Informing dugong conservation at several spatial and temporal scales in New Caledonia

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Informing dugong conservation at several spatial and temporal scales in New Caledonia

Thesis submitted by

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For the degree of Doctor of Philosophy

in the College of Marine and Environmental Sciences, James Cook University

Under a co-tutelle agreement with

Université Pierre et Marie Curie, Sorbonne Universités

July 2015

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"A husband and wife were arguing, the woman took one or two plantain bananas with her and left in the sea. Her husband was waiting for her by the sea, but she never returned. Thus, the man followed the path of his wife in the sea, and both became "Modap" [dugongs]."

Acknowledgements

Richos, Cindy and Steve!! I am looking forward to living more adventures with you all! This PhD really has given me the opportunity to develop some amazing relationships in the Pacific region.

Special thanks to Melanie Hamel for all her love. Thank you for sharing the good, the bad and the ugly days. This thesis would have never been completed without your support.

Thanks to my family, my parents Henri and Annamaria and my brothers Cédric and Sebastien for their permanent support and love, and Frederic and Colette for their love and encouragement.

I dedicate this thesis to my Breton and Hungarian grandparents, my dad Henri, my mum Annamaria and my brothers Cédric and Sebastien. With all my love.

Statement on the Contribution of Others

Research funding

Stipend scholarship

Fee subsidy scholarship

Travel and conferences

- Agence des Aires Marines Protégées (AAMP)
- Institut de Recherche pour le Développement (IRD)
- JCU College of Marine and Environmental Sciences

Research in-kind support

- Opération Cétacés
- Météo-France
- Greenseas

Infrastructure external to JCU

- Institut de Recherche pour le Développement (IRD)
- Opération Cétacés

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Editorial support

- Professor Helene Marsh
- Professor Claude Payri
- Dr. Claire Garrigue
- Dr. Mariana Fuentes
- Dr. Alana Grech
- Dr. Mark Hamann
- Dr. Susan Sobtzick
- Shannon Hogan

Contribution of Others by Chapter

Thesis Chapter	Details of publication on which paper is based	Nature of the intellectual input of each author
2	Cleguer C., Garrigue C., Everingham Y., Fuentes M.P.B., Hagihara R., Hamann M., Payri C., Marsh H. (ready for submission) Temporal changes in the relative abundance of dugongs in New Caledonia. Target journal: *Marine Mammal Science*.	The design of the study was developed with Garrigue, Marsh, the AAMP agency and the resources managers of New Caledonia. I conducted the four aerial surveys of 2011 and 2012. I estimated the dugong relative abundance for the entire time series of surveys. Hagihara and Everingham provided significant advice regarding the dugong relative density analysis. I wrote the first draft and all authors contributed to the interpretation of the results and to the editing of the manuscript.
3	Cleguer C., Grech A., Garrigue C., Marsh H. (2015) Spatial mismatch between marine protected areas and dugongs in New Caledonia. *Biological Conservation*, 184, 154-162.	Grech taught me the necessary skills to develop the spatially-explicit model of dugong distribution and relative density, I developed the model and wrote the first draft and all authors contributed to the interpretation of the results and to the editing of the manuscript.
4	Cleguer C., Fuentes M.P.B., Garrigue C., Hamann M., Marsh H. (*in prep*) Movement heterogeneity of dugongs in the lagoons of New Caledonia. Target journal: *Journal of Experimental Marine Biology and Ecology*. Non-peer reviewed outputs Cleguer, C. (2012) Informing dugong movement and habitat use behaviour in New Caledonia – A pilot study. *SireNews*. Issue 57. Cleguer, C. Garrigue C., Preston S., Liebsch N., Marsh H. (in press) Use of a Sit-down Personal Watercraft to	Marsh and Fuentes taught me the necessary skills to deploy satellite tags on wild dugongs. Garrigue assisted in the field. I wrote the first draft and all authors contributed to the interpretation of the results and to the editing of the manuscript.

Thesis Chapter	Details of publication on which paper is based	Nature of the intellectual input of each author
	safely and quickly catch dugongs (*Dugong dugon*) in the coral reefs of New Caledonia. *SireNews*.	
5	Cleguer C., Fuentes M.P.B., Garrigue C., Hamann M., Payri C., Marsh H. (*in prep*) Seasonal changes in the abundance and habitat use of dugongs in the coral reefs of Cap Goulvain. Target journal: *Coral Reefs*.	Marc Holt (pilot), Fabien Perotto (primary observer) and Romain Laigle (backup observer) conducted the ultra-light surveys after I trained them. Jean-Louis Menou deployed the water temperature data loggers. Martial Dosdane provided the aerial footage and Romain Laigle provided the underwater footage. I conducted all analyses. I wrote the first draft and all authors contributed to the interpretation of the results and to the editing of the manuscript.

Ethics Statement

All necessary permits required to capture and satellite-track dugongs were obtained from the James Cook University Animal Ethics Committee (Permits **A1735** and **A1936**) and the North (**60912155-2013/JJC**) and South (**3157-2012/ARR/DENV**) Provinces of New Caledonia.

Captured dugongs were handled in strict accordance with local and international regulations and using veterinary guidelines available in Appendix C, in this thesis.

Publications produced during my PhD candidature

Peer Reviewed Journal Articles

Chapter 2   **Cleguer C.**, Garrigue C., Everingham Y., Fuentes M.P.B., Hagihara R., Hamann M., Payri C., Marsh H. (ready for submission) Temporal changes in the relative abundance of dugongs in New Caledonia. Target journal: *Marine Mammal Science*.

Chapter 3   **Cleguer C.**, Grech A., Garrigue C., Marsh H. (2015) Spatial mismatch between marine protected areas and dugongs in New Caledonia. *Biological Conservation*, 184, 154-162.

Chapter 4   **Cleguer C.**, Fuentes M.P.B., Garrigue C., Hamann M., Marsh H. (*in prep*) Movement heterogeneity of dugongs in the lagoons of New Caledonia. Target journal: *Journal of Experimental Marine Biology and Ecology*.

Chapter 5   **Cleguer C.**, Fuentes M.P.B., Garrigue C., Hamann M., Payri C., Marsh H. (*in prep*) Seasonal changes in the abundance and habitat use of dugongs in the coral reefs of Cap Goulvain. Target journal: *Coral Reefs*.

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Garrigue C., **Cleguer C.**, Schaffar A., Oremus M. (2012b) Distribution and abundance of dugongs in New Caledonia, 2012. *Rapport de mission de la campagne de juin 2012*. 27p + annexes.

Garrigue C., **Cleguer C.,** Schaffar A. (2011a) Distribution and abundance of dugongs in New Caledonia, 2011. *Rapport de mission de la campagne de juin 2011*. 25p + annexes.

Garrigue C., **Cleguer C.**, Schaffar A., Oremus M. (2011b) Distribution and abundance of dugongs in New Caledonia, 2011. *Rapport de mission de la campagne de novembre 2011*. 25p + annexes.

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Cleguer C. (2012b) Conservation du dugong en Nouvelle-Calédonie : une étude à plusieurs échelles spatio-temporelles. *Compte rendu d'étape N°2*. 18p

Cleguer C. (2013a) Conservation du dugong en Nouvelle-Calédonie : une étude à plusieurs échelles spatio-temporelles. *Compte rendu d'étape N°3*. 54p + Annexes

Cleguer C. (2013b) Conservation du dugong en Nouvelle-Calédonie : une étude à plusieurs échelles spatio-temporelles. *Compte rendu d'étape N°4*. 53p. + Annexes

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Cleguer C., Garrigue C., Preston S., Liebsch N., Marsh H. (2015) Use of a Personal Watercraft to Safely and Quickly Catch Dugongs (*Dugong dugon*) in the coral reef lagoons of New Caledonia. *SireNews*.

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Cleguer C. & Pusineri C. (in press) The dugong. *Marine Mammal Atlas. Museum of Natural History of Paris.*

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Abstract

Comprehensive, up-to-date spatial information on species distributions and threatening processes can enhance the identification of sites for conservation and management action. Such information is often incomplete or simply unavailable at a scale that can inform real-world decision making because the cost and capacity needed for collecting reliable information are high especially when targeting species that occupy large ranges.

Obtaining data to inform conservation at the appropriate spatial scale is of particular importance for species that occupy large ranges. The dugong (*Dugong dugon*) is a seagrass specialist and marine mammal that occurs over 130,000km of coastline in the Indo-West-Pacific. The dugong attracts global conservation attention because it is listed as vulnerable (IUCN Red List) and is increasingly exposed to multiple anthropogenic hazards in most of its range. There are many regions within the dugong's range where the likelihood of survival of the species is unknown. Collecting spatial-ecological information on the dugong in these regions can inform and optimize the effectiveness of regional and national conservation and management initiatives.

The island-archipelago of New Caledonia is located in the Oceania region at the eastern edge of the dugong's range. The conservation status of the dugong in this region is unknown. The presence of the charismatic dugong in the lagoons of New Caledonia was an explicit reason for the World Heritage listing of some of the lagoons. No conservation actions have been implemented in New Caledonia to ensure the maintenance of the dugong stock except for the legislation that restricts dugong harvesting despite the species' high biodiversity, cultural and traditional value.

The goal of my thesis was to build an evidence-base to enhance the conservation and management of dugongs in New Caledonia at several spatial and temporal scales and enhance understanding of dugong ecology in tropical coral reef environments by:

1. Assessing the temporal changes in the dugong population size and the capacity of the current marine protected areas (MPAs) to protect dugongs at the scale of New Caledonia.
2. Investigating the spatial ecology of dugongs in the coral reef lagoons of New Caledonia by studying their movement patterns and habitat use at local scales.
3. Integrating scientific research conducted on dugongs as part of this thesis to inform decisions relating to dugong conservation and management regionally and internationally.

A single baseline aerial survey of dugongs in New Caledonia in 2003 estimated a population of 2026 (± SE = 553) individuals. A second similar survey in 2008 produced a lower estimate of

606 (± SE = 200) individuals, leading to concerns that the dugong population was experiencing a decline. I conducted four additional surveys in 2011 and 2012 with the objectives of updating information on the current size of the dugong population in New Caledonia and investigating evidence of decline in the population. The abundance estimates obtained from my four surveys ranged from 649 (± SE = 195) to 1227 (± SE = 296) dugongs. These results were not significantly different to the 2008 estimate but were significantly lower than the 2003 estimate. I concluded that the confounding effects of variation in environmental conditions, animal behaviour and sampling biases likely played a key role in the variation of the dugong population size estimates as I could not find any evidence external to the surveys that the dugong population had declined between 2003 and 2008 or that temporary migration was likely to have occurred.

I used the data obtained from the time series of aerial surveys to develop a spatially-explicit model of dugong distribution and relative density. This model enabled me to determine the distribution of dugongs at the scale of the main island of New Caledonia over nearly a decade of monitoring, and to detect key dugong habitats.

Dugongs were not explicitly considered in the design of the network of marine protected areas (MPAs) in New Caledonia. Thus any representation of important dugong areas in the MPA network is incidental. I used the spatially-explicit model of dugong distribution and relative density to retrospectively assess the capacity of the New Caledonia MPA network to protect dugongs from anthropogenic hazards. I quantified the amount of overlap between dugong relative density units and each type of MPA that was managed at the time of the study. I found that most of the important dugong areas in New Caledonia had a low coverage from the MPAs that provide high levels of restriction of anthropogenic activities. I identified several important dugong areas along the west and the north-east coast that were not covered by MPAs and should be considered in future conservation and management plans. The spatial mismatch between MPAs and dugong distribution was likely caused by weaknesses in the planning process. I provided guidance on how these shortcomings can be overcome for marine species of conservation concern in New Caledonia and other regions.

The lack of consideration of marine mammals in conservation tools such as MPAs often stems from their highly mobile nature and dynamic movement patterns and the difficulty of defining their specific habitat needs due to lack of knowledge. Information on the dugong's use of space among key habitats and the scale of these movements has been comprehensively studied only in Australian waters where the environment differs from the lagoons of New Caledonia. I used satellite tracking technology to document the use of space by dugongs in the lagoons of New Caledonia. I developed a method of safely and quickly capturing dugongs in coral reef habitats

and satellite–tracked 12 adult dugongs in three different regions of the west coast of New Caledonia. Animals displayed individualistic movement patterns. Their extent of movement was large relative to the size of the main island, and some individuals crossed jurisdictional boundaries. Three dugongs exited the lagoon and used the fore reef shelf (i.e., flattened coral reef area, located between the fore reef crest and deep open ocean waters) as corridor to transit from one bay to another. All tracked dugongs returned to their capture location. Home-range analyses showed that the range and core areas used by dugongs reflected the width of the lagoons. The home-range and core areas of dugongs did not differ between day and night.

I investigated the habitat use of dugongs at a local scale at Cap Goulvain to enhance understanding of seasonal changes in abundance and habitat use of dugongs in coral reef environments and to provide spatially-explicit data to help local conservation decisions in a key dugong conservation value area. Access to seagrass resources is restricted by tides and the geomorphology of habitats and small size of the lagoon restrict dugongs' space use. I used data obtained from fine-scale dedicated dugong aerial surveys conducted every two weeks over 18 months at low and high tide to determine the seasonal and tidal changes in the number of dugongs and their use of a range of habitats in Cap Goulvain. I then compared the resultant dataset with the temporal changes in water temperature inside and outside the lagoon in this region.

I found that more dugongs were sighted during the cool season than during the warm season in Cap Goulvain. At high tide, dugongs were expectedly sighted over the intertidal seagrass meadows in higher proportion than in any other monitored habitats during both seasons. As tides restricted access to the intertidal seagrass meadows there was a seasonal change in the use of other non-seagrass coral reef habitats: during the cool season, a higher proportion of dugongs was sighted outside the lagoon on the fore reef shelf than in any other habitat inside the lagoon; during the warm season the use of the fore reef shelf was less pronounced and dugongs were sighted in higher proportion inside the lagoon in the channels surrounding the intertidal seagrasses. Behavioural thermoregulation is a plausible explanation for the changes in the number of dugongs and the use of the fore reef shelf in Cap Goulvain during the cool season. Further investigation is required to assess the effect of other external factors including the temporal changes in the availability and quality of seagrass and abundance of sharks.

Dugong aggregations (i.e., group of ≥ 10 animals) were observed inside the lagoon of Cap Goulvain during the warm season and outside the lagoon during the cool season. I used aerial and underwater footage of the dugong herds located outside the lagoon to explore the behaviour of dugongs in the herds. I found that the dugongs forming the aggregations were resting and no social behaviour other than calves feeding from their mother's teats was identified. The likely

causes of dugong aggregations in this habitat include access to warm water, the number of dugongs present in the region at the time, the size of the fore reef shelf, the distance to inshore seagrass resources, and the risk of predation from sharks. These results demonstrated that both seagrass and non-seagrass habitats are important for dugongs and need to be included in future conservation and management programs in New Caledonia as well as other tropical coral reef regions.

My thesis provided opportunities to enhance the conservation and management of dugongs in New Caledonia and new insights into the spatial ecology of dugongs in coral reef environments. Future management would be enhanced by considering the important dugong habitats and corridors identified in my research and should be coordinated at an ecological scale relevant to the dugong to be effective. Given the high cultural value of the dugong to the peoples of New Caledonia, communities should be consulted about their desire to participate in community-based management. In addition, ongoing education and communication programs should be continued especially in regions where illegal hunting may occur. Future research should be directed at understanding why illegal hunting occurs in New Caledonia and how compliance with the law could be increased. Further investigating the fine-scale interaction between seagrasses and dugongs in New Caledonia would also greatly enhance our understanding of dugong and seagrass ecology in tropical lagoons and coral reefs more generically.

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Chapter 1: General Introduction

1.1　Introduction

Wildlife and their natural environments are increasingly threatened, compromising the condition of ecosystems and the benefits and services they provide to human communities (Butchart *et al.* 2010). As a result, there is a growing appreciation of the urgent need for conservation actions at local, regional, national, and international levels (Rands *et al.* 2010). Conservation, defined here as actions that are intended to establish, improve or maintain good relations with nature (Sandbrook 2015), is often practised through the design and implementation of management plans that have been developed for single species or sets of species, habitats or ecosystems. These plans generally contain the following major components: conservation objectives, and specific costed and prioritised strategies or actions to meet those objectives over specified time frames (Groves *et al.* 2002; Sutherland 2008). Whether or not these plans are optimized to protect the features of interest most cost-effectively is rarely addressed. Assessment of the adequacy of conservation plans is often limited by a lack of knowledge about the features of interest and the likely relative impact of chosen strategies. Conservation and legislative imperatives often force conservation managers to develop conservation plans based on the Precautionary Principle using anecdotal evidence (Sutherland 2008) and/or risk assessment approaches.

In order for decision-makers to choose the best options and evaluate their practice, supporting information about features of interest must be readily available in a useable format (Groves 2003). However, too often this information is incomplete, unreliable, missing, or unavailable at a scale that is useful for informing real-world decision making (Di Minin and Toivonen 2015). Failing to use relevant information on features of interest often results in allocating –often limited- conservation resources and implementing conservation actions at the wrong time and/or in the wrong place (Pressey and Bottrill 2009). In the last decades, evidence-based frameworks have emerged as one of the tools to support decision-making in conservation management and to limit this risk (Pullin and Knight 2003; Pullin *et al.* 2004; Sutherland *et al.* 2004). One of the key components of evidence-based frameworks is to promote the objective identification of knowledge gaps and, therefore, prioritisation of areas where evidence needs to be acquired through appropriate research and monitoring practices. However, I do not advocate nations, especially developing nations, postponing conservation measures in the face of scientific uncertainties.

These problems are particularly challenging in the context of developing and implementing plans for conserving marine mammals, which are becoming critical as human populations continue to increase and cause modification to the natural environments of the coastal zone

(Gales *et al.* 2003; Reynolds *et al.* 2009). Marine mammals are distributed throughout the world's coastal zones and oceans. Marine mammals include both top predators (e.g., orcas) and important low trophic level consumers and grazers (e.g., dugongs); both groups play an important role in the food webs of oceanic and coastal ecosystems (Bowen 1997; Ridgway 1998). Marine mammals have relatively large body sizes and long lifespans. They follow a K-selection strategy with few offspring, long gestation, long parental care, and a long period until sexual maturity (Boyd *et al.* 1999). As a result, most marine mammals take a relatively long time to recover from disturbance, especially unusual mortality events. Marine mammals face an array of hazards from human activities, including bycatch in fishing gear, collision with vessels, depletion of prey resources, hunting, pollution, disease, and habitat degradation and loss, and climate change (Marsh *et al.* 2003). Nearly 3% of the world's marine mammal species have become extinct due to human activities in the past 60 years (Marsh *et al.* 2003; Reynolds *et al.* 2009). The status of many species or populations of marine mammals has not been assessed due, in part, to data deficiency (IUCN 2015). Thus, there is an urgent need to assess the status of many marine mammal populations to inform conservation and management strategies.

The effective management of marine mammals is often constrained by the costs associated with implementing conservation actions at appropriate temporal and spatial scales, partly because marine mammals tend to occupy large ranges (Pompa *et al.* 2011). Spatially-explicit models of marine mammal distribution can greatly inform the strategic deployment of conservation resources over large spatial scales by identifying sites where species are most abundant, and where conservation actions should provide the greatest positive impact over their entire distributional range (Theobald 2003). Defining these critical habitats is the first step toward an effective spatial placement (or marine spatial planning) of reserves more commonly called marine protected areas that reduce hazards to species, while enhancing economically important anthropogenic activities (Ingram and Rogan 2002; Bailey and Thompson 2009).

Even basic monitoring and research to identify critical marine mammal habitats has not been carried out in many MPAs and few MPAs have developed adequate policy recommendations and adaptive ecosystem-based management guidance to guarantee effective habitat protection for marine mammals (Marsh *et al.* 2012; Hoyt 2012). Marine mammals, despite being iconic and having the potential to be used as keystones including cultural keystone (i.e., critical to the ecological function of a community or habitat), umbrella (i.e., their conservation will also conserve other species) and flagship species (i.e., their charismatic profile can leverage support for conservation), they are often overlooked in the design, establishment and management of MPAs and subsequent monitoring for adaptive management (Zacharias and Roff 2001; Schofield *et al.* 2013). The movement patterns of marine mammals are dynamic and their

habitat requirements are often unknown (Hoyt 2012). Nonetheless, advances in technologies such as telemetry devices now have the potential to provide essential information on the spatial and temporal movement patterns of individual marine mammals. This knowledge is increasingly used to identify their core activity spaces as sites worth protecting or to drive policy change (Bograd *et al.* 2010).

This thesis aims to inform the conservation and management of the dugong (*Dugong dugon*) in New Caledonia, an important population at the eastern edge of its global range. The remainder of this introduction provides a background on the issues associated with dugong conservation and a brief overview of dugong ecology. I then outline the information available on dugongs in New Caledonia and identify key information gaps required to enhance the conservation of species in that region. Finally, I present the objectives of my research and explain the structure of this thesis.

1.2   The dugong

Dugong conservation issues

The dugong is the only extant member of the family Dugongidae, and, together with the three species of manatee, one of four living species of the order Sirenia, which is one of the three mammalian orders considered to be most at risk of extinction (Purvis *et al.* 2000; Marsh *et al.* 2012). The other member of the Dugongidae, Stellers' sea cow (*Hydrodamalis gigas*), was exterminated within less than 30 years of its rediscovery in the middle of the eighteenth century because its last remaining population was over-exploited for meat (Stejneger 1887; Marsh *et al.* 2012). The extinction of this species demonstrates the vulnerability of the order Sirenia and provides justification for measures to proactively protect the four extant species.

The dugong is listed as vulnerable at a global scale on the IUCN Red List (Marsh 2008); and on Appendix I (species threatened with extinction) of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). The dugong is also listed under Appendix II of the Convention on Migratory Species of Wild Animals (CMS), which aims to conserve species crossing international frontiers (CMS 2009).

The dugong is believed to be declining or extinct in one third of its range and of unknown status in half of its range (Marsh 2008, 2011). Based on potential habitat (water <10m deep in the possible range states of the species) the estimated extent of occurrence of the dugongs is ~860,000km^2, spanning the coastal and island waters of at least 37, and to up to 44 countries

and territories (Marsh *et al.* 2012). Over much of its global range, the dugong is represented by relict populations (e.g., in Mayotte, Japan, Palau, etc.) and known only from incidental sightings and retrieval of carcasses (Marsh *et al.* 2002, 2012). The dugong no longer exists in the waters of several islands including the Maldives, the Mascarene Islands of Mauritius and Rodrigues, and Taiwan (Husar 1978; Marsh 2008), illustrating the increased vulnerability of populations in the isolated waters surrounding islands and archipelagos.

