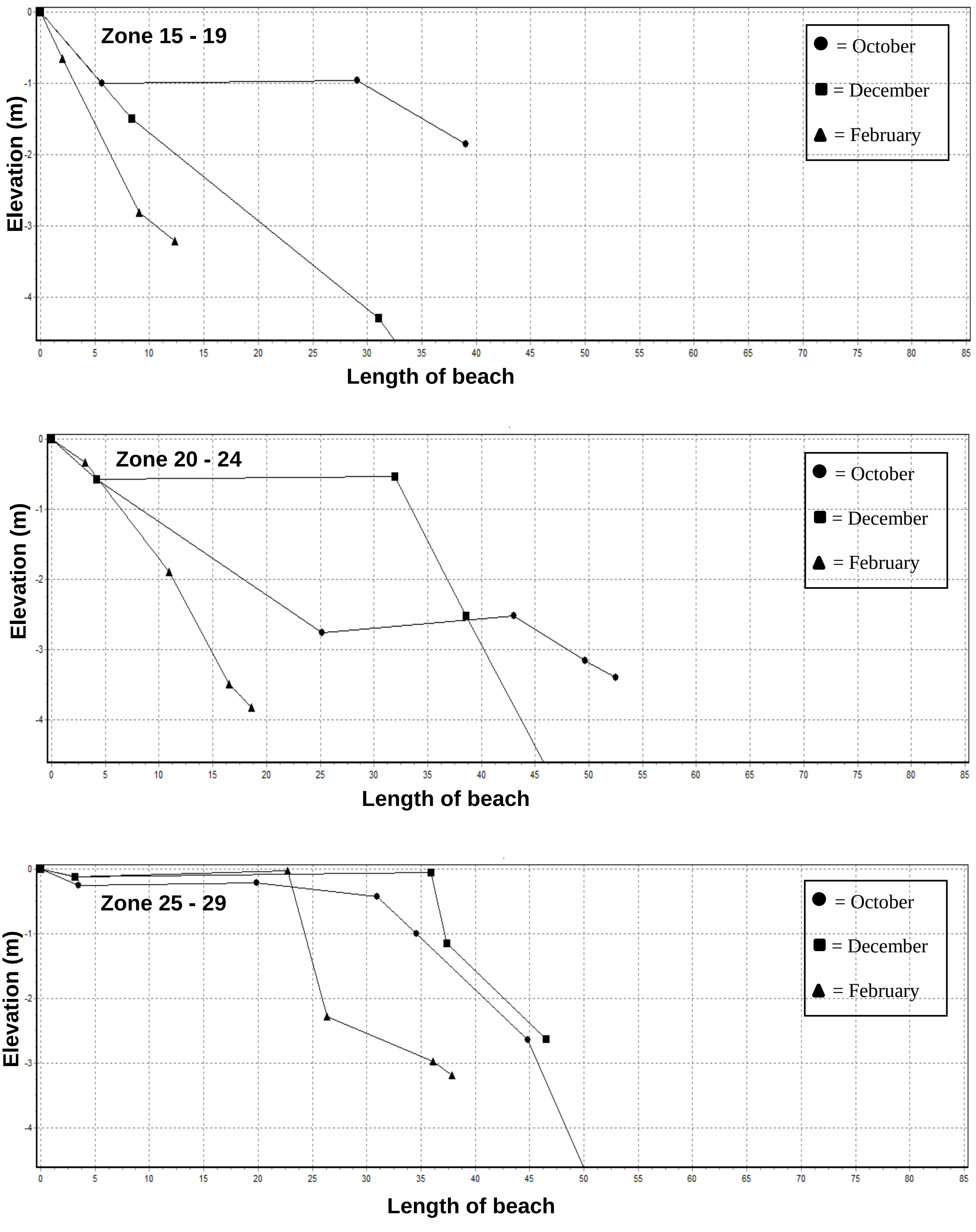

Figure 4.5 Beach profiles of each beach zone areas showing elevation change in Oct., Dec. and Feb. on Cousine Island in 2014 - 2015.