The need to address global dugong conservation and management issues was emphasized by the Thailand and the Australian governments under the auspice of the CMS, intergovernmental negotiation meetings held in 2005 and 2006 that led to the development of the CMS Memorandum of Understanding (MoU) on Dugongs and their Seagrass Habitats throughout their Range and the endorsement of its associated Conservation and Management Plan in October 2007. The CMS Dugong MoU has been signed by 26 state signatories to date (CMS 2014). The aim of the Memorandum of Understanding is to facilitate national level and trans-boundary actions that will lead to the conservation of dugong populations and their habitats. One of the objectives to help achieve this aim is to improve the knowledge of dugongs and their habitats through research and monitoring. France, the country that administers the territory of New Caledonia, is a signatory to the CMS dugong MoU.

Dugong ecology – a brief overview

Dugong ecology has been extensively investigated, mainly over the last three decades. I briefly describe some of the most important aspects that have been documented to date to provide a context for this study. This information is largely based on data collected from dugongs in Australia and in the Arabian Gulf. Marsh *et al.* (2012) provides an extensive synthesis of the information available on the ecology and conservation of dugongs and other sirenians. This synthesis has been augmented by more regionally-specific information in Hines *et al.* (2012).

Adult dugongs are usually 2-3m long (Marsh *et al.* 2012) and can live for up to 70 years (Marsh 1980; Marsh *et al.* 1984; Marsh 1995; Kwan 2002). The oldest wild dugong whose age has been estimated using the growth layer groups in its tusk was a female estimated to be around 73 years old when she died (Marsh 1995). Information on the reproductive biology of the dugong mostly comes from the analysis of material from carcasses of more than 1,500 dugongs, including some 400 individuals whose ages have been estimated (Bertram and Bertram 1970; Marsh *et al.* 1980, 1984, Marsh 1986, 1995; Kwan 2002; Marsh and Kwan 2008). Females have a minimum pre-reproductive period of 6-17 years (Marsh *et al.* 1984; Boyd *et al.* 1999; Kwan 2002; Marsh *et al.* 2012). This parameter varies among individuals and populations. The age of sexual maturity in males tends to be similar to that of females in the same population (Kwan 2002). The average

dugong calving interval is between 2.5 and 6.8 years in different populations (Marsh 1995). Population simulations indicate that even with the most optimistic combinations of life-history parameters (e.g., low natural mortality and no human-induced mortality) a dugong population is unlikely to increase more than 5% per year (Marsh 1986). Species with such a life history require very high and stable levels of adult survival to maintain their numbers and can sustain only very limited levels of mortality from human causes (Marsh *et al.* 2012).

Dugongs are the only strictly marine herbivorous mammal. They are seagrass community specialists feeding mostly on seagrass but also on other biota associated with seagrass communities such as algae and invertebrates (Marsh *et al.* 2012). Dugongs have been reported to feed on invertebrates at the subtropical limits of their range (Preen 1995). Dugongs closely associated with algal-covered, rocky reefs in the Northern Territory in Australia, have been documented by Whiting (2002, 2008) suggesting that dugongs may also subsist on algae. Feeding on individual species of structurally small seagrass in a mixed-species seagrass meadow may be difficult and individual dugongs often consume several seagrasses on a single dive (Johnstone and Hudson 1981). I further discuss the selection of seagrass and non-seagrass habitats by dugongs in Chapter 5.

As seagrass community specialists, dugongs are mostly distributed in shallow coastal habitats (up to 35m deep). Their coastal distribution puts them at risk from anthropogenic activities including: (1) direct hazards such as hunting, incidental and deliberate capture in nets, and vessel strike; and (2) indirect hazards such as the disturbance or destruction of their habitat (Marsh *et al.* 1999, 2002, 2012). The nature and level of hazards to dugongs varies across and within countries and territories across their range. Hazards to dugongs can be grouped into three main categories (Marsh *et al.* 2012): hazards experienced in the developing world; hazards more prevalent in developed regions; and hazards that are more universal. Natural factors including predation, severe climatic events, diseases, and parasites are generic hazards. In developed regions, dugongs are typically impacted by anthropogenic coastal activities including boating and shipping, coastal urbanization and industry that reflect the increasing human occupation of coastal environments (Marsh *et al.* 2012). In developing regions, urbanisation and industrialisation are likely to be less important but the dugong may still be a major food resource and is essential to food security. Consequently, the conservation of dugongs will only be effective if their hazards are investigated with regard to specific locations.

1.3   The dugong in New Caledonia

New Caledonia

The island-archipelago of New Caledonia is located in the southwest Pacific about 1,200km east of Queensland, Australia and approximately 1,500km north-northeast of New Zealand. New Caledonia is divided into three Provinces: the South, North and Loyalty Island Provinces (hereafter called Province Sud, Province Nord, Province des Iles Loyauté respectively, Figure 1.1). New Caledonia largely functions as an autonomous territory within the French Republic, and as such it is recognized as a *sui generis* territory. Sections 76 and 77 of the French Constitution, the Nouméa Accord (1989) and the New-Caledonia Organic Act (No. 99-209, 1999) provide the constitutional and legal framework under which New Caledonia and its Provinces are governed and define their institutions (Legifrance 2015).

The human population of New Caledonia was estimated in 2014 to be about 270,000 (ISEE 2014) and its growth rate was estimated in 2015 at 1.38% (Central Intelligence Agency 2015). Nouméa is the largest city in New Caledonia, with a population of 101,909 (ISEE 2014). The 'Great Nouméa', hereafter Nouméa region, includes the neighbouring Païta, Dumbéa and Mont-Dore communes. The Nouméa region is the largest urban region of New Caledonia and it has a population of approximately 155,000, accounting for two thirds of the population on the archipelago (ISEE 2014; Figure 1.1). The Voh-Koné-Pouembout (VKP) region located on the west coast of Province Nord is the second largest urban region with a population of approximately 15,000 (ISEE 2014; Figure 1.1). The Voh-Koné-Pouembout region is experiencing some major changes because of the establishment of a large metal-processing plant. The coastal developments, urbanisation and resulting human activities in these two regions are putting an increasing pressure on the marine coastal environment (David *et al.* 2010).

New Caledonia has one of the strongest economies in the South Pacific, with a Gross Domestic Product per capita of approximately US$ 36,000 in 2012 (ISEE 2014). The New Caledonia economy is driven by two main components: the financial transfers from Metropolitan France and nickel mining activities.

Most of New Caledonia's islands and coral reefs sit on a shallow shelf platform ringed by a continuous barrier reef 1,600km long (Andréfouët *et al.* 2009). New Caledonia's reefs and lagoonal formations cover an area of approximately 22,200km^2 (Andréfouët *et al.* 2009). The tropical lagoons are considered to be some of the most diverse reef systems in the world due to

their wide variety of shapes and forms within a comparatively small area. These formations range from extensive double barrier systems, offshore reefs and coral islands, to the near-shore reticulate reef formations in the west coast zone (Andréfouët *et al.* 2009). At their widest, the lagoons reach widths of 50km but narrow to 4km on the mid-west coast. The depth of the lagoons varies from very shallow (< 5m on the mid-west coast) to deep (≥ 40m) in channels that can reach 80m deep at the passes near the barrier reef. New Caledonia has a tropical climate that is moderated by the south-easterly trade winds. The warm season is from October to March when tropical depressions and cyclones occur (Météo-France 2014). After a brief transition, during which the Inter-tropical Convergence Zone shifts to the north, the cool season (April to October) begins, during which rainfall is lower than in the warm season and results from cold fronts associated with polar low pressure areas.
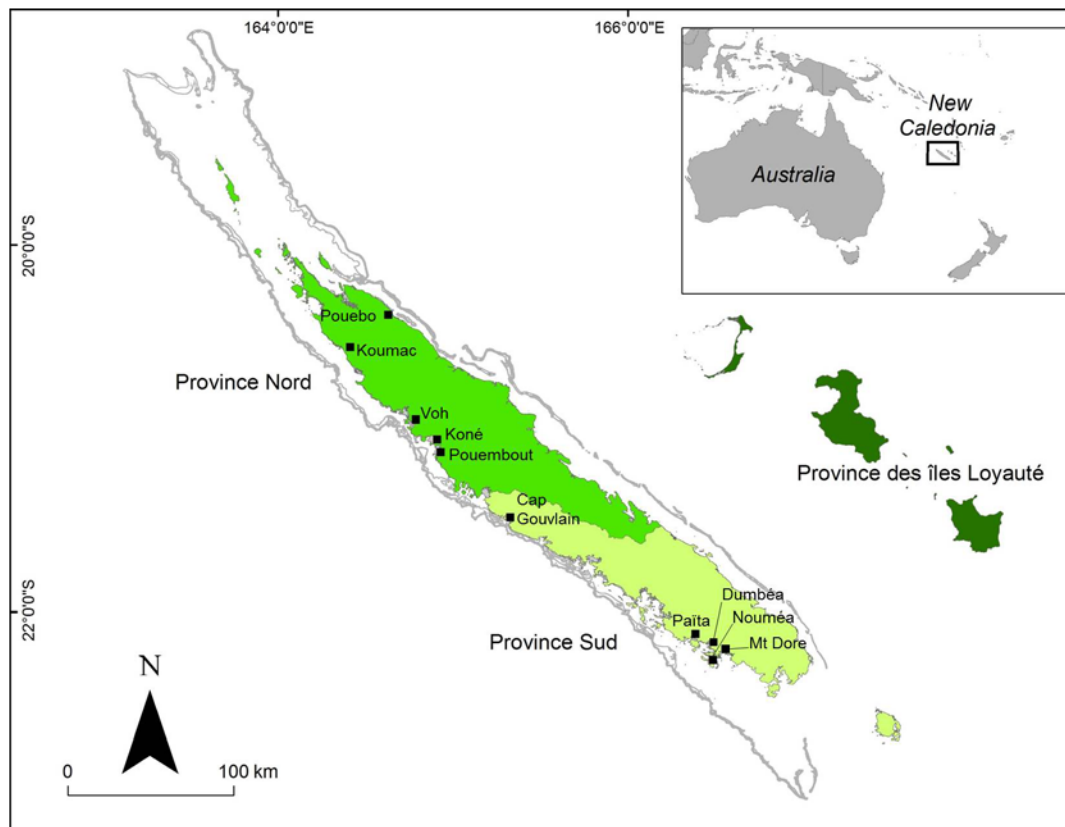
Figure 1.1: Map of the three Provinces of New Caledonia. Note the barrier reef represented by the grey lines.

The statutory powers associated with environmental protection and management, including MPAs, are shared between the French central government (international environmental law, fundamental and human rights), the New Caledonia Congress and government (natural resources of the Exclusive Economic Zone, mining activities, energy production, water management, and health, fiscal, and land planning measures etc. that are related to the environment) and the three Provinces (biodiversity, natural resources, maritime public domain etc.). Thus, Provinces are able to establish marine protected areas (MPAs) in the maritime public domain. Today, there are 33 MPAs in New Caledonia: seven in Province Nord and 26 in Province Sud (see Chapter 3). In addition to MPAs, six marine zones (henceforth UNESCO zones) representing major patterns in the diversity of coral reefs and associated ecosystems are registered as a World Heritage Area (UNESCO 2009). There are two UNESCO zones in each Province and each zone is managed by local management committees and the relevant Province management authority. Overall, patrolling and law enforcement are very weak (David *et al.* 2010).

Dugong conservation in New Caledonia

New Caledonia is among the eight confirmed dugong range states and territories with a very high Human Developed Index (UNDP 2010). It is located at the eastern edge of the dugong's range as explained above. France is signatory to the Dugong MoU under the Convention of Migratory Species (Marsh *et al.* 2012) and dugongs were an explicit reason for some of the lagoons' World Heritage listing in 2008 (UNESCO 2009). As a stronghold (Chapter 2) of the dugong in the Oceania region and a developed territory, New Caledonia has an international obligation to ensure the dugong survival.

The dugong is culturally very important to the indigenous population of New Caledonia, the Kanak people. It is an emblem of respect and care of marine wildlife in the territory and, as a result, its conservation is of considerable societal value (Garrigue *et al.* 2008; Cleguer 2010; Dupont 2015). Dugong hunting has been conducted for centuries in New Caledonia to meet the needs of certain traditional ceremonies (Leblic 2008), including the ceremony of the New Yam, weddings, bereavements and leaders' inductions. The dugong is associated with kanak chieftaincy because it is a prestige food, the "meat of the leaders" (Dupont 2015).

Regulations related to dugong take have evolved within the territory over the past 50 years. Resolution 68, implemented in 1963, was the first regulation to prohibit dugong hunting in any French territory. The most recent regulations for dugongs were implemented in 2004 in Province Sud and in 2006 in Province Nord. Dugong hunting is now prohibited in Province Sud and only allowed under special permit in the Province Nord (Province Nord 2008; Province Sud

2009). In Province des Iles Loyauté, dugong regulation remains under resolution 68 of 1963; dugong hunting is forbidden unless a special permit is granted, generally for customary purposes. Between 1962 and 1989, a total of 190 applications for special permits was received; 165 authorizations were granted (i.e., six authorizations per year) and 24 refused (Garrigue *et al.* 2008). Most permits were requested for hunting in the northeast region (46%) and along the west coast (39%) of the main island (Garrigue *et al.* 2008). No permit has been granted in Province Nord since 2004 (two permit applications were submitted to Province Nord, one in 2013 and one in 2014, but they were rejected; SMRA, DDEE, Province Nord pers. comm.).

In 2010, a Dugong Action Plan was developed and implemented jointly by the Marine Protected Area Agency, Province Nord, Province Sud, and Province des Iles Loyauté, the French Government, the Government of New Caledonia, the Customary Senate, the WWF and Opération Cetacés (a local Marine Mammal Research NGO; Jacob and Gardes 2010). The Dugong Action Plan follows the recommendations listed in the Dugong Memorandum of Understanding developed under the Convention on Migratory Species (MoU 2007) and aims to fulfil the objectives stated in the South Pacific Regional Environmental Program (SPREP) Dugong Action Plan (Gillespie 2005; SPREP 2012). One of the aims of this Dugong Action Plan is to obtain ecological information on dugongs to inform decisions relating to their conservation and management in the Pacific Island region.

Dugong ecology in New Caledonia

Abundance, distribution

Various methods exist to estimate the abundance of populations. Visual surveys and mark-recapture techniques are two methods that are often used. It is unusual for all individuals to be available to observers, necessitating methods to estimate population size. Individual counts are often interpreted as measures of relative abundance, and can be generated for a single species or communities of species (Norton-Griffiths 1978).

A single baseline dugong aerial survey conducted during the cool season of 2003 resulted in a population estimate of 2026 ($\pm$ SE = 553) animals (Garrigue *et al.* 2008). A second similar survey conducted during the warm season of 2008 to assess seasonal changes in the dugong relative abundance produced a lower estimate of 606 ($\pm$ SE = 200) individuals (Garrigue *et al.* 2009). The five year gap between these two surveys mainly resulted from a lack of funding to conduct the second survey. The discrepancy in the 2003 and 2008 estimates of dugong relative abundance prompted concerns among local resource managers who underwrote my PhD

including additional surveys to obtain an up-to-date estimation of the population size and an evaluation of its temporal variability (Chapter 2).

Population genetics

Genetic analyses by Oremus *et al.* (2011 and 2015) suggest that the status of the dugong population in New Caledonia is precarious, like in some other islands of the dugong's range discussed above. Highly significant population differentiation was found between New Caledonia and Australia, suggesting that the large dugong populations of Australia are unlikely to act as a source of immigrants to New Caledonia. This situation is further highlighted by estimates of recent migration rates suggesting no significant exchange between the dugong populations of New Caledonia and Australia over the past two generations. Furthermore, levels of genetic diversity in New Caledonia are low in comparison to Australia, a situation which could have important implications on the long-term survival of the New Caledonia dugong population. This pattern of low genetic diversity seems to be driven by the demographic history of the population, including the human colonization of New Caledonia within the last 7,000 years, as well as by a recent bottleneck event that probably occurred sometime in the last few centuries. In the context of these results, Oremus *et al.* (2011 and 2015) stressed the importance of strengthening local conservation efforts and enhancing ecological knowledge of the dugong in New Caledonia.

Habitat use

Habitat use by dugongs in New Caledonia was explored by Garrigue and Patenaude (2004). Using Multivariate (Poisson regression) and Univariate (Chi^2) analyses based on the 2003 and 2008 aerial survey data, the authors found that dugongs were: (1) preferentially using shallow coral reefs and sandy areas in the lagoon even though some individuals had been observed in deep channels and on the outer parts of the lagoon near the reef passes; (2) in highest densities in areas between five and ten kilometres from the coast and in lower numbers as the distance to the coast increased thereafter. These results need to be interpreted with caution because the data used by Garrigue and Patenaude (2004) were obtained from large scale surveys, which were not designed and conducted to investigate habitat use by dugongs at the fine scale of their analyses. A study explicitly designed to investigate dugong habitat use in New Caledonia or any other coral reef lagoonal environment had not been carried out prior to this thesis (Chapter 5).

Food resources

The interaction between dugongs and their seagrass food has also not been studied in New Caledonia. Studies of marine phanerogams in New Caledonia began with Garrigue's work in the 1980s (Garrigue 1987) investigating the macrophyte communities associated with soft bottoms in the southwest lagoon of the main island. The most complete taxonomic list of the marine flora of New Caledonia was published in 2006 (Payri 2006). Among the 65 known species of exclusively marine phanerogams, 11 species are recorded in New Caledonia. These are divided in six genera (Hily *et al.* 2010) belonging to the family of the Cymodoceaceae (*Cymodocea, Halodule,* and *Syringodium*) and the Hydrocharitaceae (*Enhalus, Halophila, Thalassia*). *In situ* observations and analyses of dugong stomach contents in other regions such as Australia and Papua New Guinea confirm that the dugong feed on both seagrass leaves and rhizomes of all of these genera (Johnstone and Hudson 1981; Marsh *et al.* 1982; Nietschmann 1984; Preen 1992; Masini *et al.* 2001; Sheppard *et al.* 2010). The marine vegetation of New Caledonia was mapped using optical remote sensing performed with multispectral imagery including several 30m resolution images obtained from Landsat 7 in 1999 and 2003. These estimates are only for seagrass in relatively shallow water (< 5m Andréfouët *et al.* 2010) and are thus likely to underestimate the spatial extent of the seagrass communities used by dugongs in this region.

Hazards to dugongs and their habitats in New Caledonia

As I explained above, generic hazards to dugongs and to their habitat have been well documented (Marsh *et al.* 2012). However, I believe that hazards to dugong need to be investigated with regard to the specific locations to inform local conservation initiatives. Hazards can be directly caused by humans or they can be natural. The line between these two categories can be difficult to distinguish as some natural hazards are exacerbated by human activities (Marsh *et al.* 2012).

A spatial assessment of the risks to dugongs from anthropogenic activities has been lacking (see Chapter 6). Based on interviews with environmental managers from Province Nord and Province Sud, Bordin (2009) suggested that interactions with vessels, illegal hunting and habitat degradation were the most likely current hazards to dugongs and their habitat in New Caledonia. Stranding information collected between 2004 and 2008 and interviews with local stakeholders confirmed that collision between dugongs and boats occur in the urban region of Nouméa but have been avoided in Voh-Koné-Pouembout (ESCAL and A2EP 2011; Claire Garrigue pers. comm.). In remote regions of New Caledonia, illegal hunting still occurs despite the current

quasi-ban on dugong take unless a special permit is granted in Province Nord (which has not occurred since 2004).

Natural hazards to dugongs in New Caledonia have not been documented although it is believed that major climatic events such as tropical cyclones represent a potential risk to the dugongs and their habitats (Garrigue *et al.* 2008; Hily *et al.* 2010). Climatic events such as strong swells, heavy rainfall and cyclones can lead to sediment displacement resulting in the uprooting of rhizomes or the burial of seagrass (Hily *et al.* 2010). In February 2011, following several years of severe storms and heavy rain, severe tropical cyclone Yasi resulted in a significant decrease of food availability for dugongs on the east coast of Australia and hence a dramatic increase in the number of carcasses salvaged (GBRMPA 2011). Given the much lower number of dugongs occurring in New Caledonia compared with Queensland, and their much lower genetic diversity, it is essential to consider the potential impact of severe climatic events on the species and its habitat in that archipelago.

Information on predation by sharks on dugongs in New Caledonia is mainly limited to anecdotal reports by sea users including sea-rangers, tourists on recreational boats, windsurfers and kite-surfers (but see Garrigue *et al.*, 2008 and unpublished data and Chapter 5).

What we need to know about dugongs in New Caledonia

Despite the discrepancy in the dugong population estimates obtained from the 2003 and 2008 surveys, New Caledonia is one of the few countries where dugongs still occur in large numbers. Thus the conservation of the dugong population in New Caledonia at the eastern end of the dugong's global range, is critical for the maintenance of the species in the Oceania region and globally. Understanding of the dugong population in New Caledonia and the current conservation strategies is limited and requires further research. Information is needed on: (1) the current size of the dugong population and its temporal variability, (2) the dugong distribution and relative density in the region, and (3) the capacity of the current management tools to protect important dugong habitats. Furthermore, very little is known about the spatial ecology of dugongs in tropical lagoons and coral reefs. Information is needed on how dugongs use space and habitats in the lagoons of New Caledonia. My thesis aims to address these gaps at several spatial and temporal scales.

1.4 Research aim, objectives and thesis structure

Primary research aim and objectives

The aim of my thesis was to: (1) build an evidence-base for the conservation and management of dugongs in New Caledonia at several spatial and temporal scales, and (2) enhance understanding of dugong ecology in tropical coral reef environments more generically by:

1. Assessing the temporal changes in the dugong population size and the capacity of the current marine protected areas (MPAs) to protect dugongs at the scale of New Caledonia; and
2. Investigating the spatial ecology of dugongs in the lagoons and coral reefs of New Caledonia by studying their movement patterns and habitat use at local scales.
3. Integrating scientific research conducted on dugongs as part of this thesis to inform decisions relating to dugong conservation and management regionally and internationally.

Research objectives and thesis structure

A schematic diagram of the structure of this thesis is provided in Figure 1.2. This diagram will be repeated at the beginning of each chapter of my thesis to provide the reader with a quick reference of the location of the chapter within the conceptual framework of my thesis. I will now discuss the structure of the thesis in the context of the objectives listed above.

Objective 1: Assessing the temporal changes in the dugong population size and the capacity of the current Marine Protected Areas (MPAs) to protect dugongs at the scale of New Caledonia

As explained above, there was a discrepancy in the estimates of dugong relative abundance resulting from the 2003 and 2008 aerial surveys in New Caledonia. In **Chapter 2,** I describe how I conducted additional aerial surveys in New Caledonia to examine the temporal variation in the indices of dugong population size over nearly 10 years. I discuss several hypotheses that could explain the observed variability in the dugong relative abundance estimates.

Protected areas are a significant tool that has been widely used to enhance the conservation of sirenians and other marine mammals (Marsh *et al.* 2012; Hoyt 2012; Marsh and Morales-Vela 2012). A network of marine protected areas (MPAs) is in place in New Caledonia but dugongs were not considered in the planning process. In **Chapter 3,** I use data from the ten year time-series of aerial surveys conducted in New Caledonia to develop a spatially-explicit model of

dugong distribution and relative density and retrospectively assess the capacity of the network of MPAs to protect dugongs.

Objective 2: Investigating the spatial ecology of dugongs in the coral reef lagoons of New Caledonia by studying their movement patterns and habitat use at local scales.

Spatially-explicit information on the movement patterns of marine wildlife species can play a central role in the development of management strategies including the design of marine protected areas (MPAs). Despite a considerable body of research describing the movement heterogeneity and habitat use of dugongs (see Marsh *et al.* 2012 for synthesis), these aspects of dugong ecology have not previously been investigated in a coral reef environment, such as the lagoons and coral reefs of New Caledonia. In **Chapter 4,** I use GPS satellite telemetry to: (1) investigate the dugongs' movement patterns; (2) examine the size of their home-ranges and identify their core activity spaces; and (3) identify the use of specific movement corridors to transit between key habitats.

How dugongs have adapted to coral reef environments, in particular areas where space is limited by a small continental shelf and small patches of intertidal seagrasses distributed on top of reef patches is unknown. In **Chapter 5,** I used data obtained from fine-scale aerial surveys conducted in different seasons and at different tides to investigate the seasonal changes in abundance and habitat use of dugongs in the lagoon and coral reefs of Cap Goulvain, an important dugong and seagrass habitat located on the mid-west coast of New Caledonia. I combined data from the fine-scale surveys with opportunistic dugong sightings from transit flights and video footages to investigate the spatial and temporal and behavioural patterns of dugong herds in the region.

Objective 3: Integrating scientific research conducted on dugongs as part of this thesis to inform decisions relating to dugong conservation and management regionally and internationally.

In **Chapter 6**, I discuss my results in relation to their capacity to inform dugong conservation management in New Caledonia and elsewhere and outline directions for future research on dugong ecology and conservation management.

Christophe Cleguer

Chapter 1
General introduction

Objective 1
Assess the temporal changes in dugong abundance and conservation strategies in New Caledonia

Chapter 2
Temporal changes in the relative abundance of dugongs

Chapter 3
The spatial coverage of dugongs by marine protected areas

Objective 2
Enhance understanding of spatial ecology of dugongs in coral reef environments

Chapter 4
Dugong movement heterogeneity in the coral reef of New Caledonia

Chapter 5
Seasonal changes in the abundance and habitat use of dugongs in the coral reefs of Cap Goulvain

Objective 3
Integrating scientific research conducted on dugongs as part of this thesis to inform decisions relating to dugong conservation and management regionally and internationally.

Chapter 6
General discussion

Figure 1.2: Schematic diagram of the structure of this thesis.

The position of the chapter within the thesis is indicated by the red frame.

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Chapter 2: Temporal changes in the relative abundance of dugongs in New Caledonia

Chapter 1
General introduction

Objective 1
Assess the temporal changes in dugong abundance and conservation strategies in New Caledonia

Chapter 2
Temporal changes in the relative abundance of dugongs

Chapter 3
The spatial coverage of dugongs by marine protected areas

Objective 2
Enhance understanding of spatial ecology of dugongs in coral reef environments

Chapter 4
Dugong movement heterogeneity in the coral reef of New Caledonia

Chapter 5
Seasonal changes in the abundance and habitat use of dugongs in the coral reefs of Cap Goulvain

Objective 3
Integrating scientific research conducted on dugongs as part of this thesis to inform decisions relating to dugong conservation and management regionally and internationally.

Chapter 6
General discussion

Sound understanding of temporal changes in abundance is required for assessing the status of wildlife species and for effective conservation and management. In New Caledonia, a single baseline dugong aerial survey conducted in 2003 resulted in a population estimate of 2026 ($\pm$ SE = 553) animals. A second similar survey conducted in 2008 produced a lower estimate of 606 ($\pm$ SE = 200) individuals, prompting local concerns. I conducted additional dugong surveys in New Caledonia and investigated the temporal variation in the relative abundance and density of dugongs. I generated hypotheses explaining the variation in the dugong population size estimates and explored evidence for each of these hypotheses and suggested generic ways of reducing some of the uncertainties associated with interpreting the results of a time series of aerial surveys of marine mammals.

2.1 Introduction

Monitoring counts, indices, and estimates of wildlife populations provide an indicator of the likelihood of the population continuing to exist. This information is important for managing harvested and endangered species, triggering interventions, informing decisions, documenting compliance with regulatory requirements, and detecting changes (Gibbs *et al.* 1998, 1999). Nonetheless, one key challenge for the conservation and management of many wildlife populations is the lack of robust data on trends (IUCN 2015). Thus focusing efforts on surveying and assessing trends in wildlife populations is essential especially for coastal marine species because increases in human population in coastal areas has resulted in growing pressure to marine ecosystems (Crain *et al.* 2009).

As explained in Chapter 1, dugongs are an important component of tropical and subtropical coastal ecosystems and are internationally recognized as vulnerable to extinction by the IUCN (Marsh 2008). Dugong populations are at high risk of local extinction in several parts of their range. Prospects for the survival of the dugong are positive in some regions such as Shark Bay, Western Australia, and Torres Strait (located between Australia and Papua New Guinea). Nonetheless, the situation is of concern in most of the species range, including the limits of its range in east Africa to the west and in the Pacific Islands to the east (Marsh *et al.* 2012).

Dugong numbers have been estimated for 20 countries using aerial surveys methods (Marsh *et al.* 2002, 2012). Yet in the Western Pacific region, information on dugong abundance is largely anecdotal, apart from New Caledonia where standardized aerial surveys were conducted during the cool season in 2003, resulting in a relative population estimate of 2026 (± SE = 553) dugongs (Garrigue *et al.* 2008). Results obtained from this single baseline survey suggest that New Caledonia supports one of the most important dugong populations in Oceania. However, a second survey conducted during the warm season of 2008 resulted in an estimate of only 606 (± SE = 200) individuals (Garrigue *et al.* 2009), prompting local concerns. Moreover, as I explained in Chapter 1, recent genetic studies have highlighted the vulnerability of the dugong population of New Caledonia. This population has a low genetic diversity and is isolated from the large stocks of dugongs in Australia (Oremus *et al.* 2011, 2015).

I conducted additional dugong aerial surveys in New Caledonia to determine the current size of the dugong population and examine its temporal variability. Monitoring changes in abundance requires multiple surveys over a long period of time and preferably at the same time of year to avoid the confounding effect of season (Caughley 1977; Aragones *et al.* 1997). The surveys of 2003 and 2008 conducted prior to my PhD research were carried out in different seasons to

determine if there was any seasonal change in the dugong distribution. Thus, I conducted four additional aerial surveys in New Caledonia: one in each of the cool and warm seasons of 2011 and 2012 to verify any potential effect of season in the estimates. I present the results of these surveys in this chapter in the context of a reanalysis of the entire time-series.

2.2 Methods

Survey design

All the surveys conducted since 2003 have covered all the lagoons around the main island (Figure 2.1). The Loyalty Islands have not been surveyed because of the absence of anecdotal reports of dugong sightings in this area. A total of six systematic aerial surveys were conducted in June 2003 (cool season; Garrigue *et al.* 2008), January 2008 (warm season; Garrigue *et al.* 2009), June 2011 (cool season), November 2011 (warm season), June 2012 (cool season), and November 2012 (warm season). I conducted the surveys in 2011 and 2012 as part of my PhD research.

Given that the dugong population of New Caledonia is isolated geographically from other dugong populations and genetically from at least the Australian population (Marsh *et al.* 2002; Oremus *et al.* 2011, 2015) animals are unlikely to move outside the area covered by a comprehensive survey of all potential dugong habitats. This situation provides an opportunity to overcome the problem of absence bias (animals have moved from the study area and cannot be counted; *sensu* Lefebvre *et al.* 1995).

Aerial survey methodology

Aerial surveys are a cost effective method of estimating the numbers of large animals inhabiting a large area (Quang and Becker 1996; Pople *et al.* 1998; Nishi *et al.* 2000; Rowat *et al.* 2009). Using an aircraft as the survey platform enables large areas to be surveyed relatively quickly so that the likelihood of counting the same animal twice is minimised. Aerial surveys are most useful for surveying species of marine mammals that are: (1) easy to identify from the air, (2) difficult to see from a boat, and (3) relatively dispersed (Aragones *et al.* 1997).

The surveys used a variant of the strip transect technique which has been standard in Australia since the 1980s and detailed in Marsh and Sinclair (1989a). Transects delineated under a stratified random sampling design were flown by a 4-seater, high wing, single engine Cessna aircraft (Figure 2.2) as close as possible to a ground speed of 100 knots. In order to meet the
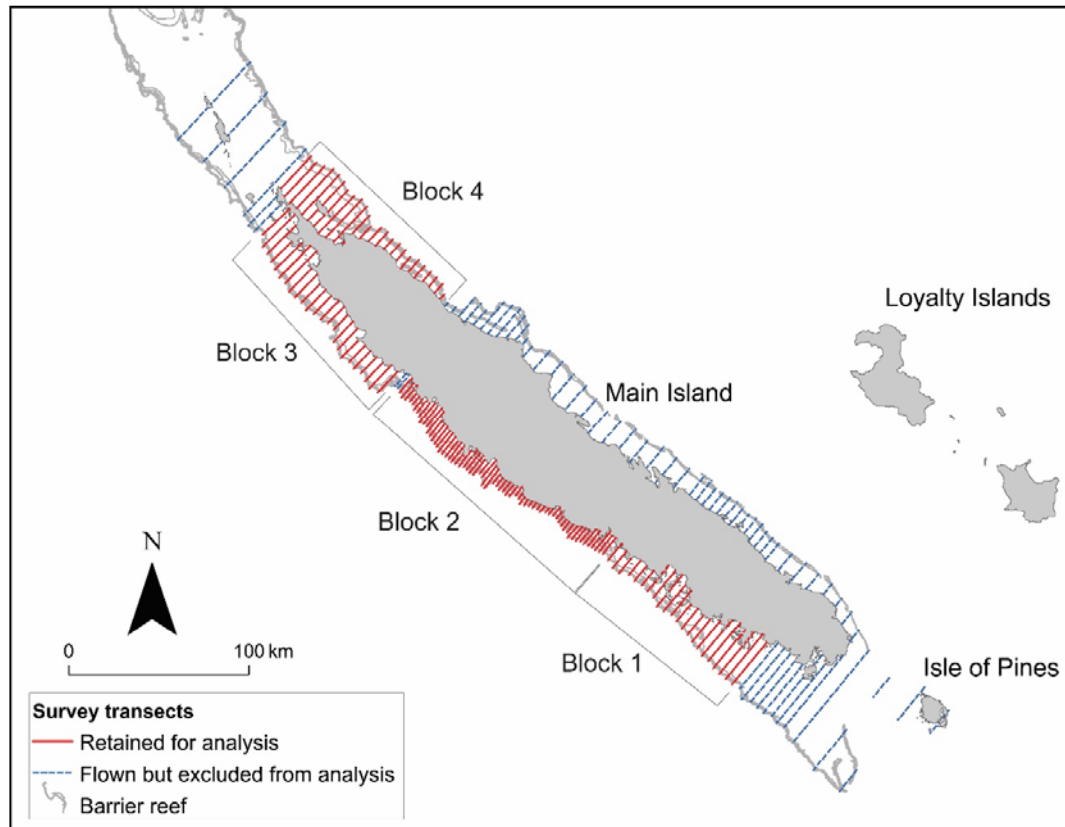
Figure 2.1: Aerial survey blocks and transects used in 2011 and 2012 for the analysis of dugong relative abundance and density.

Figure 2.2: Photograph of the Cessna 206 used for the dugong aerial surveys in New Caledonia.

New Caledonia safety requirements for single engine aircraft over water, the flight altitude (900 feet, or 274m) was twice that used in the standardized surveys in Australia which use twin-engine aircraft (Marsh and Sinclair 1989a). The experimental work of Bayliss (1986), Marsh and Sinclair (1989b) and Hodgson *et al.* (2013) indicate that there should be no difference in dugong sightability between survey heights of 900 feet and the 500 feet at which surveys are conducted in Australia.

Fiberglass rods attached to the structure of the aircraft were used to demarcated 400m transects (Figure 2.3). The configuration inside the aircraft remained constant over the survey years, with one observer on each side at the rear of the aircraft and a flight coordinator next to the pilot at the front. The observers, trained as in Marsh and Sinclair (1989a), recorded dugong sightings onto an audio-recorder (Microtrack II, M-Audio). Dugongs sighted outside of the strip transect were recorded as opportunistic sightings but were not included in abundance estimates and density analyses. The glare intensity and water turbidity were called out for each group of animal sighted and sea state was recorded every two minutes during a transect (Marsh and Sinclair 1989a,b).

Distance categories (100, 200 and 300m) within the strip were marked by color bands on the wing struts. However, experiments conducted by Marsh's group in Australia showed that there was a large amount of measurement error in the assignment of dugong sightings to distance classes within the transect strip (Pollock *et al.* 2006). The color bands are a less than satisfactory way of delineating distance classes for animals such as dugongs, which surface cryptically and for only 1-2 seconds (Anderson and Birtles 1978; Chilvers *et al.* 2004; Helene Marsh. pers. comm.). The cryptic nature of dugong surfacing and the often high sighting rate also meant that it would be difficult for observers to take their eyes off the water to read an inclinometer. Thus following Pollock *et al.* (2006), I decided not to use distance category as a co-variate in the analyses.

The 2003-2008 sampling design was stratified by the known and probable distribution of seagrass and historical dugong hunting grounds (see Garrigue *et al.* 2008 for details). The distance between adjacent transects was 2.5 NM (Sampling Intensity, SI = 16%) in regions supporting known seagrass meadows, and 5 NM (SI = 8%) outside these areas. The 2011-2012 survey design (Figure 2.1), for which the sampling intensity varied between 4.5% and 34% was based on the 2003-2008 survey results using the principles of adaptive stratified sampling (Appendix A Table A.1; Norton-Griffiths 1978; Dawson *et al.* 2008). Transects were flown perpendicular to the coast and covered all lagoons and major coastal habitats. The limits of each transect were defined by the 500m depth contour or 1 NM outside the barrier reef, whichever was closer to the land (Figure 2.1).

Figure 2.3: Fiberglass rods attached to the structure of the aircraft to delineate transects 400m wide on the water surface on each side of the aircraft. Note the colour bands on the wing strut that were used to delineate zones within the transect.

Analysis

Standardized estimates of relative population size

Limitations associated with aerial surveys (e.g., not all animals on the transect line are detected) can make the interpretation of estimates difficult (Caughley 1974, 1977; Pollock *et al.* 2006; Dawson *et al.* 2008). Marsh and Sinclair (1989a, b) explain that the probability of detecting an animal during an aerial survey involves two overlapping processes: (1) availability bias, which occurs when submerged animals are not available to observers due to environmental conditions (e.g., water turbidity, sea state, cloud cover, surface glare) and/or animal characteristics (e.g., group size, body color, body size, diving patterns); and (2) perception bias, which occurs when animals available to be seen are missed by observers.

In this study, standardized estimates of dugong relative abundance were based on the method developed by Pollock *et al.* (2006). This method attempts to correct for availability bias, and perception bias (*sensu* Marsh and Sinclair 1989a). Pollock et al. (2006) estimated availability

bias using two sets of information: (1) information on turbidity and sea state specific to sighting events to account for the varying depth of the detection zone; and (2) estimates of the average time dugongs spend in detection zones of various depths. The estimated probabilities of dugongs being in the detection zones used in my analysis and which allowed to estimate availability of dugongs under specific conditions are detailed in Appendix A Table A.2.

Survey-specific correction factors for perception bias, as described by Marsh and Sinclair (1989a), could not be estimated because the aircraft could accommodate only two observers rather than the four required to estimate perception bias. Hence, I used a single observer correction for perception bias ($0.72, \pm SE = 0.0159$) derived from Marsh and Sinclair (1989a).

Dugong abundance was estimated separately for each of the blocks surveyed. Population estimates were not calculated for blocks in which fewer than five dugong groups were sighted. When a herd of dugongs (i.e., groups of ≥ 10 dugongs) was encountered, the aircraft switched from passing mode to circling mode in order to count all animals in the herd. Thus, all the animals were assumed to be counted and availability corrections were not required. Any dugong herd was first excluded from the calculations and later added to the estimates of population size and density as outlined in Norton-Griffiths (1978).

Temporal changes in dugong relative density

Dugong relative density was calculated by dividing the corrected counts of dugongs obtained using the Pollock et al. (2006) methodology by the area of the relevant transect (in km^2). As there were transects on which no dugongs were sighted (Appendix A Table A.3), zero-inflation was examined using bar-plots. Zero inflation means that there is far more zeros in a dataset than what would be expected for a Poisson or Negative Binomial distribution. Not accounting for zero inflation can result in the estimated parameters and standard errors to be biased, and the excessive number of zeros to cause over dispersion (Zuur et al. 2009). Over dispersion was assessed based on dispersion statistics generated by generalized linear models assuming the data were distributed according to: (a) Poisson and (b) Negative Binomial distributions. Only the dispersion statistics of the Negative Binomial model were within acceptable levels (Zuur *et al.* 2012). As the statistical analysis required at least one observation in each row of each year and block combination further examination was conducted only on blocks 1, 2, 3 and 4. To assess the random effect of transect, only transects that were flown in all six surveys were included in the subsequent analyses.

Based on this exploratory analysis, a zero-inflated model with a Negative Binomial distribution was used. To explore temporal and spatial variations in dugong density (based on corrected

number of dugongs per transect area), season, year and block were used as categorical explanatory variables. Models were generated using the pscl R package (Zeileis *et al.* 2007). Two main components were generated from the models: (1) a count component including surface area (km^2) as an offset, for transects on which at least one dugong was sighted during the time series of surveys; and (2) a zero-inflation component providing an estimate of the number of transects on which no dugong was sighted on transect. The models with and without season as a categorical explanatory variable were not significantly different, indicating the absence of seasonal effect. Thus, the two surveys within each of 2011 and 2012 could be combined to further assess the temporal changes in dugong relative densities across years.

Proportion of calves

Logistic regression was used to examine if the proportions of calves differed over the time series of surveys and between blocks. The total number of dugongs sighted was used as weight in the model because this varied among years and blocks. Post-hoc general linear hypotheses and multiple comparisons were conducted to investigate the differences between blocks (R package 'glht-multcomp'; Hothorn *et al.* 2008).

Temporal changes in the distribution of dugongs across bathymetric ranges

A log-linear model was used to examine whether or not the frequency distribution of the counts of dugongs corrected for availability and perception biases (response variable) was impacted by water depth categories and/or surveys (independent categorical variables). Water depth was identified using the bathymetric model generated by Lefevre *et al.* (Institut de Recherche pour le Développement; unpublished). Each dugong sighting was classified into a 5m bathymetric bin as follow: < 5m, 5-10m, 10-15m, 15-20m and >20m. The coverages of the depth categories surveyed differed within the survey area. For example, waters in the depth class 15-20m were relatively uncommon (841km^2), compared with shallow waters of less than 5m (2,068km^2). To account for these differences, the surface area of each depth category was offset in the log-linear model.

2.3   Results

Environmental conditions

Flights were conducted in the best possible weather conditions (i.e., calm sea with low wind < 19km/h and low cloud coverage) and at times of days that minimised glare (mid-morning and/or mid-afternoon). Time on the ground during the surveys varied between 19 and 58 days as a result of rough weather (e.g., high winds, mostly easterly trade-winds; Table 2.1), cloud cover and rainfall, and logistical issues (e.g., aircraft maintenance). In 2003, the aerial survey was interrupted for a period of 13 consecutive days (5-17 June 2003) because of strong northerly winds generated by an unusual out-of-season category 3 tropical cyclone (Météo-France 2014). Nonetheless, the mean and maximum daily wind speeds recorded during this interruption did not differ from other survey years (Table 2.1). Results for transects flown within block 1 both before and after the interruption were included in the population estimates for all survey years. In 2008, a total of 58 days was spent on the ground because of strong easterly trade-winds and

rain. Transects flown after this interruption were not included in the population estimates because the blocks surveyed did not meet the minimum sighting requirements explained above.

I conducted a post-hoc determination of the number of days taken to complete the surveys of block 1 because the estimates of dugong relative abundance for this block in 2003 were substantially different from those in other survey years. This timeframe was used as a proxy of the likelihood of double counting individuals during a survey of that block. The number of days taken to complete the surveys of block 1 ranged from one (warm season 2011; Table 2.1), to 25 (cool season 2012). The number of days of interruption for block 1 was similar for the survey conducted in June 2003 and the two surveys of 2012 (Table 2.1).

Table 2.1: Survey interruption and period taken to complete surveying block 1.

Date of survey	Jun 2003 (cool season)	Jan 2008 (warm season)	Jun 2011 (cool season)	Nov 2011 (warm season)	Jun 2012 (cool season)	Nov 2012 (warm season)
Time on the ground (days)	19	58	19	25	32	27
Time to complete block 1 (days)	21	2	2	1	25	21
Mean daily wind speed (km/h) during interruptions of the survey of block 1[a]	21	na[b]	na[b]	na[b]	21	21
Max daily wind speed (km/h) during interruptions of the survey of block 1[a]	45	na[b]	na[b]	na[b]	48	43

[a] Data obtained from (Météo France 2014).

[b] Not applicable because there was no interruption of the survey.