Mean profile lengths or width of beach between the different beach zone areas did not differ significantly in October ($p = 0.47$), December ($p = 0.94$) nor February ($p = 0.24$). However, when examining them individually and between months using Tukey Post-Hoc Tests, significant differences were found. The width of beach in October differed significantly to the width of beach in February (February being the widest) in zones 0 - 4 ($p < 0,001$) and zones 5 - 9 ($p < 0.05$). The width of beach in October differed significantly to the width of beach in February (October being the widest) in zones 15-19 ($p < 0.05$), zones 20 - 24 ($p < 0.05$) and zones 24 - 29 ($p < 0.05$). No significant differences in widths were found however in zones 10 - 14 ($p = 0.310$). The beach widths also differed significantly between December and February (February being the widest) in zones 0 - 4 ($p < 0.001$) and zones 5 - 9 ($p < 0.05$). The beach widths also differed significantly between December and February (December being the widest) in zones 10 - 14 ($p < 0.05$), zones 15 - 19 ($p < 0.001$), 20 - 24 ($p < 0.05$) and 25 - 29 ($p < 0.05$). No significant differences in beach widths between October and December were found except in zones 10 - 14 ($p < 0.05$) and zones 15 - 19 ($p < 0.05$), with December being the widest. A visual representation of beach width change between October, December and February is shown in Figure 4.6.

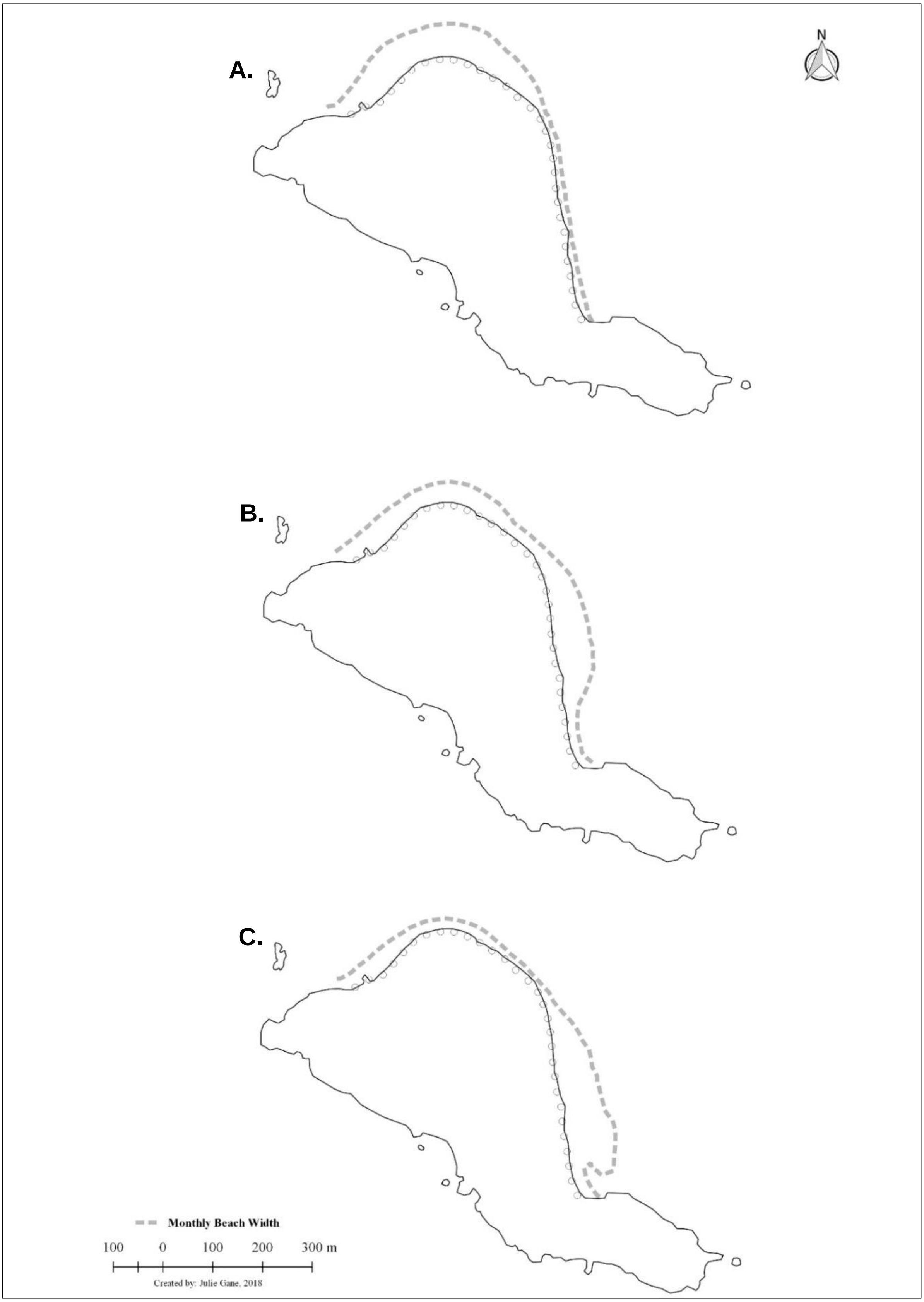

Figure 4.6 Beach width change on Cousine Island between **A**. October, **B**. December and **C**. February during the 2014\15 hawksbill nesting season.