Dugong abundance

Estimates of dugong population size in New Caledonia ranged from 2026 individuals in 2003 ($\pm$ SE = 553, CV = 0.27; Figure 2.5A, Appendix A Table A.4 and A.5; maps of dugong sightings for all survey years are shown in Appendix A Figure A.1) to 606 individuals in 2008 ($\pm$ SE = 200, CV = 0.33). The population size estimates ranged from 100 to 500 individuals per block in all blocks regardless of year except for block 1 in 2003 for which the dugong population size was estimated to be 919 individuals ($\pm$ SE = 414; Figure 2.5B). The counts of dugong groups, individuals and individuals per transect within a block in New Caledonia was also higher in block 1 in 2003 than in any other block in any year (Figure 2.4A-C, Appendix A Table A.4). Comparison between individual blocks shows that for most blocks, the 2003 population size estimates were above the estimates for other years (exception is block 3; Figure 2.5B).
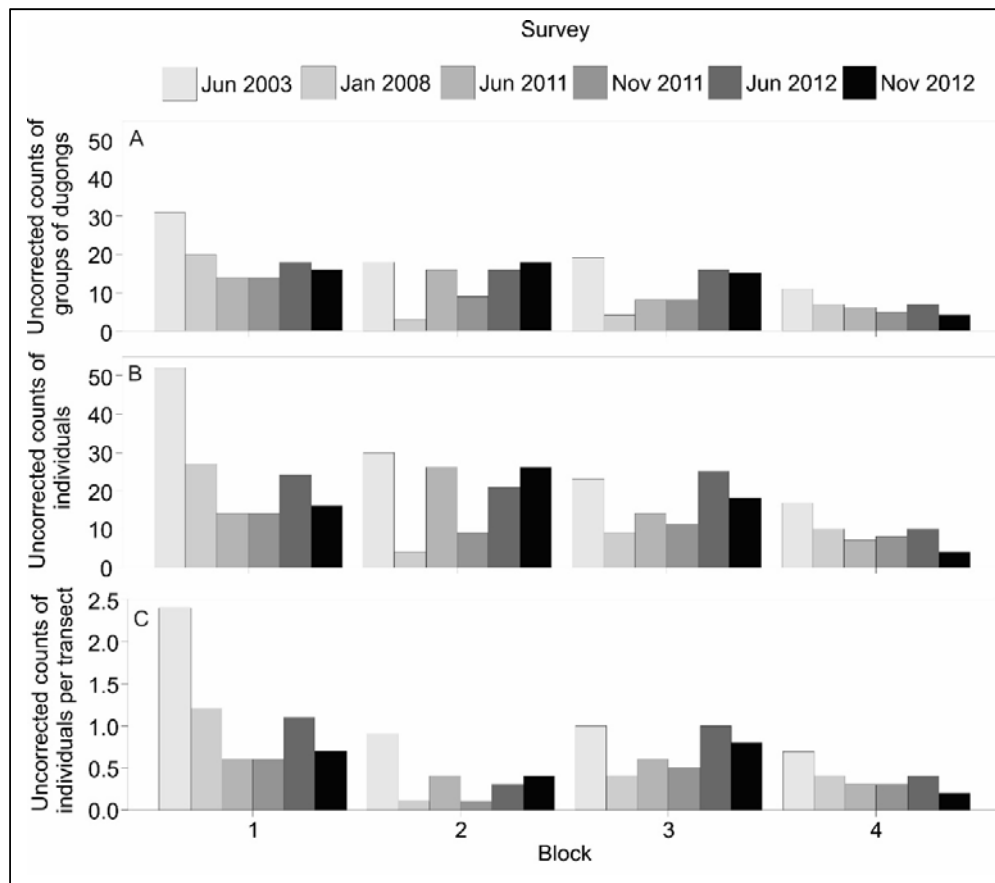
Figure 2.4: Details of the counts of (A) groups of dugongs, (B) individuals, and (C) individuals per transect for individual blocks across the time series of systematic aerial surveys in New Caledonia. The column shading varies according to the survey. Note that this figure excludes a sighting of a herd of 69 dugongs (including 5 calves) in block 2 in June 2011. The herd was added to the final population estimate.
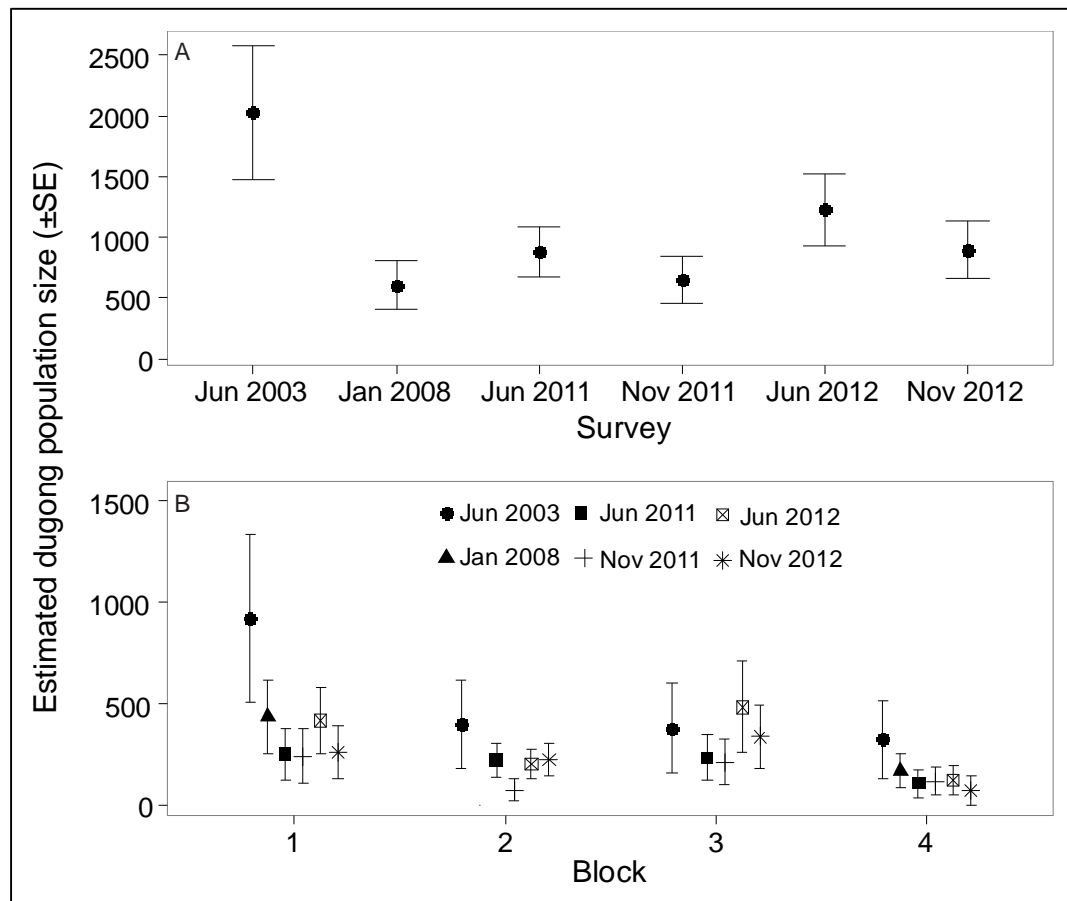
Figure 2.5: Time series of estimates of relative abundance of dugongs ($\pm$ SE); (A) across surveys, and (B) for individual blocks from the standardized aerial surveys in New Caledonia.

Temporal and spatial patterns in dugong relative density

Year and blocks had an effect on dugong counts and there was no significant interaction between year and block. This result means that the variation in dugong relative density in each block did not vary significantly across year. Thus, a model without interaction between year and block was generated to describe the dugong relative density across years and among blocks.

Year comparison

Dugong relative density was significantly higher in 2003 than in any of the other survey years ($p < 0.05$ for all survey years compared to 2003, df = 15; Table 2.2, Figure 2.6, Appendix A Table A.6). There was no significant difference in dugong relative density between 2008, 2011 and 2012.

Table 2.2: Pair-wise comparisons of dugong relative density across survey years in New Caledonia.

Year	Count component[a]			
	2003	**2008**	**2011**	**2012**
2003		↓*[b, c]	↓**	↓*
2008	↑*			
2011	↑**			
2012	↑*			

[a] Estimated from corrected counts with area of transect as an offset.

[b] Example to aid interpretation: 2008 had significantly lower dugong counts than 2003

[c] Significance codes: $< 0.001 = ***$; 0.001 to $< 0.01 = **$; 0.01 to $\leq 0.05 = *$
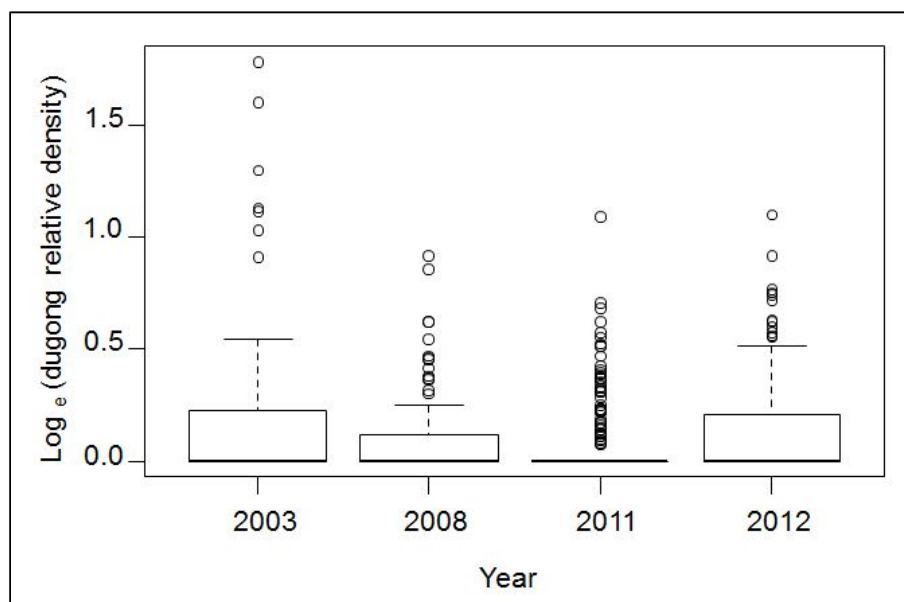
Figure 2.6: Log $_e$ dugong relative density (per km^2) based on dugongs observed in the aerial surveys in New Caledonia between 2003 and 2012. Error bars represent 95% credible intervals and lines in the boxes represent the mean. Circles represent estimated values of dugong relative density for each survey transect included in the analysis.

Block comparison

For the count components (transects with ≥ 1 dugong), the dugong relative density in block 1 was generally significantly lower than in block 2 ($p < 0.01$, df = 15) and block 3 ($p < 0.05$, df = 15) but not significantly different from block 4 (Table 2.3 and Figure 2.7). The dugong relative density in block 4 was significantly lower than in blocks 2 ($p < 0.001$, df = 15) and 3 ($p < 0.05$, df = 15) on transects with dugong sightings ≥ 1.

For the zero-inflation component, there were significantly fewer transects with no dugong observations in block 1 than in any other block ($p < 0.001$, df = 15 for all block comparisons), indicating that dugong sightings were more spread out in block 1 than in any other block (Table 2.3). The number of transects without any dugong observations was higher in block 2 than in any other survey block, indicating that the dugong sightings were clustered in block 2 more than in any other block and explaining why the dugong relative density was lower in block 1 compared to block 1.

Table 2.3: Pair-wise comparisons of dugong relative density among blocks in New Caledonia.

Block	Count component[a]			
	1	2	3	4
1		↑**[b,c]	↑**	
2	↓**			↓**
3	↓**			↓*
4		↑**	↑*	

Block	Zero-inflation[d]			
	1	2	3	4
1		↑***[b]	↑***	↑***
2	↓***		↓***	↓***
3	↓***	↑***		
4	↓***	↑***		

[a] Estimated from corrected counts with area of transect as an offset

[b] Example to aid interpretation: for transects that have dugong counts > 0 there were more counts of dugongs in block 2 than in block 1; there were more transects with no dugong observations in block 2 than in block 1.

[c] Significance codes: < 0.001 = ***; 0.001 to < 0.01 = **; 0.01 to ≤ 0.05 = *

[d] Between block comparison of the number of transects where no dugongs were sighted

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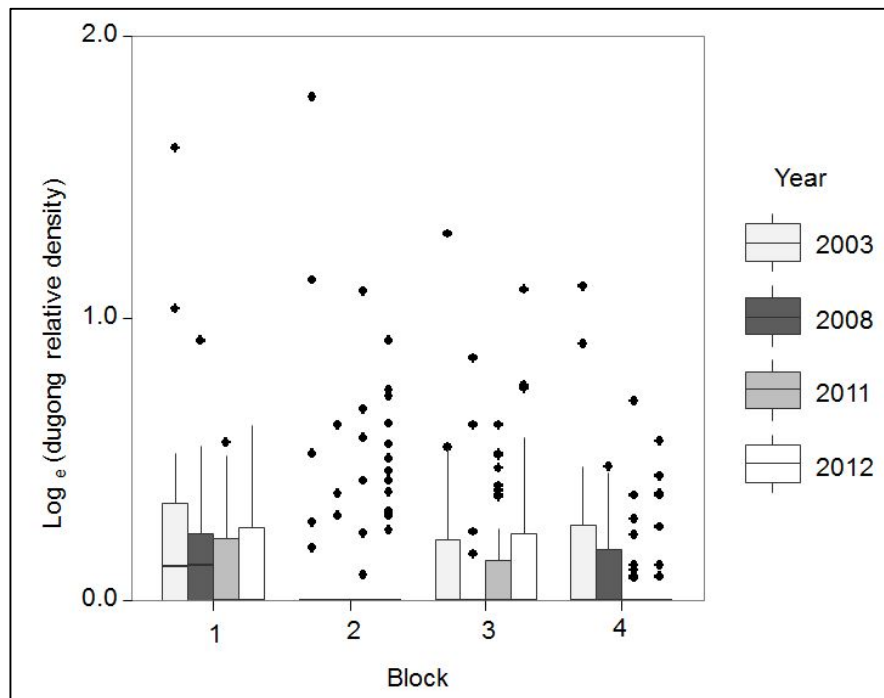
Figure 2.7: Log $_e$ dugong relative density (per km^2) plotted for each block and year. Error bars represent 95% credible intervals and lines in the boxes represent the mean. Black dots represent estimated values of dugong relative density for each survey transect included in the analysis.

Proportion of calves

The proportion of dugong calves increased from June 2003 (7.4%) to June 2011 (18.0%) and then decreased to reach its lowest value in November 2012 (4.7%) but these variations were not significant (Figure 2.8A, Appendix A Table A.7). There was substantial variation in the proportions of dugong calves within each block (Figure 2.8B). Overall, the proportions of dugong calves in blocks 3 and 4 were significantly higher than block 1 (Tukey multiple comparisons tests, $p \leq 0.05$, z-value = 2.662 and 3.387 respectively; Figure 2.8B). The proportion of calves in block 1 varied from no calves sighted in June 2011 and November 2011 and 2012 to 11.0% of the total number of dugongs sighted in that block in January 2008.
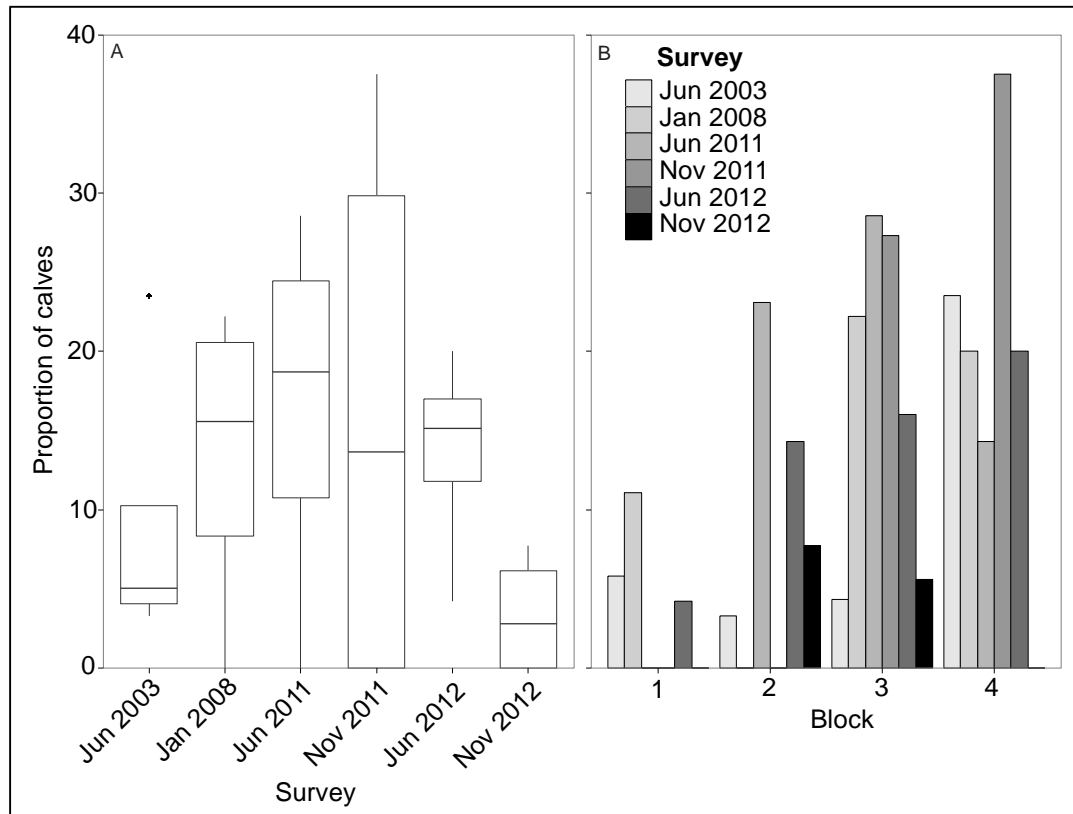
Figure 2.8: Proportions of dugong calves (A) across blocks within surveys, and (B) within blocks in each survey. Lines in the boxes in (A) represent the mean.

Temporal changes in the distribution of dugongs across bathymetric ranges

Dugongs were seen in waters up to 239m deep (not corrected for tides ranging to up to 2m) outside the lagoon on the barrier reef slope (Chapters 4 and 5). Over the entire survey area, the corrected counts of dugongs were the highest in water less than 5m deep and less than 10m deep (245 and 265 dugongs counted in these depths, respectively, that is 24% and 26% of the total counts across all years, Figure 2.9). The dugong distribution (weighted for area of depth category) varied significantly across depth categories but not across years (Appendix A table A.8; dugong sightings for each survey year are shown in Appendix A Figure A.1).
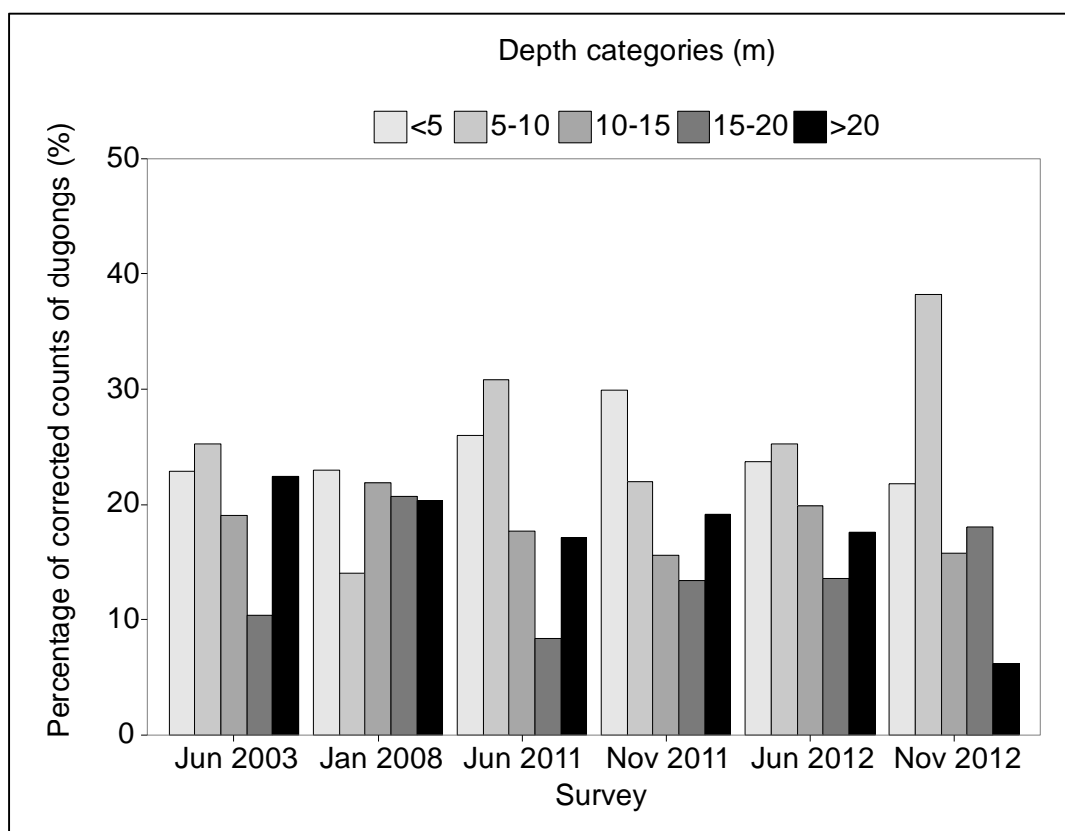
Figure 2.9: Frequency distribution of dugong sightings with respect to bathymetry during the dugong aerial surveys in New Caledonia.

2.4   Discussion

There were some significant differences in dugong relative abundance and density between survey years in New Caledonia. In particular, the estimates from the recent 2011 and 2012 surveys are not significantly different from the results of the 2008 survey (Garrigue *et al.* 2009) but are significantly lower than those obtained in 2003 (Garrigue *et al.* 2008). The lack of a significant interaction between year and block in dugong relative density suggests that the dugong relative density in a block did not vary significantly across years (some blocks always had higher density across years). Thus, mass movement of dugongs across block is unlikely to have occurred during the time series of surveys but movements of dugongs could have still occurred within blocks.

I hypothesize that discrepancies between the 2003 dugong relative abundance estimates and estimate from other survey years could be a result of: (1) actual reduction in the size of the dugong population between 2003 and the other years; (2) temporary migration within the survey area; or (3) unaccounted biases associated with detection probability. The evidence for each of these hypotheses is explored below.

Reduction in the size of the dugong population between 2003 and the other years

To accept this hypothesis, it is necessary to assume that the New Caledonia dugong population is closed. This assumption is likely to be valid because the geographic and genetic evidence indicates that this population is isolated (Oremus *et al.* 2011, 2015) and our aerial surveys covered all potential dugong habitats in the region. However, if this hypothesis were true a 45% decrease in the dugong population size would have occurred between 2003 and 2008 (based on lower bound of Standard Error of the 2003 estimates and upper bound of Standard Error of estimates of 2008), presumably from unsustainable anthropogenic or natural mortalities or a combination of both factors.

Anthropogenic hazards

Urban areas, ports and mining industries are rapidly expanding in New Caledonia especially on the west coast where most dugongs have been sighted (David *et al.* 2010; Cleguer *et al.* 2015; Chapter 3). The development of ports and shipping channels for the mega coastal mines have been reported to wipe out hectares of seagrass in several regions of New Caledonia but comprehensive quantification of the loss of seagrass meadows in the region is not available

(Hily *et al.* 2010). Deaths of dugongs from collisions with boats occurs in several urbanized regions of Australia (Eros *et al.* 2007; Hodgson and Marsh 2007) and have been reported on the west coast of New Caledonia in urban areas such as Nouméa (Province Sud), Voh and Koné (Province Nord; ESCAL and A2EP 2011) and confirmed from post mortem examination of stranded carcasses (Claire Garrigue pers.comm.). The growth of the tourism industry and associated boating activities along the west coast is likely to aggravate this risk.

Dugongs have been harvested for food by Melanesian people for centuries (Garrigue *et al.* 2008; Marsh *et al.* 2012). As explained in chapter 1, this practice is now restricted in New Caledonia by strict legislation rules which prohibit hunting in the Province Sud and require special permits in the Province Nord and Province des Iles Loyauté (Resolution 68 dated 25 June 1963; Province Nord 2008, Province Sud 2009). Nonetheless, people continue to hunt dugongs illegally in New Caledonia (Louis-Harris 2005; TNS 2005) and poaching activities are reported from time to time around the mainland. The number of dugongs killed from illegal harvesting is unknown (Cleguer 2010; Resource managers of the Province Sud and Province Nord, pers. comm.).

The number of dugong carcasses salvaged in New Caledonia is low but increased slightly from one individual per year in 1999, 2000 and 2002 (n = 3) to 2.3 carcasses per year between 2003 and 2008 (n = 14; Garrigue *et al.* 2009), and three carcasses per year between 2009 and 2012 (n = 12). The known causes of dugongs' death (40% of the total number of carcasses) varied between collisions with boats (13%) and illegal take (27%; Claire Garrigue pers. comm.). Salvaged carcasses are underestimates of actual mortality because an unknown proportion of carcasses is not recovered.

I estimated the sustainable level of human-related mortalities for dugongs using the Potential Biological Removal method (PBR). This method estimates the maximum number of dugongs, not including natural mortalities, which can be removed from the population (Wade 1998).

The following is the formula to calculate the PBR:

$$PBR = N_{min} \times 0.5\ R_{max} \times RF$$

where

N_{min} = the 20th percentile of a log-normal distribution based on an absolute estimate of the number of animals N in the population.

R_{max} = the maximum rate of increase, for which Marsh *et al.* (2004) use a range of estimates of 0.01-0.05 due to uncertainty of estimates of age of first reproduction, fecundity and natural mortality levels

RF = a recovery factor of between 0.1 and 1, which if < 1, allows population growth and uncertainties in estimates of N_{min} or R_{max}.

Using the data from the aerial surveys conducted in New Caledonia (Minimum population estimate (N_{min}) ranging from 462 to 1,617), a maximum rate of increase (R_{max}) of 0.03; and a recovery factor (RF) of 0.5, I found that the Potential Biological Removal values ranged between three and 12 dugongs per year (results for Recovery Factors 0.1, 0.5, and 1.0 are presented in Appendix A Table A.9).

Given the underestimated number of dugong carcasses, it is possible that the anthropogenic mortality of dugongs since 2003 in New Caledonia is unsustainable and could lead to a slow decrease of the population. However, there is no evidence of the level of anthropogenic mortality required to explain the difference between the results of the 2003 survey and the later surveys, especially as most of this mortality would have had to have occurred between 2003 and 2008.

Natural hazards

Temporal changes in the distribution of the dugong seagrass food is a common case of unusual levels of natural mortality in dugongs (Sobtzick *et al.* 2012). Marsh *et al.* (2012) summarize the evidence that the life history and reproductive rate of female dugongs are adversely affected by seagrass loss which causes dugongs to breed later and less often. Meager and Limpus (2014) demonstrated that sustained periods of elevated freshwater discharge, which is associated with seagrass loss, have an adverse impact on dugong survival. Habitat degradation due to extreme weather events such as cyclones is another potential driver of resource degradation that can substantially adversely affect dugongs. For example, in February 2011 following several years of severe storms and heavy rain, severe tropical cyclone Yasi resulted in a significant decrease of food availability for dugongs on the east coast of Australia and hence a dramatic increase in the number of carcasses salvaged (GBRMPA 2011). No exceptional weather events could explain a sudden widespread degradation in the dugong's seagrass food between 2003 and 2008 and there is no evidence of such loss of seagrass in New Caledonia (Météo-France 2014).

Calf counts

If the dugong population of New Caledonia had been subjected to widespread habitat loss, a reduction in fecundity and increase in neonatal mortality evidenced by low calf counts might be expected (Marsh *et al.* 2012) as observed in Australia following extreme weather events such as floods and cyclones (Preen and Marsh 1995; Marsh *et al.* 2012; Sobtzick *et al.* 2012). Such changes are not indicated here because: (1) I did not find any evidence of major seagrass habitat loss; and, (2) the percentages of calves recorded during the aerial surveys increased between 2003 and 2008. However, if there had been a reduction in the dugong population that was independent of habitat loss, fecundity could have increased as a density dependent response (Marsh and Kwan 2008).

Temporary migration of dugongs

Dugongs are highly mobile (Chapter 4) and fluctuations in dugong population estimates observed in repeated surveys of the same area in both Australia and the Arabian region, where the dugong's ranges are extensive, have been largely attributed to temporary migrations within the survey area (Hagihara *et al.* 2014) and between the survey area and adjacent regions (Gales *et al.* 2004; Marsh *et al.* 2004; Preen *et al.* 2012; Sobtzick *et al.* 2014). New Caledonia is an isolated archipelago. The aerial survey sampling design covered all the lagoons of the main island. Thus I consider that is unlikely that dugongs moved out of the survey area between 2003 and 2008 and remained outside.

The statistical analysis does not support the hypothesis that dugongs moved across survey blocks between survey years. Nonetheless, dugong movements within survey blocks are likely (Chapter 4). Home-range estimates for individual dugongs can vary from 0.5 to 733km^2 (Sheppard *et al.* 2006). Large home-ranges are a result of dugongs making large-scale movements even over relatively short time periods. For example a dugong satellite tagged in north-eastern Australia travelled 560km in just under 17 days (Sheppard *et al.* 2006). These individual movement patterns may lead to double counting of individuals over the course of a survey especially if a survey is prolonged.

Dugongs also move to sheltered areas in response of strong winds (Nietschmann and Nietschmann 1981; Nietschmann 1984). For example, in Torres Strait, north of Australia, dugongs move from large offshore seagrass meadows to leeside reefs and island borders during the south-east trade-wind season, in response to strong winds and low tides. Similar observations have been reported by local fishermen in New Caledonia in rough weather (Nathalie Baillon, pers. comm.). Survey block 1 in the south west of New Caledonia was where

the dugong abundance estimates differed most between 2003 and the following years (Figure 2.5B). However the time to complete the surveys of block 1 and the strength of the winds that caused the survey interruptions appear to be similar in 2003 and 2012. Although dugong movement and double counting remains a plausible cause of at least part of the variation in abundance estimates, the evidence is insufficient to accept or reject this hypothesis.

Unaccounted biases associated with detection probability

Unaccounted fluctuations in the availability of dugongs to observers

The analysis conducted here assumes that the proportion of time a dugong spends at the surface does not vary with location and depth. However, recent studies carried out on dugong diving and surfacing patterns in soft bottom habitats in Australia show that this assumption is false and that the dugong's availability for detection varies with water depth (Hagihara *et al.* 2014). The probability of sighting a dugong at the surface from the air is lowest in water between 5m and 25m deep (Hagihara *et al.* 2014). Thus, changes in dugong abundance estimates in New Caledonia could be partially explained by the difference in water depth used by dugongs in 2003 compared with other survey years. My analysis of the distribution of dugongs in relation to bathymetry across survey years does not support this conclusion. Nonetheless, data on dugong diving behaviour in relation to bathymetry should be obtained in New Caledonia to estimate dugong numbers more accurately.

Variation in the timing of the New Caledonia surveys with respect to the tidal cycle may account for at least some of the variation in population estimates because a different proportion of animals may have been sighted in deep versus shallow waters. Lanyon (unpublished data) found a 43% decrease in dugong population estimates during a low-tide survey of Moreton Bay banks compared with a high-tide survey on the same day under otherwise identical conditions. In Moreton Bay dugongs are prone to use deeper areas at low tide than at high tide because of the inaccessibility of some of the shallow feeding grounds. This situation is different from that of the lagoon in the Nouméa regions where most of the difference in the estimate of dugong numbers between 2003 and subsequent survey years was found. The lagoon in the Nouméa region is relatively deep for a coastal environment (mean depth = 18m) and most seagrasses occur in subtidal areas (Garrigue 1995, 1998; Chapter 4). There was no major change in the distribution of dugongs in this region across survey years. Thus, it is unlikely that tides have played a significant role in the changes in the estimates of dugong numbers in the Nouméa region.

Observer error

Observer error is an important variable in any aerial survey (Caughley 1974). Observer error in surveys of marine megafauna can include: missed observations, misidentification of species, and individuals sighted outside the transect (Fuentes *et al.* 2015). The dugong aerial survey conducted in 2003 in New Caledonia was the first marine megafauna survey in the region. We cannot dismiss observer error as a cause of part of the temporal variation between surveys reported here, despite the experience and training of the 2003 crew. Measurement of the perception bias of observers is missing in these surveys; it would have aided assessment of differences in observer capacity between surveys.

2.5   Conclusion

The additional standardized aerial surveys I conducted in 2011 and 2012 have not detected a significant change in dugong relative density compared to 2008 but were significantly lower than the baseline survey in 2003. Precaution should be taken when interpreting variability in estimates of relative abundance as there is usually a low power to detect population trends in marine mammals, particularly those that occur in low abundance (Taylor and Gerrodette 1993). Detecting trends in marine mammal populations in a time frame useful to conservation and management is very difficult. Marsh (1995) calculated that it would take at least 10 years of annual aerial surveys before it could be determined that a regional dugong population, apparently declining at 5% per year, was in fact declining even if the availability bias and perception bias were constant. This problem is not unique to aerial surveys, it applies to other survey techniques such as boat and land-based surveys.

If the reduction of the estimated dugong population size in New Caledonia over the last 10 years was real, the population would likely qualify as 'Endangered' under criterion A2b of the IUCN Red List (IUCN 2012a, b). However, my study shows that it is impossible to conclude with certainty why the 2003 estimate of a population size is an outlier from the remainder of a time series.

My results highlight the need to replicate the baseline monitoring of marine mammal populations. Replicating baseline surveys would: (1) provide a greater confidence in the inference made regarding the trends in population estimates, and (2) ensure that these estimates are not specific to the circumstances that may have prevailed during a single study (Gilbert 1999; Johnson 2002; Brown *et al.* 2005). This work also highlights concerns about animal movement during a survey. In boat (Palka and Hammond 2001) or aerial surveys of marine

mammals (Marsh and Sinclair 1989a, b) observation platform speeds are generally set sufficiently high for animal movements between transects within the survey period to be ignored. However, it is impossible to know how many animals will move during a long interruption and what distance they will swim, especially when the interruption is caused by strong winds and high seas. Consequently, if a survey is not completed within a short time frame it is possible for animals to be double counted or missed. Decision rules should be developed to decide when a specific region needs to be completely re-surveyed for a target species. These strategies should improve population estimates and enhance the information provided to management.

2.6   A critical evaluation of my approach

Population trends are frequently based on temporal comparison of indices of relative abundance (Gerrodette 1987; Taylor and Gerrodette 1993; Zielinski and Stauffer 1996). However, as pointed out in this Chapter, relative indices do not always reliably reflect changes in population abundance because of the uncertainties associated with population estimates (Colyvan *et al.* 1999). I highlighted that uncertainties including the timing of surveys, observer error, heterogeneity in the environmental conditions and the behaviour of dugongs may have influenced the variability in the dugong population size estimates in New Caledonia.

Observer error could not be assessed in the surveys conducted in New Caledonia because at the time of the surveys there was no aircraft available that could accommodate two rows of observers, which is necessary to evaluate perception bias (Marsh *et al.* 1989a, b). Using a larger aircraft in New Caledonia could enable to use two independent observers on each side of the aircraft and hence to estimate the observer's ability to detect animals. This approach would provide more confidence in the interpretation of the estimates of dugong population size.

The estimates of dugong relative abundance I obtained are likely to be underestimates because of the underestimation of the availability correction factor. Indeed, the analysis I conducted in this Chapter assumes that the proportion of time a dugong spends at the surface does not vary with location and water depth. However, recent studies conducted on dugong diving and surfacing patterns in soft bottom habitats in Australia show that this assumption is false: the dugong's availability for detection varies with water depth (Hagihara *et al.* 2014). Data on dugong diving in New Caledonia are required to estimate dugong numbers more accurately in New Caledonia where the topography is different from the area where Hagihara *et al.*'s (2014) data were collected. Dugong dive data were obtained at the end of the dugong satellite tracking study (see Chapter 4) as 11 out of the 12 tag attachment assemblies were recovered with nine of

them equipped with time depth recorders (TDRs) attached to the peduncle end of the tether. I have recently facilitated collaboration between the principal investigator of the Hagihara *et al.* (2014) study, a local Marine Mammal research NGO (Opération Cétacés) and the resources managers of New Caledonia, owners of the TDRs, to analyze these data and improve the precision of the estimates of dugong relative abundance in New Caledonia. This analysis has yet to be completed.

2.7   Chapter summary

- I conducted four additional dugong aerial surveys in New Caledonia in 2011-2012 to determine the current size of the dugong population and examine its temporal variability, and I investigated evidences to explain this variability.

- I reanalysed the entire time-series and found that the dugong population size and relative density in 2011-2012 were not significantly different from the 2008 survey but were significantly lower than the 2003 survey.

- I explored reasons to explain the discrepancies between the 2003 dugong relative abundance estimates and estimate from other survey years. I hypothesized that the results could originate from: (1) an actual reduction in the size of the dugong population between 2003 and the other years; (2) temporary migration across the survey area; or (3) unaccounted biases associated with detection probability.

- I did not find any evidence that could explain a real decline in the dugong population in New Caledonia. It is possible that movement of dugongs at least within survey blocks and unaccounted biases associated with detection probability and human error, have all influenced my results.

- My results highlight the necessity of conducting multiple baseline surveys to enhance interpretation of changes in wildlife population size estimates.

- The dugong population of New Caledonia is small and genetically isolated from the large dugong stocks from Australia. Monitoring should be continued while minimising methodology biases as much as possible to aid interpretation of results. Chapters 3, 4, 5 and 6 provide evidence-based opportunities to improve the conservation and management of dugongs in the region.

Chapter 3: The spatial coverage of dugongs by marine protected areas

Chapter 1
General introduction

Objective 1
Assess the temporal changes in dugong abundance and conservation strategies in New Caledonia

Chapter 2
Temporal changes in the relative abundance of dugongs

Chapter 3
The spatial coverage of dugongs by marine protected areas

Objective 2
Enhance understanding of spatial ecology of dugongs in coral reef environments

Chapter 4
Dugong movement heterogeneity in the coral reef of New Caledonia

Chapter 5
Seasonal changes in the abundance and habitat use of dugongs in the coral reefs of Cap Goulvain

Objective 3
Integrating scientific research conducted on dugongs as part of this thesis to inform decisions relating to dugong conservation and management regionally and internationally.

Chapter 6
General discussion

Dugongs were not explicitly considered in the design of the network of MPAs in New Caledonia, despite being one of the region's World Heritage values. In this Chapter, I retrospectively assess the capacity of the New Caledonia MPA network to protect dugongs from anthropogenic hazards. I develop a spatially-explicit model of dugong distribution and relative density based on information collected from ~10 years of aerial surveys (Chapter 2). I quantify the amount of overlap between areas supporting high densities of dugongs and MPAs.

A version of this chapter has been published as: Cleguer C., Grech A., Garrigue C. & Marsh H. (2015) Spatial mismatch between marine protected areas and dugongs in New Caledonia. *Biological Conservation*, 184, 154-162.

3.1 Introduction

Marine protected areas (MPAs) are a powerful tool for the conservation and management of marine resources (Gaines *et al.* 2010; Agardy *et al.* 2011; Lockwood *et al.* 2012). The levels of protection provided by MPAs range from restrictions on one or more human activities (e.g., fishing and tourism; Eagles *et al.* 2002; Pauly *et al.* 2002), to the comprehensive protection of an area from all anthropogenic impacts. Systematically designed MPAs use goals and targets to ensure the representation and persistence of biodiversity features and ecological processes at multiple spatial and temporal scales (Margules and Pressey 2000; Lourie and Vincent 2004). MPAs designed for the preservation of ecosystems are widely advocated over single-species approaches as the ecosystem approach provides conservation benefits for more species at a comparable cost (Pomeroy and Douvere 2008). Nonetheless, ecosystem-based MPAs need to incorporate ecological information and targets to ensure the protection of species and habitats of conservation concern (Hooker and Gerber 2004; Fernandes *et al.* 2005; Dobbs *et al.* 2008).

The MPAs of New Caledonia were designed to mitigate the adverse effects of human activities on marine biodiversity and the World Heritage listed lagoon ecosystem. An explicit reason for the 2008 World Heritage inscription of the lagoons was their globally important dugong population (UNESCO 2009). New Caledonia is critical to the persistence of dugongs at the eastern edge of its range and globally (Marsh *et al.* 2012). Protecting the dugong as a charismatic 'umbrella' species is also beneficial to other coastal species that utilise seagrass habitats, which are threatened by multiple human activities (Jones *et al.* 1995; Marsh and Morales-Vela 2012). Explicit targets for dugongs were not included in the design of New Caledonia's MPA network, and the ability of the network to protect the species is unknown.

I assessed the capacity of New Caledonia's network of MPAs to protect important dugong habitats. I developed a spatially-explicit model of dugong distribution and relative density using information collected from Chapter 2's time-series of aerial surveys and geostatistics. The overlap between the model and the current MPA network was used to assess the representation of important dugong habitats in various types of protected areas. I identified the potential drivers of spatial mismatch between dugong habitats and MPAs, and provide guidance on how these shortcomings can be overcome for dugongs and other marine species of conservation concern in New Caledonia and other regions.

3.2   Study area and species

New Caledonia's MPAs were originally designed to protect sites of great natural beauty from local informal fisheries (i.e., any activity that is conducted without a license or outside any institutional framework) and tourism (Service de l'environnement de la Province Sud, pers. comm.; David *et al.* 2010). In the early 2000s, the focus of MPA design changed to the conservation of connectivity and biodiversity informed by empirical studies on fish and sea bird breeding areas. Information on dugong relative abundance and distribution derived from a standardised aerial survey conducted in 2003 (~2026 ± 553 individuals *sensu* Garrigue *et al.* 2008 and see Chapter 2) was not used in subsequent MPA design.

Today, there are 33 MPAs in New Caledonia: seven in Province Nord and 26 in Province Sud. These areas are divided into five types: Integral reserves (IUCN Ia), wilderness reserves (IUCN Ib), natural reserves (IUCN IV), sustainable management reserves (IUCN VI) and Province parks (IUCN II; Table 3.1). Each Province is responsible for managing the MPAs within its administrative boundaries (Table 3.1). Each type of MPA is supported by a different set of regulations with different levels of restrictions, ranging from highly restricted-no access areas to areas with very few limitations on human activities (Table 3.1). The extent to which the regulations benefit dugongs and their seagrass habitats varies among each type of MPA (Table 3.1). In addition to MPAs, six marine zones (henceforth UNESCO zones), representing major patterns in the diversity of coral reefs and associated ecosystems, are registered as a World Heritage Area (UNESCO 2009; Figure 3.1). There are two UNESCO zones in Province Nord, two in Province Sud, one in Province des Iles Loyauté and one at the Entrecasteaux reefs. Each UNESCO zone is managed by local management committees and the relevant Province management authority.

Direct hazards to dugongs in New Caledonia include by-catch in gill-nets, illegal harvest, and collision with boats (Louis-Harris 2005; TNS 2005; Bordin 2009; Cleguer 2010; ESCAL and A2EP 2011; Pilcher *et al.* 2014). Urban development, mining and aquaculture are also likely to disturb the dugong's lagoon seagrass habitats (David *et al.* 2010; Hily *et al.* 2010). With the exception of by-catch in gill-nets and poaching, the anthropogenic hazards to dugongs and their seagrass habitats occur primarily on the west coast of New Caledonia, especially around the capital-city of Nouméa and in the Voh- Koné-Pouembout region (Bordin 2009).

3.3   Methods

I used information derived from the 10-year time series of aerial surveys described in Chapter 2 to develop a spatially-explicit model of dugong distribution and relative density in New Caledonia. I followed the methods of Grech and Marsh (2007) and Grech *et al.* (2011) to: (1) correct data from the aerial survey for sampling intensity variations between blocks and across surveys; and then (2) model dugong distribution and relative density using geostatistics. The spatial autocorrelation in the corrected aerial survey data was assessed using a variogram analysis in ArcGIS® 10.0 (ESRI 2011). The corrected aerial survey data were interpolated to the spatial extent of the aerial survey region (24,359km^2; Chapter 2 Figure 2.1) using universal kriging. Dugong distribution and relative density were calculated at a grid size of 1.6km x 1.6km (2.56km^2 cells). This scale accounts for: (a) the width of the transects; (b) slight changes in altitude of the aircraft which affect transect width at the surface; and (c) the area unavailable for observation under the aircraft. Each grid cell in the final model was regarded as a dugong density unit with a relative value of dugongs/km^2. I grouped the dugong relative density estimates based on their frequency distribution following the method of Grech and Marsh (2007) and Grech *et al.* (2011). I binned the values into four arbitrary categories: low density (0 dugongs/km^2); medium density (0-0.10 dugongs/km^2); high density (0.10-0.5 dugongs/km^2); and very high density (> 0.5 dugongs/km^2). Density units with 0 dugongs/km^2 were included in my analysis to ensure that the spatial layers extended across the entire survey region and to account for undetected dugongs that may have been present or moved between units (Chapter 4). The spatially-explicit model was tested by comparing the values of dugong relative density generated by the model to observed values using a cross validation analysis. Moran's I Spatial Autocorrelation statistics were used to assess clustering of dugong density units.