4.5 Discussion

4.5.1 Crab density and distribution

The highest density of ghost crab burrows was found on the backshore across the entire hawksbill turtle nesting season. This corresponded to other studies done on ghost crabs favouring the backshore areas of the beach (Lucrezi *et al.,* 2009; Turra *et al.,* 2005). Ghost-crabs live in both wet and dry sediment but are reliant on water to moisten their gill chambers (Fisher and Tevesz, 1979; Wolcott, 1976). In a study done by Lucrezi *et al.* (2009), the density of ghost crab burrows was positively correlated to higher sand moisture. This contrasted with our results as the foreshore had higher sand moisture due to being in contact with waves. However, higher temperatures are also reported to increase crab burrow density (Lucrezi *et al.,* 2009) and could be the influencing factor for the high backshore densities on Cousine Island. Crab densities though were only significantly higher on the backshore during the middle and end of the nesting season. The backshore is closer to incubating turtle nests which are predominantly found on the dune crest or over the dune crest (Chapter 2). This is more likely an explanation for the significantly higher burrow numbers on the backshore. Furthermore, the middle and end of the nesting season have the highest number of incubating nests available for crabs to prey on, which could explain why the density increased as the nesting season progressed. Increasing numbers of turtle nests as the season progressed could also explain the overall density results which showed that crab numbers across all zones were at their highest at the end of the season.

When examining the available sandy beach area in relation to crab density (crabs/m²) we found that they correlated negatively to one another. When beach area was at its highest in times of accretion, crab’s density was at its lowest and the smallest beach areas (during times of erosion) had the highest crab densities. When examining across all zones and across the whole season, the total amount of sandy beach was at its highest during the middle of the season which was also when the density of crabs was at its lowest. We further investigated crab distribution across the beach area zones and found that the two zone areas which are bordered by rocks and native forest on each ends of the nesting beach (zones 0 - 4 and zones 25 - 29) had significantly higher crab burrow numbers than the other beach zones. These areas could have higher crab numbers because the presence of rocks and the fringing native forest would provide crabs with a safe refuge area and an area to possibly supplement their diet. Mortimer (1995) reported that there is higher predator presence near rocks on nesting beaches. Cumulatively these results indicated that crab density regulates according to the available amount of burrow medium and food availability.

We examined variation in crab burrow numbers across the season and found that zones 0 - 4 (South Beach) showed the highest variation between the different seasons, with the highest number of crabs occurring at the end of the nesting season but having the highest density of crabs at the beginning of the season. This again indicates that density is affected by the amount of available sandy beach. Zones 25 - 29 (North Beach) showed more consistent high burrow numbers and high densities across the season, with a slight increase towards the end of the season. Zone 25 - 29 receives the highest number of turtle nests each season (Chapter 2) which is possibly why crab density did not vary as greatly as in the other beach area zones.

In terms of management implications, nest translocation for reducing predation risk would be ineffective as the actual nests appear to be one of the main causes of increased crab density. Nests nearer to rocks and in areas with less sandy beach or small beach widths are however at a slightly higher risk. Predator proofing for increasing hatchling recruitment success would be advised as an alternative to translocating.

4.5.2 Beach morphology

Results suggest that the beach dynamics on Cousine Island are cyclical (Hitchens per. comm. 2014) and that the beach is prone to higher levels of erosion than accretion. More active sediment removal from erosion was seen than accretion during the entire nesting season on Cousine with the mean beach area and length being the smallest at the end of the season. The biggest change in elevation across the entire beach was seen between October and December when storms and rainfall from the northwest monsoon were possibly at their highest. The hawksbill turtle nesting season of the inner islands in Seychelles coincides with the northwest monsoon rainy season (Mortimer and Bresson, 1999) and creates elevated periods of erosion. In terms of management implications, hawksbill turtle nest translocations need to be systematically placed according to the erosion and accretion patterns observed in this study. Nests placed in the widest part of the beach during October have a high probability of being washed away during the end of their incubation period. Therefore, delineating safe areas in accordance to time in the nesting season can minimise nest loses and increase hatching success.