I developed a composite layer of all MPAs in New Caledonia from layers provided by resource managers from Province Sud and Province Nord. The UNESCO zones in Province des Iles Loyauté were removed from my analysis because dugong aerial surveys were not conducted in this Province. I overlaid the dugong distribution and relative density model with the composite MPA layer in ArcGIS® 10.0 to calculate the proportion of dugong density units within each MPA type (Table 3.1).

3.4   Results

The spatially-explicit model of dugong distribution and relative density showed a heterogeneous and clustered distribution of dugongs in the lagoons surrounding New Caledonia (Moran's I, z-score = 15.99, p ≤ 0.0001; Figure 3.1). The average dugong relative density across the entire survey region was 0.01 dugongs/km^2, and ranged from 0 to 1.49 dugongs/km^2. The predicted dugong relative density and the aerial survey data were highly correlated (cross validation analysis RMSS = 0.98). Units of very high dugong relative density were located in the Cap Goulvain region on the west coast between Province Sud and Province Nord (Figure 3.1 and 3.2). Units with high dugong density were located: (a) at several locations on the west coast: near Koumac, north of Voh, near and south of Nekoro, in the Moindou region and between the Nouméa and the Paita region; and (b) on the north-east coast between Pouebo and Touho (Figure 3.1 and 3.2).

Units of high to very high dugong relative density were poorly represented by the MPAs that provide high levels of restriction on anthropogenic activities. Units supporting a very high dugong density were not covered by any of the integral reserves (IUCN Ia), wilderness reserves (IUCN Ib), natural reserves (IUCN IV) and sustainable management reserves (IUCN VI). Instead, units of very high dugong density were located in the UNESCO zones (22%) and Province parks (90%, Figure 3.2). Most of the units of high dugong density were in non-MPA areas (74%) or covered by Province parks (12%) and UNESCO zones (17%).
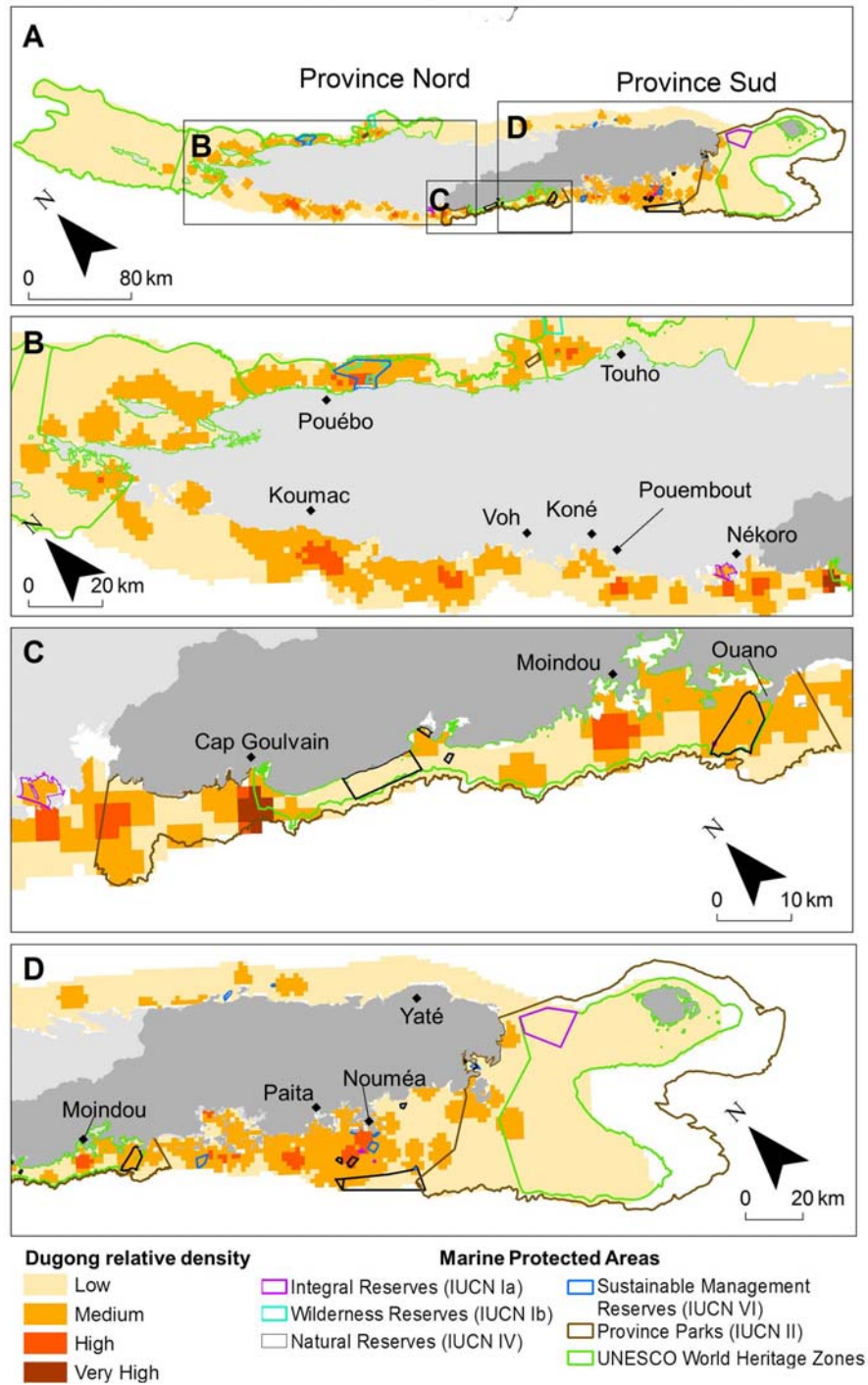
Figure 3.1: The spatially-explicit model of dugong distribution and relative density (number of dugongs sighted per km^2, grid cell size = 2.56km^2) in New Caledonia (A), on the north-east coast (B), the west coast (C), and in the south of New Caledonia (D). Most of the important dugong areas were distributed on the west and north east coast of the mainland. Note that: (1) the UNESCO zones of the Province des Iles Loyauté and one at the Entrecasteaux reefs are not shown in this figure; (2) maps of dugong sightings for all survey years are shown in Appendix A Figure A.1.
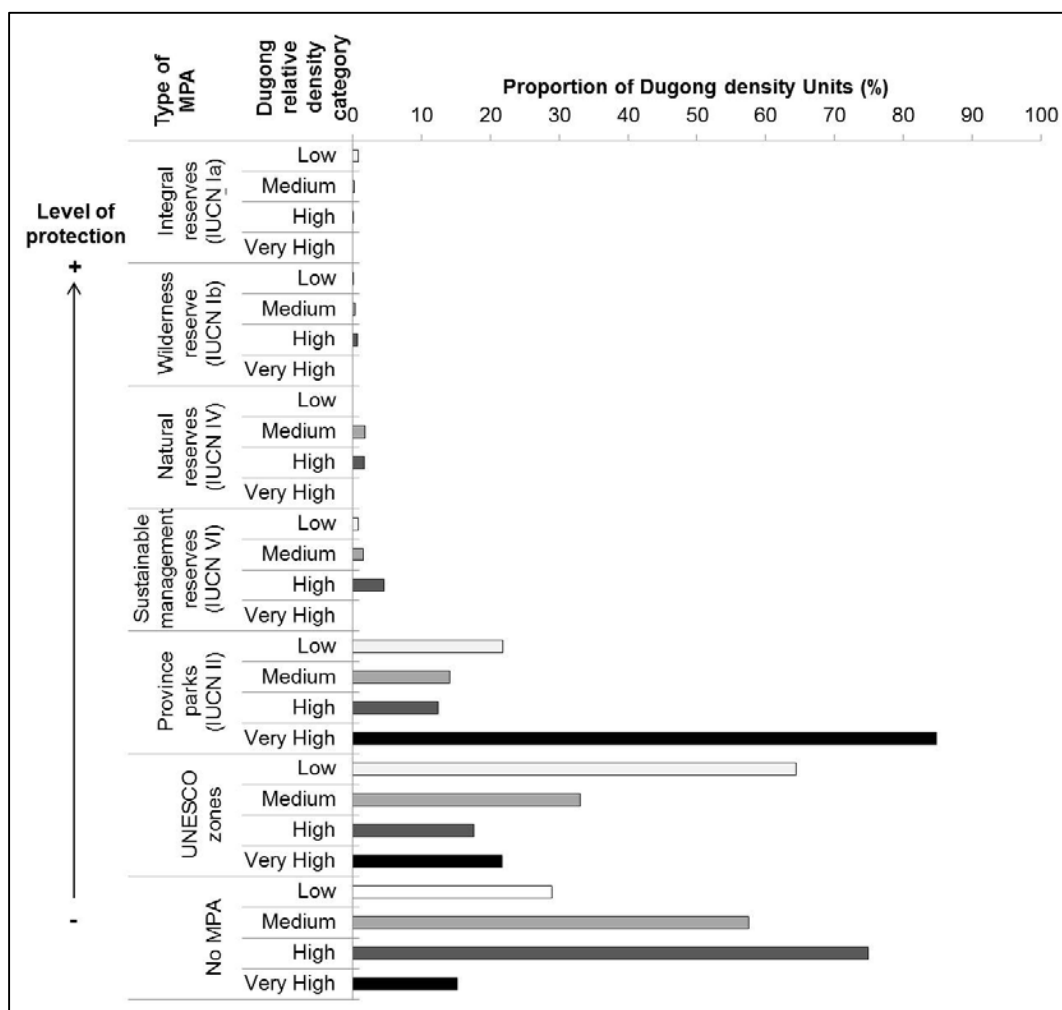
Figure 3.2: The relative frequency of each category of modeled dugong density units in each type of marine protected area (MPA) in New Caledonia. Most (84%) of the very high dugong relative density units occur in Province Parks (IUCN II), which are absent from Integral reserves (IUCN Ia). The sum of percentages within each density category does not equal 100% because MPA types overlap.

Table 3.1: Marine protected areas (MPAs) in New Caledonia and their relevance to dugong protection (Bertaud 2011; Province Nord 2008; Province Sud 2009). MPAs are listed in decreasing order of level of protection to dugongs.

IUCN category	Type of MPA	Location	Name of MPA	Date of creation (year)	Management objective and relevance to dugong protection
Ia	Integral reserve	Province Nord	Réserve Naturelle Intégrale de la Baie de Nekoro	2000	Strictly protected areas set aside to protect biodiversity and where human visitation, use and impacts are strictly controlled and limited to ensure protection of the conservation values. **Relevance of the regulation to dugongs:** human visitation, use and impacts are strictly controlled and limited
		Province Sud	Ilot Goéland	1996	
			N'Digoro	1998	
			Récif Sèche Croissant	1994	
			Yves Merlet	1995	
Ib	Wilderness reserve	Province Nord	Réserve de Nature Sauvage de Dohimen	2009	Preserve habitats' natural characteristics intact with a very low level of intervention except when addressing invasive species issues is necessary. **Relevance of the regulation to dugongs:** limitation of fishing activities (special permits), no disturbance of wildlife, limitation on human access (special permits)
			Réserve de Nature Sauvage de Pewhane	2009	
			Réserve de Nature Sauvage de Whan-denece Pouarape	2009	
			Réserve de Nature Sauvage de Whanga ledane	2009	
IV	Natural	Province Sud	Aiguille de la baie de Prony	1993	Maintain, conserve and rehabilitate threatened

IUCN category	Type of MPA	Location	Name of MPA	Date of creation (year)	Management objective and relevance to dugong protection
	reserve		Epave du Humboldt	1996	endemic and emblematic species and to restore or reconstruct altered habitats.
			Grand port	1993	**Relevance of the regulation to dugongs:** all
			Grand récif Aboré et de la passe de Boulari	2006	fishing is banned
			Ile Verte	1995	
			Ilot Bailly	1995	
			Ilot Larégnère	1998	
			Ilot Signal	1989	
			Ouano	2004	
			Passe de Dumbéa	1994	
			Poé	2006	
			Roche Percée et de la Baie des Tortues	1993	
VI	Sustainable management reserve	Province Nord	Aire de Gestion Durable des Ressources de Hyabe-Le Jao	2009	Enable the presence of human activities with no negative effect on biological diversity. Must be associated with a management plan which sets
		Province Sud	Ilot Amedee	1995	

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IUCN category	Type of MPA	Location	Name of MPA	Date of creation (year)	Management objective and relevance to dugong protection
			Ilot Canard	1993	the level of protection of the biodiversity feature occurring in the defined area. In the absence of a management plan in the Province Sud, the MPA area has the status of a natural reserve (IUCN IV). **Relevance of the regulation to dugongs:** depends on the management plan for each protected area
			Ilot Casy	2006	
			Ilot Maitre	1993	
			Ilot Moinde-Ouemie	1995	
			Ilot Tenia	Unknown	
			Pointe Kuendu	2005	
			Ilot Amedee	1994	
II	Province park[a]	Province Nord	Parc Provincial de Hyega	2009	Ensure the stability of ecological processes; preserve representative biological communities, genetic resources and species, by regulating the activities and needs of the local population. **Relevance of the regulation to dugongs:** "preserve natural equilibrium"
		Province Sud	Parc de la Zone Cotière Ouest	2009	
			Parc du Grand Lagon Sud	2009	

[a]In New Caledonia, Province parks do not meet the IUCN definition of Category II protected areas as they are intended to accommodate public use (Dudley 2008).

3.5   Discussion

Identifying the location of sites where dugongs are at risk from anthropogenic activities is critical to the long-term management of the species in New Caledonia. My analysis indicates that there is a spatial mismatch between locations that support a high density of dugongs and MPAs that provide the greatest protection from anthropogenic activities. My spatially-explicit modelling approach revealed a heterogeneous distribution of dugongs at the scale of New Caledonia, and identified important dugong areas in regions highly affected by human activities including the Nouméa and the Voh- Koné-Pouembout regions.

Appropriate conservation targets and spatial data are critical to the effective planning and management of threatened marine species (Pressey *et al.* 2007). The potential benefits of MPAs are compromised without this information. For example, the status of the vaquita (*Phocoena sinus*) in the Gulf of Mexico continues to deteriorate and the species is now listed as critically endangered because the reserve designed to protect the species and established in 1993 failed to cover 40% of its core habitat (Rojas-Bracho *et al.* 2006); although measures have recently been taken to tackle this issue (Braulik 2015). In the Mediterranean, seasonal legislation and MPAs do not cover the core breeding and feeding areas of the endangered loggerhead sea turtle, (*Caretta caretta*); (Schofield *et al.* 2013). The vaquita and loggerhead examples, my study and others are indicative of a global trend towards the declaration of 'residual' MPAs that fail to separate species from the activities that threaten them (Devillers *et al.* 2014).

I identified five potential drivers of the spatial mismatch between important dugong areas and the New Caledonia MPA network. I discuss each of these drivers below and provide generic guidance on how such shortcomings can be avoided for marine species of conservation concern.

Lack of explicit conservation goals and targets

In the past, terrestrial parks were primarily selected on the basis of their scenery and wilderness quality (Lockwood *et al.* 2012). This selection process also occurs in the marine environment (Margules and Pressey 2000; Devillers *et al.* 2014), including New Caledonia. The primary goal of protected areas should be the long term conservation of nature and the associated ecosystem services and cultural values (Dudley 2008). Some MPAs are also designed to conserve biodiversity specifically (i.e., minimise extinction risk), protect ecosystems, and enhance the size and productivity of harvested fish or invertebrate populations that support fisheries (Hooker and Gerber 2004). The design of effective MPAs requires clear conservation goals and targets (Margules and Pressey 2000; Pressey and Bottrill 2009). A goal is a broad statement about what

the protected area is attempting to achieve; a target is a quantitative measure of what needs to be accomplished to reach this goal (Margules and Pressey 2000).

This study demonstrates that the absence of conservation goals and targets increases the likelihood that MPAs will not benefit some species of conservation concern because they are of inadequate size and/or location. Conservation goals and targets should: (1) incorporate if not prioritise the most threatened biodiversity features or species, especially if such protection can benefit other less charismatic species (Dobbs *et al.* 2008; Devillers *et al.* 2014), and (2) reflect the needs of coastal communities as much as possible. The protection of 50% of all high priority dugong areas was an explicit target in the 2003 rezoning of the Great Barrier Reef Marine Park, Australia (Dobbs *et al.* 2008). A similar target-based approach should be applied in other countries and territories, including New Caledonia, to improve the protection of threatened species (McCook *et al.* 2010).

Omission of spatial information on species' distribution

The first proposal for the inscription of New Caledonia's lagoons as a World Heritage Area was rejected by the majority of the elected representatives, local descisions makers, and the French government in 2001. David *et al.* (2010) suggest that this proposal failed because of disagreements between public authorities and a local environmental Non Governmental Orgnization (NGO) on mining projects in New Caledonia. The spatially-explicit outputs of the first dugong aerial survey (Garrigue and Patenaude 2004; Garrigue *et al.* 2008) were provided to local resource managers in 2004 when proposals for the construction of two metal-processing projects were under assessment: Goro Nickel south of Nouméa and Falconbridge in the Voh-Koné-Pouembout region. Public authorities feared that inscribing the lagoons as a World Heritage Area would deter the project's investors (David *et al.* 2010). The World Heritage proposal was reopened after the Goro nickel metal-processing project commenced in 2005. Thus, controversy over the two metal-processing projects may have influenced the failure of public authorities to consider dugongs when planning the design of new MPAs and the World Heritage zones.

The omission of spatial information on dugong distribution at the planning stage of subsequent MPAs in New Caledonia contributed to the observed spatial mismatch, even though information was available. In other overseas regions, especially developing countries, spatially-explicit information on the range, migration, feeding and reproductive areas of marine mammals is often limited and prohibitively costly to obtain. Data-poor areas often receive little or no protection from MPAs even though they may be just as important or more important for species of conservation concern such as marine mammals (Hooker and Gerber 2004; Hoyt 2012). MPA

design requires the use of the best available ecological data. When data are absent, expert opinion can be used to define operational principles and critical sites for protection (e.g., Fernandes *et al.* 2005). An alternative is to design large MPAs inclusive of all the places that the population might be using, although this approach has also been criticized (Weaver and Johnson 2012; Singleton and Roberts 2014). Irrespective of the approach, resource managers should provide a solid and effective management mechanism along with appropriate management aims and strategies that explicitly prioritize the conservation of target species.

Mismatch of spatial scales

The New Caledonian MPA network was designed and is managed at the provincial scale. The provincial scale is not congruent with the ecological scale of marine mammals such as dugongs (Grech *et al.* 2011; Hoyt 2012). In Australia, repeated time series of dugong aerial surveys in the same region suggest that dugongs undertake large-scale movements (Preen and Marsh 1995; Marsh and Lawler 2002; Gales *et al.* 2004; Marsh *et al.* 2004; Gredzens *et al.* 2014). For example, in Torres Strait between Australia and Papua New Guinea, dugongs cross international boundaries in all directions (Gredzens *et al.* 2014). These movements support the importance of management and monitoring at ecological scales that cross jurisdictions (Marsh *et al.* 2002, 2012). The need to address cross-jurisdictional dugong conservation and management issues is confirmed by the inclusion of the dugong on Appendix I of the Convention on Migratory Species of Wild Animals (CMS 2015) and is one of the priorities of the Dugong Memorandum of Understanding signed by 26 signatories of which France (Mayotte and New Caledonia) is party (MoU 2007). Nonetheless, when developing strategies for mobile marine mammal conservation, politico-jurisdictional considerations should not prevail over ecological considerations. Cross-jurisdictional frameworks in which decisions about spatial scale are made explicit can improve the development of ecologically functional networks of MPAs or alternative conservation tools (Mills *et al.* 2010) as exemplified by: (1) the consortium of countries developing a regional framework for protection of the environment and sustainable development of coastal and marine resources, including dugongs in the Red Sea region (Gladstone *et al.* 2003); (2) the multilateral Coral Triangle Initiative in south-east Asia which aims to coordinate dugong conservation efforts throughout that region (Secretariat 2009); (3) the integrated and comprehensive management of Australia's Great Barrier Reef (Day and Dobbs 2013), and (4) the UNEP-CMS Global Dugong, Seagrass and Coastal Communities Initiative (CMS 2010). In conjunction with the recent development of a Dugong Action Plan in New Caledonia (Jacob and Gardes 2010), the results of my study provide scope to improve dugong conservation planning at multiple scales and across jurisdictions.

Cost considerations

I found that important dugong areas in New Caledonia received limited protection from direct hazards such as nets in small-scale fisheries and boating, and indirect hazards such as growing coastal urbanisation and the development of coastal mining industries (e.g., there is no MPA in the Voh- Koné-Pouembout region where the mining industry is booming and boating activities are expected to increase; David *et al.* 2010). In contrast, areas of low dugong conservation value are highly protected. The lack of protection of key habitats and species within the boundaries of protected areas occurs in terrestrial regions (Scott *et al.* 2001) and is becoming an issue of concern in the marine environment (Dryden *et al.* 2008; Edgar 2011; Devillers *et al.* 2014). Focusing on the conservation of areas where hazards are not significant diverts attention and resources from actions that address real hazards or more highly threatened areas (Agardy *et al.* 2011). This problem, which is often referred to as "residual protection", occurs where the cost to industry is minimised by locating protected areas where the level of extractive use or commercial potential is low (Devillers *et al.* 2014). One of the major disadvantages of residual protection is that species most associated with extractive uses (e.g., coastal marine species), and most in need of protection, continue to decline without effective intervention (Margules and Pressey 2000). Political leadership is required to transform scientific knowledge to effective conservation and management strategies (Day and Dobbs 2013).

Incorrect application of IUCN protected area categories

New Caledonian MPAs that cover most of the important dugong areas allow extractive activities such as fishing, even though they are designated as Category II IUCN protected areas. The most recent guidelines from the IUCN clearly state that commercial or recreational fishing is inappropriate in MPAs designated as category II protected areas (Dudley 2008). The correct application of IUCN categories to MPAs is important because it: (1) ensures that the IUCN categorization remains internationally meaningful; and (2) enables the accurate tracking of conservation progress towards international and national biodiversity targets (Fitzsimons 2011). Furthermore, the incorrect application of IUCN categories can create an illusion that the MPA is fulfilling a role when in fact it is not (Agardy *et al.* 2011). This illusion of protection may eventually reduce public trust in MPAs and has negative effects on their management. Increased efforts to clarify the definitions of IUCN categories relevant to MPAs and enforcement of the global framework are required.

3.6 Conclusion

The outputs of my study provide an important decision support-tool that can be used to improve the protection of dugongs in New Caledonia. While this improved protection could be addressed by establishing additional MPAs, other non-spatial management approaches such as community engagement, public education and codes of environmental best practice should also be considered (Kenchington and Day 2011; Day and Dobbs 2013). Approaches to comprehensively assess the existing and potential hazards to dugongs and options to mitigate these hazards should also be examined in the face of the uncertainties regarding the relative effect of human activities that threaten dugongs and their habitats in New Caledonia (e.g., Grech and Marsh 2008; Redfern *et al.* 2013).

To prevent spatial mismatch of future MPAs and species of conservation concern, management agencies should ensure that: (1) the best available data on the target species and the precautionary principle (i.e., coping with possible risks where scientific understanding is yet incomplete) are used and, when appropriate, knowledge inferred from studies conducted elsewhere (e.g., biology and life history); (2) explicit goals, preferably translated into quantitative, operational targets are set; (3) jurisdictional boundaries and political considerations do not preclude effective planning (Chapter 4); (4) MPAs incorporate the needs of threatened species and do not favour areas with the least value for extractive use; (5) MPA designations follow global conservation frameworks; and (6) if MPAs are to be established, the communities involved have a positive attitude towards them as lack of acceptance is potentially dangerous to their effective functioning (Agardy *et al.* 2003), especially in situations where resources for monitoring and enforcement are lacking (McMahon 2005; Arias *et al.* 2014), (7) integrate spatially-explicit information on the movement patterns of the species of interest if that data are available (Chapter 4), (8) optimize the chances of conservation of dugongs by using an adaptive management approach whereby management actions are taken and assessed through effective monitoring and changes are made for future actions based on the results.

3.7   Chapter summary

- Dugongs were not explicitly considered in the design of the network of MPAs in New Caledonia.

- In this chapter, I retrospectively assessed the capacity of the New Caledonia marine protected area (MPA) network to protect dugongs from anthropogenic hazards using information collected from ~10 years of aerial surveys in the region (Chapter 2). I developed a spatially-explicit model of dugong distribution and relative density and overlaid it with the layer of the New Caledonia MPA network.

- I identified high dugong relative density areas in the lagoons of New Caledonia and found that most of these important dugong habitats had a low coverage of MPAs that provide high levels of restriction on anthropogenic activities.

- The spatial mismatch between MPAs and dugongs was likely caused by weaknesses in the planning process, including the: (1) lack of explicit conservation goals and targets; (2) omission of spatial information on species' distribution; (3) mismatch of spatial scales; (4) cost considerations; and (5) incorrect application of the IUCN protected area categories.

- I provide guidance on how these shortcomings can be overcome for marine species of conservation concern in New Caledonia and other regions.

- Similar spatially-explicit models of dugong distribution and relative density have been used as a key decision support tool in Australia to inform the conservation and management of dugong and the outputs from this Chapter could aid future conservation plans in New Caledonia.

Chapter 4: Movement heterogeneity of dugongs in the lagoons of New Caledonia

Chapter 1
General introduction

Objective 1
Assess the temporal changes in dugong abundance and conservation strategies in New Caledonia

Chapter 2
Temporal changes in the relative abundance of dugongs

Chapter 3
The spatial coverage of dugongs by marine protected areas

Objective 2
Enhance understanding of spatial ecology of dugongs in coral reef environments

Chapter 4
Dugong movement heterogeneity in the coral reef of New Caledonia

Chapter 5
Seasonal changes in the abundance and habitat use of dugongs in the coral reefs of Cap Goulvain

Objective 3
Integrating scientific research conducted on dugongs as part of this thesis to inform decisions relating to dugong conservation and management regionally and internationally.

Chapter 6
General discussion

Effective protection of large marine megafauna is often hampered by a lack of information on their use of space. In this chapter, I examine the heterogeneity in movement patterns of 12 dugongs which I captured and satellite tracked in three different regions in the lagoons of New Caledonia. I discuss the ecological significance of my findings. The conservation and management implications are discussed in Chapter 6.

Christophe Cleguer

4.1   Introduction

Spatially-explicit information on the movement patterns of marine wildlife species can play a central role during the development of management strategies including the design of marine protected areas (MPAs); (Cañadas *et al.* 2005; Lovvorn *et al.* 2009; Hoyt 2012; Hussey *et al.* 2015). The objectives of individual MPAs vary but they typically aim to conserve marine biodiversity by separating species and their habitats from anthropogenic activities (Chapter 3; Edgar *et al.* 2007; Fox *et al.* 2012). Marine protected areas often fail to reach their full potential, in part at least as a consequence of a lack of biological information on critical habitat connectivity, animal movements and use of space (Dryden *et al.* 2008; Agardy *et al.* 2011; Bearzi 2012; Schofield *et al.* 2013). For example, the protection of highly mobile marine megafauna species, including species of marine mammals, tends to be sub-optimal because MPAs are often too small or placed in locations that offer incomplete spatial protection (Flores and Bazzalo 2004; Bearzi 2012; Hoyt 2012). Thus understanding the use of space in marine megafauna can have profound implications for their conservation, especially for species such as dugongs that live in coastal environments under increasing pressure from anthropogenic activities.

Remote recording devices have been used to examine how dugongs use space in order to inform their conservation. For example Marsh and Rathbun (1990) first documented the movements and habitat use of dugongs using remote recording devices (satellite and VHF transmitters). Their motivation was to assess the efficacy of the Great Barrier Reef Marine Park Authority zoning strategy, which provided a high level of protection for some inshore seagrass areas that support large numbers of dugongs. Most of the dugongs tracked by Marsh and Rathbun (1990) remained in the vicinity of localised highly protected inshore and intertidal and subtidal seagrass beds. However, one pubescent male dugong moved between two bays about 140km apart three times in nine weeks (Marsh and Rathbun, 1990). This heterogeneity in dugong movements has been confirmed as technology has improved and more dugongs have been tracked (De Iongh *et al.* 1998; Holley 2006; Sheppard *et al.* 2006; Gredzens *et al.* 2014). For example, Sheppard *et al.* (2006) found that of the 70 dugongs tracked in Queensland and the Northern Territory, 26 (37%) moved less than 15km from their capture sites, 28 (40%) moved 15-100km and 14 (20%) moved over 100km away. Large-scale movements of dugongs were also identified in Shark Bay, Western Australia (Holley *et al.* 2006). In Indonesian waters four dugongs tracked moved distances between 17km and 65km (De Iongh *et al.* 1998). Most of the tracking periods were relatively short (i.e., weeks or months) so it is likely that this tracking underestimated the extent of movement between habitats as demonstrated by Cope *et al.* (2015) using pedigree analysis.

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Information on the use of space by dugongs is used in management. Detailed maps of possible movement corridors and core habitats informed the zoning of the Great Sandy Strait Marine Park Zoning in Queensland (Sheppard 2008). Evidence of dugong movements outside of reserve structures have been obtained in Western Australia where dugongs undertake seasonal movements (Holley 2006) and in Torres Strait where tracked dugongs underused the sanctuary specifically designed for their protection (Gredzens *et al.* 2014). Both satellite and acoustic tracking technologies have been used to document the movement patterns of dugongs in Moreton Bay in an area adjacent to the Port of Brisbane, Australia's third busiest port (Zeh *et al.* 2015), suggesting that dugongs regularly move in and out of Go-Slow zones (i.e., zones where speed is limited to a non-planing speed to reduce the risk to dugongs and marine turtles from collision with boats, see Chapter 6). By comparing observed boat movements with those of tracked dugongs, Maitland *et al.* (2006) suggested new boating routes to minimise collisions with dugongs while limiting imposition on boaters.

The dugong's use of space may differ between localities within the species' range. Gredzens *et al.* (2014) found substantial differences in the dugong range sizes and depth zone preferences between Torres Strait and Shoalwater Bay, suggesting that the relative availability of deeper water and shallow-water habitat, the presence of reefs, the location and size of available seagrass meadows and the regional dugong population size may influence these patterns. Thus, enhancing understanding of the dugong's use of space requires investigation on the movements of dugongs in disparate habitats in order to obtain generic insights in specific habitats to inform conservation initiatives.

In Chapter 2, my analysis of the dugong relative abundance and density suggested that dugong movements may occur at least within survey blocks but this could not be verified. In Chapter 3, I used aerial survey data and spatially-explicit modelling to obtain information on the locality of important dugong habitats and on the capacity of the MPA network to protect these areas. In this Chapter, I use GPS satellite telemetry to examine the scale and heterogeneity of the use of space by dugongs in the lagoons of New Caledonia by capturing 12 individuals in three locations of high dugong conservation value. My primary research objectives were to: (1) describe the dugongs' movement patterns; (2) estimate the size of their home-ranges and identify core activity spaces; and (3) identify any specific movement corridors used by dugongs to transit between important habitats. I then discuss the ecological and conservation and management implications of my findings.

4.2   Methods

Study sites

Twelve dugongs were satellite tagged in three high dugong density locations (Cap Goulvain, Ouano, Nouméa) identified on the basis of the spatially-explicit model of dugong distribution and relative density (Chapter 3; Figure 3.1) based on the aerial surveys (Chapter 2).

Cap Goulvain is the most remote of all three study sites. It is located 200km north of Nouméa and supports one of the highest dugong densities in New Caledonia (Cleguer *et al.* 2015; Chapter 3). The lagoon in Cap Goulvain is approximately four kilometres wide. It is shallow (< 10m) in the reticulated reef and inshore intertidal seagrass meadow areas but deeper (> 10m) in the channels. The lagoon widens north of Cap Goulvain to reach 15km in the Koné region and narrows southward to 2km wide between Cap Goulvain and Bourail. The Ouano region is located approximately half way between Cap Goulvain and Nouméa. In the Ouano region, the lagoon is up to 10km wide, it is shallow north of Ouano (most areas are < 10m deep) and it increases in depth (> 10m deep) further south. The southwestern lagoon surrounding the Nouméa region is funnel shaped with a width varying from 40km in the southeast to about 5km in the northwest, and a mean depth of approximately 17.5m.

Dugong capture

Seven dugongs were tagged in Cap Goulvain, two in Ouano and three in the Nouméa region (Figure 4.1 and Table 4.1). Tracking animals like cetaceans and sirenians that spend all of their lives in the water can be difficult as there are numerous challenges associated with tag deployment (Irvine 1983; Marsh and Rathbun 1990). Tag deployment is particularly challenging when animals need to be physically captured. Capturing dugongs to deploy satellite tags risks injuring both the animals and the research team (Marsh and Rathbun 1990). Thus, using a safe technique for capturing and tagging dugongs is essential.

The most commonly-used technique for catching dugongs to fit GPS satellite transmitters is the rodeo technique, first used by Marsh and Rathbun (1990) and described in detail by Lanyon *et al.* (2006). This technique requires a close pursuit of an individual dugong, preferably in clear, shallow waters to increase the chances of following the animal as it moves through the water column. The pursuit is usually carried out using an outboard-powered speed-boat - also called a 'catch-boat' - until the animal is fatigued and then caught manually by personnel jumping from the vessel (Lanyon *et al.* 2006). Given the dugong's short burst capabilities during a pursuit

Figure 4.1: Locations of the three dugong satellite tagging sites. Boxes in the map provide details about the dugongs tagged in each study region. This map shows also the extent of movements of dugongs from the three study regions. Note the letter assigned to each dugong tracked. These letters were then used in the text of this Chapter to simplify identification of individuals.
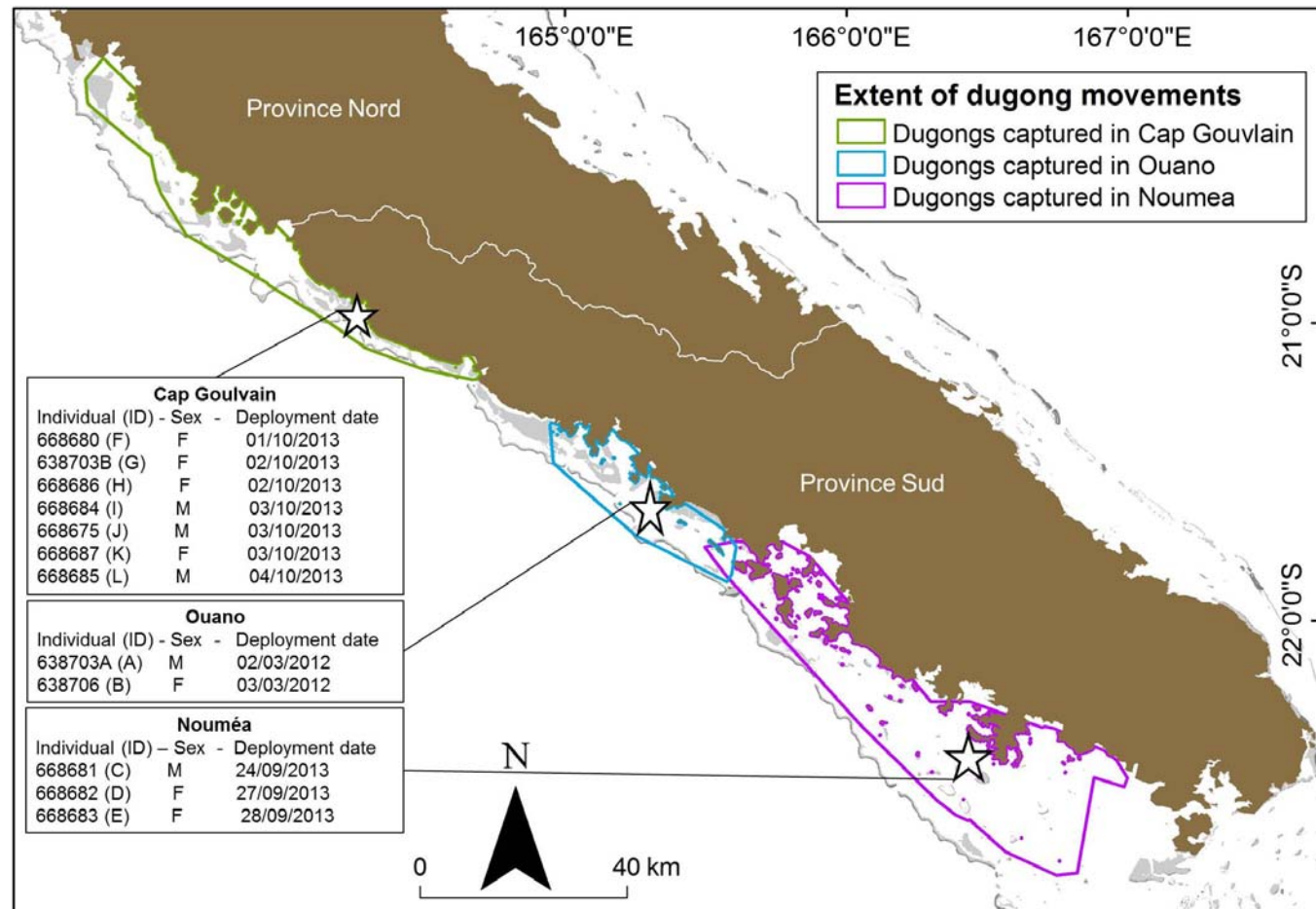
(Marsh *et al.* 1981), the catch-boat needs to be capable of accelerating to speeds of up to 20km per hour within seconds and to have high manoeuvrability as dugongs can swim in unpredictable directions with great agility (Marsh *et al.* 1981; Heithaus and Dill 2002; Shimada *et al.* 2012). The use of front steering boats allows drivers to keep the animals in their sight during the pursuit in order to reduce the risk the animal being hit by an outboard powered vessel (Lanyon *et al.* 2006).

The challenges involved in catching dugongs are exacerbated in shallow areas over reef flats, where boat access is difficult. The dugongs that were pursued, captured and tagged in Cap Goulvain and Ouano were located over shallow reef flats. When a pursuit was initiated, the animals tended to zigzag between coral heads just centimetres below the surface. Following dugongs in such an environment using a standard outboard-power vessel was very difficult because we had to be careful to not hit the coral heads while following the target dugong.

To address this issue, I developed a safe and efficient way of catching dugongs in clear shallow reef waters using a Personal Watercraft (PWC; Figure 4.2) that can carry two people. This technique has several advantages over the use of a standard outboard-powered dinghy. The PWC is small and manoeuvrable and can reach the required speed and slow down within a very short timeframe. The driver can sit or stand up and can easily follow the animal. These factors also allowed the driver to place the jumper in a position that increases the chances of a successful and safe catch. A PWC has a very shallow draft, which allowed the catching team to successfully follow a dugong at speed in shallow waters and in areas where there were physical obstacles such as coral reef bommies.

Most importantly, the use of a PWC was safer than the outboard powered vessels typically used to catch dugongs, because its propeller is in the turbine, which is located inside the plastic shell. This feature eliminated the risk of dugongs or personnel being hit by propellers.

The catching technique consisted of a driver/secondary catcher, and a primary catcher, seated behind the driver on the PWC (a two seater 3m See-do). Two assisting vessels and a safety mother-ship were also used: (1) the first assisting vessel had two additional catchers and a skipper on board and acted as a secondary catch-boat; (2) the second assisting boat had two assistants and a skipper. The assistants' task was to help the catchers to secure the dugongs against their boat, measure and sex the animal, take a skin sample for genetics and help fitting the GPS satellite transmitter before releasing the animal.
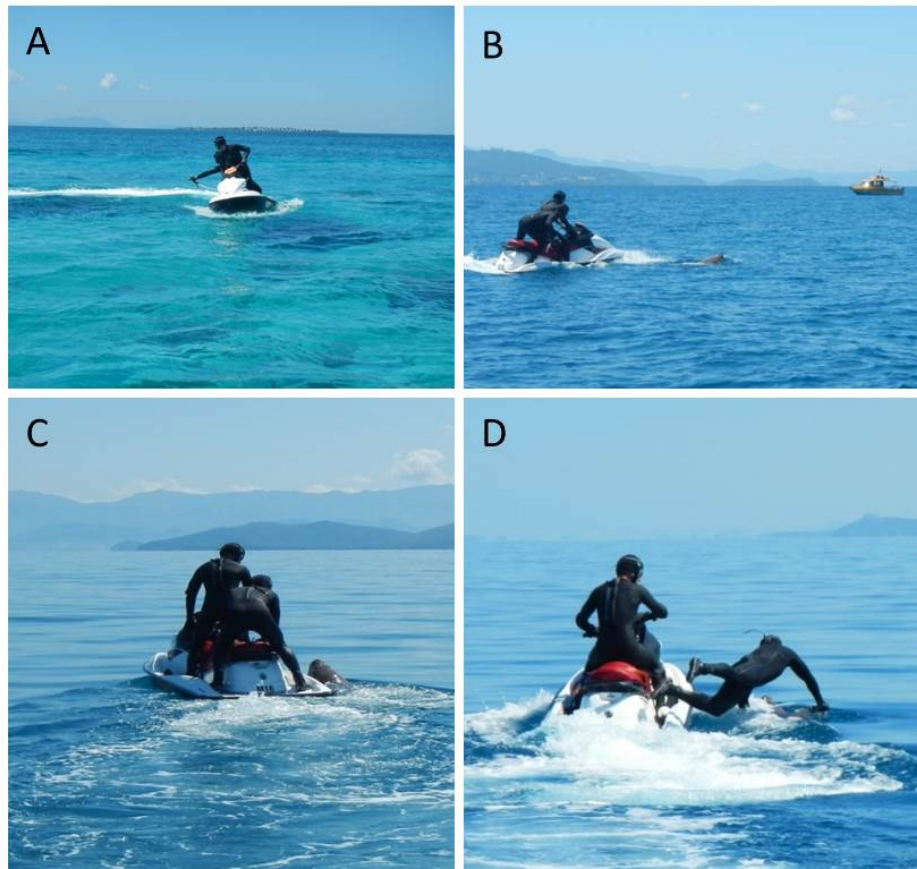
Figure 4.2: Use of a Personal Watercraft (PWC) to approach and catch dugongs in New Caledonia: (A) primary catchers pursuing a dugong in a shallow coral reef environment, the primary catcher is pointing at the animal; (B and C) PWC approaching the dugong at a catchable distance –note the safety boat in the background in (B); (D) primary catcher jumping from the back of the PWC onto the dugong's fluke to restrain the animal.

Once a dugong was spotted, priority was given to the PWC approaching and pursuing it. The dugong was allowed to surface and breathe at least twice prior to capture (Lanyon *et al.* 2006). Following the second breath, the driver maintained a reasonable sighting distance from the dugong and gradually approached from behind as the animal surfaced for its third breath (Figure 4.2A, B). When the animal reached the surface the driver positioned the PWC parallel and at a maximum distance of one meter from the animal to facilitate efficient jumping and catching (Figure 4.2C).

Dugong capture proceeded with the primary catcher jumping on the dugong and holding its caudal peduncle to prevent it from escaping (Figure 4.2D). The secondary catch-boat slowly approached, allowing the two catchers to jump in and secure the dugong from the front and to maintain its head at the surface to enable it to breathe freely. If needed, the driver/secondary catcher from the PWC could also jump to help maintain the animal at the surface and secure it against the second assisting boat. The PWC was equipped with a circuit breaker connected to the wrist of the driver. If the driver/secondary catcher jumped on the dugong, the vessel stopped and was secured by the secondary catch-boat skipper. Dugong monitoring and restraint protocol followed Lanyon *et al.* (2006) and Flint (2013; see Appendix C).