Beach gradient and beach elevation have an effect on the nesting ecology of turtles (Horrocks and Scott, 1991; Mortimer, 1995; Wood and Bjorndal, 2000). The mean vertical elevation drop of 5.37 m on Cousine is substantially higher than the ideal mean of 1.1 m reported by Horrocks and Scott in 1991. Most turtles coming onto Cousine Island to nest would however not nest as high as the dune crest where the reference point was situated and most probably nest between 2-4 m above sea level. Hawksbill turtles are adaptable but prefer nesting between 0.3 and 1.8 m above sea level and can be sensitive to elevation during nest selection (Horrocks and Scott, 1991; Wood and Bjorndal, 2000). Steeper, shorter beaches with steep approaches, such as the nesting beach on Cousine, have been reported to be preferred by nesting females due to having lower travel costs and lower predation risks (Mortimer, 1995; Horrocks and Scott, 1991). Although the beach on Cousine may appear less optimal than more stable beaches, its narrow and eroded areas can reduce energy expenditure during nesting and improve nesting success (Lamont and Carthy, 2007). However, the beach width changes could be a limiting factor for nesting success due to the high energy costs needed to find an optimal nesting site. The width of the beach in nearly all of the beach zone areas changed significantly throughout the season which can limit nesting success and affect hatching success if nests are placed too low on the beach and get washed away during erosion periods. As mentioned above, nest management can mitigate these risk factors and improve hawksbill turtle hatching success. There is a need for on-going long-term monitoring of the beach elevation due to predicted sea level rise in the future and due to the sensitivity of hawksbill turtles to elevation during nest site selection.

In conclusion it is clear that turtle nests on Cousine Island are under threat because of high densities of crabs and losses due to erosion. Nesting ecology and nest site selection are also at risk from both crab predation and high levels of erosion. All turtle nesting beaches represent compromises between several biological and physical characteristics, yet still have turtles coming to nest on them each year (Mortimer, 1995). Turtles are adaptable and have evolved with nesting habitat changes from natural causes such as seasonal accretion, seasonal erosion and high-tide flooding (Fish *et al.,* 2005). However, with the hawksbill turtle being Critically Endangered and with nest losses from crab predation and seasonal erosion being so high on Cousine, it is of upmost importance to develop the most effective management plan to safeguard the species into the future. Although beach morphology cannot be controlled by management, its effects can be mitigated. We hope that this study can assist in generating predictions of beach morphology across the beach zone areas and across the hawksbill turtle nesting season which can be practically applied for managing nests against losses and to maximise hatchling recruitment success.

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4.8 Appendices

Appendix 4.A: Mean beach profile data collected in each of the beach zone areas during the 2014\2015 nesting season on Cousine Island.

Zones 0-4 (South Beach)			
Month	**Beach Segment**	**Length of segment (m)**	**Slope angle (degrees & minutes)**
October	1	4.6	-29.3
	2	4.5	-4.3
	3	9.2	-11.6
December	1	4.2	-28.2
	2	14.7	-7.4
February	1	4.2	-22.7
	2	27.9	-3.1
	3	34.6	-1.1
	4	32.9	-3.2
	5	18.6	-4.0
	6	2.5	-1.4

Zones 5-9			
Month	**Beach Segment**	**Length of segment (m)**	**Slope angle (degrees & minutes)**
October	1	2.5	-31.2
	2	11.5	-9.4
December	1	2.3	-35.6
	2	10.2	-12.4
	3	4.5	-2.2
	4	5.5	-4.4
February	1	2.3	-31.2
	2	46.9	-0.2
	3	17.9	-5.6
	4	6.8	2.1
	5	1.9	-9.3

Zones 10-14			
Month	**Beach Segment**	**Length of segment (m)**	**Slope angle (degrees & minutes)**
October	1	3.7	-28
	2	8.7	-17
	3	2	-5
	4	1.5	-7.2
December	1	3.7	-28
	2	25.3	-2.7
	3	15.5	-4.4
February	1	3.7	-28
	2	16.0	-3.9
	3	6.2	-26.4
	4	3.9	-4.3

Zones 15-19			
Month	**Beach Segment**	**Length of segment (m)**	**Slope angle (degrees & minutes)**
October	1	5.7	-10.6
	2	23.4	-0.7
	3	10.1	-5.5
December	1	8.5	-10.7
	2	22.9	-7.2
	3	5.9	-12.3
	4	20.8	-9.4
	5	1.9	-5.3
February	1	2.1	-18.3
	2	7.4	-16.5
	3	3.3	-7.3

Zones 20-24			
Month	**Beach Segment**	**Length of segment (m)**	**Slope angle (degrees & minutes)**
October	1	4.2	-7.5
	2	21.1	-5.6
	3	17.8	-0.5
	4	6.7	-5.3
	5	2.9	-4.5
December	1	4.2	-7.5
	2	27.8	0.5
	3	6.9	-16.4
	4	8.5	-16.6
	5	2.0	-8.2
February	1	3.1	-6.3
	2	8.0	-11.1
	3	5.8	-16.9
	4	2.1	-9.2

Zones 25-29 (North Beach)			
Month	**Beach Segment**	**Length of segment (m)**	**Slope angle (degrees & minutes)**
October	1	3.5	-4.6
	2	16.4	-0.7
	3	11.1	-1.4
	4	3.7	-9.9
	5	10.4	-9.5
December	1	6.6	-21.4
	2	1.4	-11.4
	3	3.2	-2.7
	4	32.8	0.7
	5	1.8	-37.7
	6	9.3	-9.9
February	1	3.2	-2.7
	2	19.6	-0.2
	3	4.2	-32.7
	4	9.8	-4.3

CHAPTER 5

Conclusions

The hawksbill turtle *Eretmochelys imbricata* is a Critically Endangered species and is highly dependent on conservation for its survival (Blumenthal *et al.* 2009, Groombridge and Luxmoore 1989, Mortimer and Bresson 1999). With several conservation frameworks and strategies being effective for promoting population recovery (Hamann *et al*. 2010), deciding which conservation measures to apply to a specific nesting population is challenging. Sea turtle conservation measures are easiest and most feasible at the nesting phase (Mazaris *et al*. 2009) which has led to the majority of hawksbill turtle conservation measures being focused on the protection of nests and their nesting beaches (IUCN 2008). These conservation actions which are undertaken at the nest level and at the nesting site have generally led to an increase in hatchling recruitment success and increased nesting populations of sea turtles (Bjorndal *et al*. 1999, Mazaris *et al*. 2009, Chaloupka *et al*. 2008, Wyneken *et al.* 1988). However, choices in the application of conservation measures are often made in the absence of adequate data and have the potential to jeopardize population recovery (Mortimer pers. comms 2013).

In this study we clearly demonstrate that management measures can have both positive and negative effects on the nesting ecology of the hawksbill turtle and hatchling recruitment success in particular (Chapter 2; Chapter 3). Results provide insights into how the spatial distribution and environmental variations (Chapter 2), and predation barriers (Chapter 3) influence hatchling recruitment success rates and levels of predation. These results further substantiate how the location of a nest can differ in condition and which, according to Mazaris *et al*. (2009), can significantly affect embryonic development, fitness, sex determination, hatching success and the risk of predation. We further investigated the risk of predation and nest losses from erosion on the Cousine Island nesting beach and found that nests are at higher risk for both predation and erosion according to locality (Chapter 4).

Our focus on hatchling recruitment success and minimising predation rates was in line with Cousine Island's sea turtle management objective of maximising the output of hatchlings to sea (Hitchens pers. comm. 2014). The translocation of nests and the use of crab barriers, which are both conservation measures used on Cousine Island, have been reported to be positive conservation strategies in terms of maximising hatchling output (Wyneken *et al*. 1988). Our results demonstrated that the overall hawksbill hatchling recruitment success of nests protected with a crab barrier method of either netting or fencing, was significantly increased and predation was significantly decreased (Chapter 3). An important consideration as we also found that the hawksbill clutches incubating without crab barriers on Cousine were susceptible to losing on average a third or more eggs to crab predation than those with a crab barrier in place (Chapter 3).

High levels of predation at the egg stage have been reported to affect an entire sea turtle population and can slow down the recovery of a threatened population (Barton and Roth 2008, Leighton *et al.* 2011). Predation caused by ghost crabs (*Ocypode* spp.) is one of the most serious observed threats to incubating sea turtle nests on small oceanic islands (Marco *et al.* 2015). We examined the best possible incubation scenario for eggs in order to maximise hatchling recruitment and minimise the risk of predation with limited negative consequences (Chapter 3; Chapter 4). We found firstly, that translocating nests for the purpose of reducing predation risk would be ineffective as the actual eggs appear to be one of the main causes of increased crab density (Chapter 4). Secondly, we found that nests incubating in full sun surrounded by shade-cloth netting displayed the highest rates of success and lowest predation; and nests incubating in full shade with no crab barrier displayed the highest predation rates and the lowest rates of success (Chapter 3). Thirdly we found that when netting was used as a crab barrier it had a considerable cooling effect on the incubating eggs, which was substantial enough to have an effect on the sex ratio of a nest (Chapter 3). These results substantiate how important it is to carefully consider particular conservation measures, especially if the objective is to maximise hatchling recruitment success.

The hatchling recruitment success on Cousine was also found to be affected by nest losses from erosion each season (Chapter 2; Chapter 4). We found that the beach dynamic on Cousine is cyclical and discovered that the nesting beach is prone to higher levels of erosion than accretion which created significant changes to beach width across the season (Chapter 4). Not only does this affect the hatchling recruitment success, but can affect the nesting ecology of the nesting population on Cousine Island (Chapter 2; Chapter 4). The mean vertical beach elevation drop on Cousine is higher than what hawksbills have been reported to prefer (0.3 and 1.8 m above sea level) and can influence how females select their nest sites (Horrocks and Scott 1991, Wood and Bjorndal 2000). However, all turtle nesting beaches represent compromises between several biological and physical characteristics (Mortimer 1995), and turtles are adaptable and have evolved with nesting habitat changes such as seasonal accretion, seasonal erosion and high-tide flooding (Fish *et al.* 2005). With losses from seasonal erosion being so high on Cousine, we generated a baseline data set of beach morphology across the beach zone areas and across the hawksbill nesting season (Chapter 4). We therefore delineated safe areas for nests to be placed in accordance to the time during the nesting season. In terms of management implications, nest translocations on Cousine will require the systematic placement of nests according to these outlined erosion and accretion patterns observed in this study (Chapter 4).

When focusing turtle conservation measures at the nesting site, hatchling output can be increased and the nesting population can be increased in the long term (Bjorndal *et al.* 1999, Marcovaldi and Chaloupka 2007, Mazaris *et al.* 2009). This is a crucial period where the opportunity to minimise mortality and increase output exists. The natural mortality of hawksbill incubating eggs and hatchlings on Cousine is high and hatchling recruitment success rates are lower than in other areas where research studies have been conducted on hawksbill hatch success (Ditmer and Stapelton 2012, Horrocks and Scott 1991, Wyneken *et al.* 1988) (Chapter 2; Chapter 3). Results from this study have provided an opportunity for managers to minimise mortality at the egg stage and counterbalance overall mortality by adapting conservation measures accordingly (Chapter 3; Chapter 4). Collecting data over a long period (Chapter 2) is critical to monitor the population in terms of population dynamics and allows for additions to data on regional movements. We hope that this study will inform management decisions to protect this unique nesting population on Cousine Island and guide turtle programmes regionally thereby assisting in minimising the threat of extinction.

5.1 Findings for management consideration

Chapter 2

1. Results indicated that the number of nesting individuals is increasing; however the clutch frequency is very low compared to other study areas.
2. Night-time nesting is increasing, most likely due to increased disturbances (predation or human).
3. Clutch sizes decreased significantly across the season with a significant drop in hatchling recruitment success rate with clutch sizes exceeding 200 eggs.
4. Nests incubating in full sun showed the highest mean hatchling recruitment success rate and had the shortest mean incubation duration.

Chapter 3

1. Nests protected with netting had significantly higher hatchling recruitment success rates and nests protected with fencing had significantly lower predation rates than nests with no crab barrier.
2. Nests incubated in full sun displayed the highest hatchling recruitment success rates while nests which incubated in full shade had the highest predation rates.
3. Nest temperatures significantly differed between netted and control nests. Netting has a substantial cooling effect.
4. Sex ratios from natural nests were skewed towards females and netted nests skewed towards males.

Chapter 4

1. Crab burrow numbers were highest on the backshore and in location of turtle nests.
2. Crab density correlated negatively with available beach area.
3. The mean vertical beach elevation drop on Cousine is higher than what hawksbills have been reported to prefer. We suggest the continuation of beach elevation monitoring.
4. The biggest change in elevation across the entire beach was seen between October and December.
5. Nests placed in the widest part of the beach during October have a high probability of being washed away during the end of their incubation period. Therefore delineating safe areas in accordance to time in the nesting season can minimise nest loses and increase hatching success.

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