Dugong satellite tracking

Harness attachment and release mechanism

Satellite tags or the antennae thereof need to be at the surface to acquire and transmit a location because radio signals are attenuated by the high electrolyte content of salt water (Marsh and Rathbun 1990). In most species of cetaceans, satellite tags are deployed on or next to the animals' dorsal fin (Hooker and Baird 2001; Andrews *et al.* 2008) while in pinnipeds tags are glued to the animals' pelage (Fedak *et al.* 1983; Geschke and Chilvers 2010). Dugongs do not have a dorsal fin to clamp a tag onto or sufficient body hair to glue a tracking device on their body. They also tend to roll and to rub their skin against the bottom. Thus, the peduncle offers the only secure attachment point for external devices (Marsh and Rathbun 1990; Reid *et al.* 1995) making a dugong harness assembly necessary. The dugong harness was first used by Marsh and Rathbun (1990) and its design has evolved to increase the number of transmissions of location fixes as well as ensuring that the telemetry devices and harness do not jeopardize animal welfare (De Iongh *et al.* 1998; Holley 2006; Sheppard *et al.* 2006). Satellite tags were attached to the dugong's peduncle via a 3m long flexible tether fitted with a padded tailstock belt (Figure 4.3). This system allows the tag to float to the surface when the animal is in shallow water, increasing the frequency of signals being transmitted to the satellites. The harness assembly incorporates a weak link that can be broken by the animal if it becomes entangled in marine obstructions such as coral or mangroves and a backup corroding link. If the tether does not get entangled, the link slowly corrodes in a galvanic reaction in seawater and releases the harness.
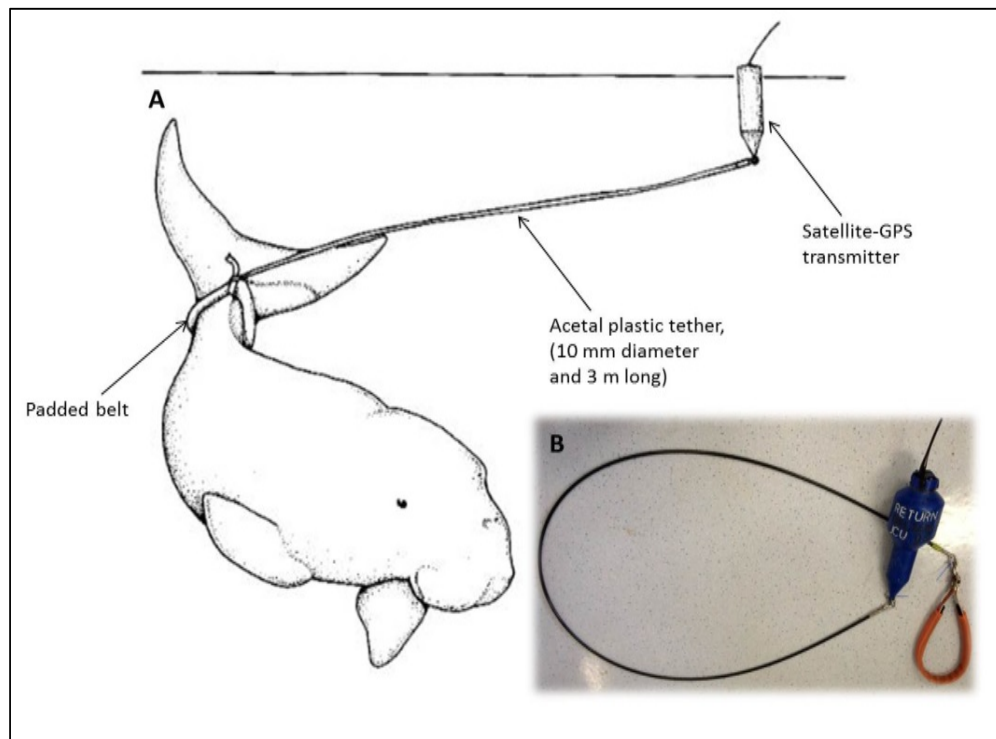
Figure 4.3: A dugong with a harness assembly to attach a GPS satellite transmitter (A); (adapted from Marsh and Rathbun 1990) and photograph of the apparatus (B). See Appendix B for more details on the design of the attachment apparatus).

The release mechanisms incorporated in the harness assemblies used immediately prior to my project showed signs of malfunction (Colin Limpus pers. comm.) with the weak link breaking under inconsistent pulling strength. Consequently, I undertook collaborative work with manatee specialist Dr. James Powell (Sea to Shore Alliance, Florida, USA), Helene Marsh's research group and engineers at James Cook University in Townsville to improve the harness assembly. The new harness assembly was designed to be used with TMT 462 GPS/ARGOS tags (Telonics^{TM}). The goal was to update the belt-tether-tag design initially used by Marsh and Rathbun (1990) and which had proven more satisfactory than the more recent models. The attachment devices I used incorporated holes of specific size drilled into the belt end of the tether to act as a weak-link. The strength required to break the weak link was set, and successfully trialled in a lab, at 160kg (average adult weight of a dugong is above 300kg and ranges up to 530kg). A hollowed zinc bolt acting as a corrodible link was used to attach the belt around the dugong's peduncle. A full description of the new harness assembly can be found in Appendix B. I also deployed archival Time Depth Recorders (TDRs; Model MK9 manufactured by Wildlife Computers) on all the captured dugongs. The TDRs were attached to the peduncle

end of the tether. The primary aim of deploying Time Depth Recorder was to investigate the diving patterns of dugongs in the lagoons of New Caledonia to enhance the estimates of dugong relative abundance in this region (Chapter 2). However this analysis was beyond the scope of my thesis.

Global positioning system (GPS) satellite tags

I used the Gen4 GPS receiver technology developed by Telonics. Gen4 systems incorporate a GPS receiver for obtaining positional data. The fix time of this GPS receiver ranges between 30 and 90 sec assuming a clear view of the sky (Telonics 2013). Typical GPS position accuracy is 2-10m. The units also employed a fast acquisition GPS tracking technology entitled Quick Fix Pseudoranging (QFP) technology developed for marine mammals that surface for only short periods of time. The QFP technology obtains location fixes with as little as 3 seconds of surfacing time. QFP locations are categorized by locational accuracy into three categories: resolved QFP, resolved QFP (uncertain), and unresolved QFP. Telonics (2012) states that 98.4% of resolved QFP positions are within 30m of the actual position, resolved QFP (uncertain) positions are generally within 75m, and unresolved QFP positions are over 100m.

Data processing

All raw data were transmitted via the ARGOS network (Argos-system.org), downloaded from ARGOS via the transmitter manufacturer-supplied software (Telonics Data Converter) and converted to the Universal Transverse Mercator (UTM) coordinate system. Dugong location data were used from the time of release of the animal until a transmitter stopped transmitting or detached. Transmitter detachments were identified by: (1) acquisition of successive GPS location classes at consistent time intervals (e.g., on the hour, every hour), (2) prolonged consistent movement indicative of a drifting tag, or (3) signals from one location for an extended period of time (e.g., days) indicative of a stranded tag.

Because the use of QFP technology in animal tracking is relatively new, objective filtering techniques were developed to maintain the accuracy of acquired locations. For fine-scale analysis, the data were initially filtered by location class, using only successful GPS, and resolved QFP location classes to maintain accuracy of 30m. After initial filtering, data were corrected for: (1) over-speed errors: identified by the distance and time between successive fixes necessitating speeds beyond the maximum sustained swimming speed for dugongs of 10km hr^{-1} (Marsh *et al.* 1981), (2) temporal duplicates: fixes which were simultaneously obtained but associated with different level of quality index (the fix with higher quality index was retained), and (3) fixes obtained inland: locations more than 30m inland were removed as 30m is the error

estimate for the most precise QFP locations (Telonics 2013). Corrections were conducted using the data-driven method described by Shimada *et al.* (2012) and the associated R-package.

After filtering and correcting the dataset, the location data from each dugong were standardized by dividing the remaining location points into 1 hour duty-cycles and selecting the most accurate location within each duty-cycle. One hour was chosen to retain as many location points as possible while minimising differences in the number of location points per day per animal. In addition, duty cycles were used to reduce the effects of autocorrelation and effects resulting from differences in transmitter performance. These measures were necessary as sample size has been shown to significantly affect home-range estimates (Boyle *et al.* 2009). The best location was chosen using two criteria: (1) the location with the greatest number of satellite uplinks, and (2) if multiple locations had the same number of uplinks, the final choice was the location with the lowest error in position. When multiple locations had the same error value, the location closest to the median time point within each duty-cycle was chosen.

Analysis

Data from all tracked dugongs were used to analyse the duration of satellite tag deployment and to explore the movements of the tracked individuals. Three dugongs were subsequently removed from the analyses because their GPS transmitters detached after a week or less, which was regarded as a too short tracking period to undertake meaningful analysis of home range (Table 4.2). Thus, home-range and core area calculations and the analyses on the diurnal comparison of home-range, seagrass and depth zone distribution and use of marine protected areas describe below included data from nine dugongs: two dugongs captured in Nouméa, two dugongs captured in Ouano, and five dugongs captured in Cap Goulvain.

Extent of movements

Minimum convex polygons (MCP) were calculated using the Minimum Bounding Geometry tool in ArcGIS 10.2 (ESRI, 2013) to define the extent of movement of dugongs in each of the three study regions. The maximum distance each individual swam from its capture location was determined using the least-cost path analysis tool in ArcGIS 10.2.

Home-ranges and core areas

The space used by dugongs was defined by their home-range – 95% Kernel density estimates (Kde) and the core areas were defined by the 50% Kde. For both, the fixed Kernel density estimation was used and isopleth tools in the Geospatial Modelling Environment software

(GME; Beyer, 2012) at a resolution of 30m. This resolution was selected because the mean accuracy of filtered QFP GPS locations is within 30m of the true location. I tested several smoothing parameters including Least-squares Cross-validation (LSCV), Smoothed Cross-validation (SCV), Biased Cross-validation (BCV) and Likelihood Cross-Validation (CVh). After exploratory data analysis, CVh was chosen as the most biologically relevant smoothing parameter for the dataset. This approach is consistent with other recent analyses of dugong home-ranges and core areas (Gredzens *et al.* 2014; Zeh *et al.* 2015). The sizes of the 95% home-range and 50% core areas (area in which an individual is predicted to be 95% and 50% of the time respectively) of the nine tracked dugongs were calculated in ArcMap 10.2 from the 95% and 50% contour polygons generated in GME. Any areas of the 95% and 50% polygons that overlapped with land were removed before the size of each polygon was calculated. Home-ranges were calculated for each animal using data from the entire period in which it was tracked.

Diurnal comparisons of home-ranges

I calculated the diurnal and nocturnal home-ranges for each animal using all filtered data, recorded respectively during the day (6am-6pm hours) and during the night (6pm-6am hours). Differences between day and night ranges were determined by: (1) calculation and comparison of day/night estimated range sizes; (2) using the Utilisation Distribution Overlap Index (UDOI; Fieberg and Kochanny 2005) to measure the degree to which day/night estimated ranges of each individual shared space. Calculations UDOI were conducted in R (R Development Core Team 2010) using the 'adehabitatHR' package (Calenge and Calenge 2015). The UDOI equals zero for two home-ranges that do not overlap and equals 1 if both home-ranges are uniformly distributed and have 100% overlap. UDOI can be greater than 1 if the two home-ranges are non-uniformly distributed and have a high degree of overlap (Fieberg and Kochanny 2005).

Seagrass and depth zone distribution

A bathymetric model with a resolution of 100m generated by Lefevre *et al.* (Institut de Recherche pour le Développement; 2013 unpublished) was used to determine the depth zones used by each tracked animal. Each layer was stored in raster format, reclassified into 5m depth zones and converted to vector format to allow the home-range vector polygons to be overlaid. Total individual ranges of each individual (both 95% home-ranges and 50% core areas) were then overlaid on the reclassified bathymetry layer and the total area over each depth zone was calculated for each individual.

The only georeferenced seagrass map layer available at the spatial scale of our study was a layer of the maximum extent of shallow seagrasses (< 5m) generated from Landsat imagery (Andréfouët *et al.* 2010). I calculated the sizes of the 95% home-ranges and 50% core areas of the combined tracks of animals by region overlapping with the seagrass layer. Dugongs are likely to use seagrasses that are not identified by the seagrass layer because the seagrass map is restricted to seagrasses present in shallow waters (< 5m). Thus this analysis provided an indication only of the proportion of the range of dugongs using shallow seagrasses.

Use of marine protected areas

A composite GIS layer of all MPAs in New Caledonia was provided by resource managers from Province Sud and Province Nord and was integrated into ArcGIS. The MPA layer was overlaid with the filtered dugong GPS tracks and the proportion of GPS location fixes contained in each type of MPA was calculated for each tracked individual to obtain an indication of the amount of time spent by each dugong within the boundaries of the MPAs.

4.3   Results

Dugong catching and tagging

Of the 12 animals captured and satellite tagged, seven were females and five were males. Total lengths ranged from 2.15-2.90m with a mean of 2.52m, $\pm$ SE = 0.07m (Table 4.1). There was no difference in the mean lengths of males and females (Independent T test: p = 0.13).

The mean chase initiation to release time of the 12 dugongs captured was 15 min 44 s (range: 7 min to 44 min; Table 4.1). The upper bound reflects the circumstances under which individual D was captured. This dugong was sighted in deep (> 10m), clear water off Nouméa. It did not swim away from our catching vessel. Manually capturing individual D was very difficult because atypically it was not followed and therefore not fatigued.

Filtered location points

Out of 16,262 location fixes, 6,241 filtered data locations were retained for analysis. The number of filtered data locations for individual dugongs ranged between 33 and 2,720 locations over the total tracking time for each individual. An average of 14 filtered data points was obtained per animal per day ($\pm$ SE = 0.94; Table 4.2). Individual variation was low within each study region, ranging from 16 to 21 filtered data points per individual in Ouano, 11 to 13

filtered data points per individual in Nouméa and 10 to 16 filtered data points per individual in Cap Goulvain. The number of locations was fairly evenly distributed between day (48% of locations obtained between 6am and 6pm) and night (52% of locations obtained between 6pm and 6am) throughout the tracking period of all individuals (Table 4.2).

Tracking duration and distance from capture location

Individual dugongs were tracked for between three and 192 days (mean = 35.9 days, median = 18 days, ± SE = 15.31 days, n = 12 individuals; Table 4.2). The extent of movements for the tracked dugongs reflected the southeast/northwest orientations and width of the lagoons (Figure 4.1). The extent of movements for the seven dugongs captured in Cap Goulvain extended over 100km from the Koné Bay to the Bourail Bay (Figure 4.4). Movements of the two dugongs captured near Ouano extended over 46km from Moindou in the north to Tenia Islet in the South (Figure 4.5). There was an overlap, near Tenia Islet, between the areas traversed by dugongs tracked from Ouano and that of dugongs tracked from Nouméa (Figure 4.1). Movements of dugongs tracked near Nouméa extended south to Redika Island (25km south of Nouméa Figure 4.6).

The tracked dugongs moved a mean maximum distance of 37.7km (± SE = 5.2) from their capture location (range: 13.8km to 72.9km; Table 4.3). There was no significant relationship between the maximum distance that the dugongs moved from their capture location and their tracking period (Pearson's correlation coefficient = -0.14). Individual I ranged farther from its capture location than any other tracked dugong (Figure 4.4A and Table 4.3), going on a seven day trip 73km north from Cap Goulvain into the Koniène coral reef-seagrass plateau before swimming back to its capture location. The shortest distance a dugong moved away from its capture location was 14km; individual H remained between Cap Goulvain and the Poya Pass (Figure 4.4B and Table 4.3).

Table 4.1: Details of the dugongs' identification number and capture and tagging event in New Caledonia. The mean following to release time of the 12 dugongs captured was 16 min. The upper bound reflects the circumstances under which individual D was captured.

Study region	Transmitter No.	Individual ID	Capture location (Lat/Lon; Decimal Degrees)	Date tagged	Sex	Size (m)	Spotting time of day[a]	Capture time of day	Release time of day	Duration between approach initiation and release	Duration animal was held
Ouano	638703A	A	-21.82 / 165.8	2/03/2012	Male	2.7	na	na	na	na	0:20:00
	638706	B	-21.78 / 165.66	3/03/2012	Female	2.3	na	na	na	na	0:12:00
Nouméa	668681	C	-22.29 / 166.47	24/09/2013	Male	2.5	14:24:00	14:26:00	14:36:00	00:12:00	0:10:00
	668682	D	-22.32 / 166.37	27/09/2013	Female	2.8	9:16:00	9:51:00	10:00:00	00:44:00	0:09:00
	668683	E	-22.33 / 166.38	28/09/2013	Female	2.6	11:37:00	11:40:00	11:44:00	00:07:00	0:04:00
Cap Goulvain	668680	F	-21.52 / 165.2	1/10/2013	Female	2.7	10:55:00	11:18:00	11:28:00	00:33:00	0:10:00
	638703B	G	-21.51 / 165.18	2/10/2013	Female	2.9	8:53:37	8:54:21	9:02:00	00:08:23	0:07:39
	668686	H	-21.51 / 165.17	2/10/2013	Female	2.3	8:49:10	8:49:20	8:57:23	00:08:13	0:08:03
	668684	I	-21.52 / 165.22	3/10/2013	Male	2.2	9:09:09	9:13:34	9:18:31	00:09:22	0:04:57
	668675	J	-21.51 / 165.21	3/10/2013	Male	2.4	7:57:09	8:02:50	8:08:30	00:11:21	0:05:40
	668687	K	-21.53 / 165.19	3/10/2013	Female	2.7	8:34:35	8:35:16	8:41:51	00:07:16	0:06:35
	668685	L	-21.53 / 165.22	4/10/2013	Male	2.3	9:25:00	9:34:40	9:41:44	00:16:44	0:07:04

[a] Time of day and duration are indicated in hh:mm:ss format.

Table 4.2: Tracking period and details for each dugong on the numbers (No) of total and filtered location points and their 95% home-range and 50% core area sizes. The number of location points was evenly distributed between day (48% of locations obtained between 6am and 6pm) and night (52% of locations obtained between 6pm and 6am). Values of the Utilisation Distribution Overlap Indexes (UDOI) close to or ≥ 1 show that there was a high degree of overlap between day and night 95% home-ranges and 50% core areas (also see Figure 4.11). The 95% home-range, 50% core areas and UDOI were not calculated for the dugongs with short tracking periods (i.e., ≤ 7 days); (na).

Study region	Individual ID	Tracking period (days)	No of filtered location points	Mean No of location points per day	No of filtered location points (day)	No of filtered location points (night)	95% home-range	50% core area	UDOI
Ouano	A	26	535	21	252	283	45.60	5.00	1.37
	B	21	356	16	152	204	117.40	17.40	1.46
Nouméa	C	3	33	11	15	18	na	na	na
	D	13	156	12	83	73	455.80	47.20	1.25
	E	40	505	13	242	263	250.30	12.30	2.02
Cap Goulvain	F	12	137	11	74	63	206.00	42.60	1.20
	G	7	67	10	34	33	na	na	na
	H	20	261	13	132	129	74.10	12.60	0.91
	I	16	191	13	102	89	82.10	3.90	4.66
	J	76	1223	16	582	641	12.80	1.00	1.88
	K	5	57	11	32	25	na	Na	na
	L	192	2720	16	1305	1415	12.40	2.30	1.18

Table 4.3: Distance analysis and movement attributes of the 12 dugongs tracked in New Caledonia. Each tracked individual except for individual C (tracked for only three days) returned to its capture site after moving away from it. All dugongs stayed within 8km from the shore. Dugongs J, K, and L used the fore reef shelf to make short visits 20km south in Bourail Bay.

Capture location	Individual ID	Maximum distance from capture location (km)	Distance to any land (km)			Animal returned to capture location after exploratory movements	Comment on movement pattern
			min	max	mean (± SD)		
Ouano	A	28.08	0.02	3.90	0.89 (0.60)	Yes	-
	B	38.59	0.01	6.25	1.59 (1.47)	Yes	Southern range overlapping with individual E
Nouméa	C	25.04	0.04	2.59	0.53 (0.53)	No	-
	D	31.82	0.09	6.77	1.81 (1.51)	Yes	-
	E	67.99	0.00	5.12	1.21 (1.09)	Yes	Northern range overlapping with individual B
Cap Goulvain	F	49.69	0.07	6.35	2.74 (1.42)	Yes	Movements across jurisdictional boundaries
	G	41.13	0.07	5.44	2.25 (1.33)	Yes	Movements across jurisdictional boundaries & used fore reef shelf
	H	13.78	0.03	5.49	1.74 (1.31)	Yes	-

Capture location	Individual ID	Maximum distance from capture location (km)	Distance to any land (km)			Animal returned to capture location after exploratory movements	Comment on movement pattern
			min	max	mean (± SD)		
	I	72.86	0.05	7.78	1.13 (1.65)	Yes	Movements across jurisdictional boundaries
	J	19.21	0.07	5.16	1.06 (0.61)	Yes	Used fore reef shelf
	K	32.94	0.68	5.60	2.28 (0.90)	Yes	Used fore reef shelf
	L	31.72	0.00	4.56	0.49 (0.44)	Yes	Used fore reef shelf

Movement patterns, home-ranges and core areas

Cap Goulvain

The seven dugongs tracked in Cap Goulvain had individualistic movement patterns. Thus each dugong showed movement patterns different from all others (i.e., different direction and scale of movements among individuals; Figure 4.4A-C). Three dugongs (F, H and I) moved north (Figure 4.4A, B), whereas individuals J, K and L spent their tracking time between their capture locations and Bourail Bay located approximately 20km to the south (Figure 4.4C). Individuals J, K, and L travelled from Cap Goulvain to Bourail Bay along the fore reef shelf near the barrier reef outside the lagoon with no evidence of stopping.

Data from five of the seven tracked dugongs were used in the home-range and core area analysis. The home-range and core areas of four dugongs (H, I, J, L) were small. Their 95% home-range areas ranged from 12.4km^2 to 82.1km^2 (median = 43.5km^2; Figure 4.7 and Table 4.2) and their 50% core areas ranged between 1km^2 and 12.6km^2 (Figure 4.4E and Figure 4.7). The fifth dugong (I) had a substantially larger home-range (95% home-range of 206km^2 and a 50% core area of 42.6km^2; Table 4.2). The areas most intensively used by dugongs tracked in Cap Goulvain were located in the bay of Cap Goulvain, between Cap Goulvain and the Poya Pass, around the Mueo Pass and on top of coral reef plateaus located north of the Pindai Peninsula (Figure 4.4E).
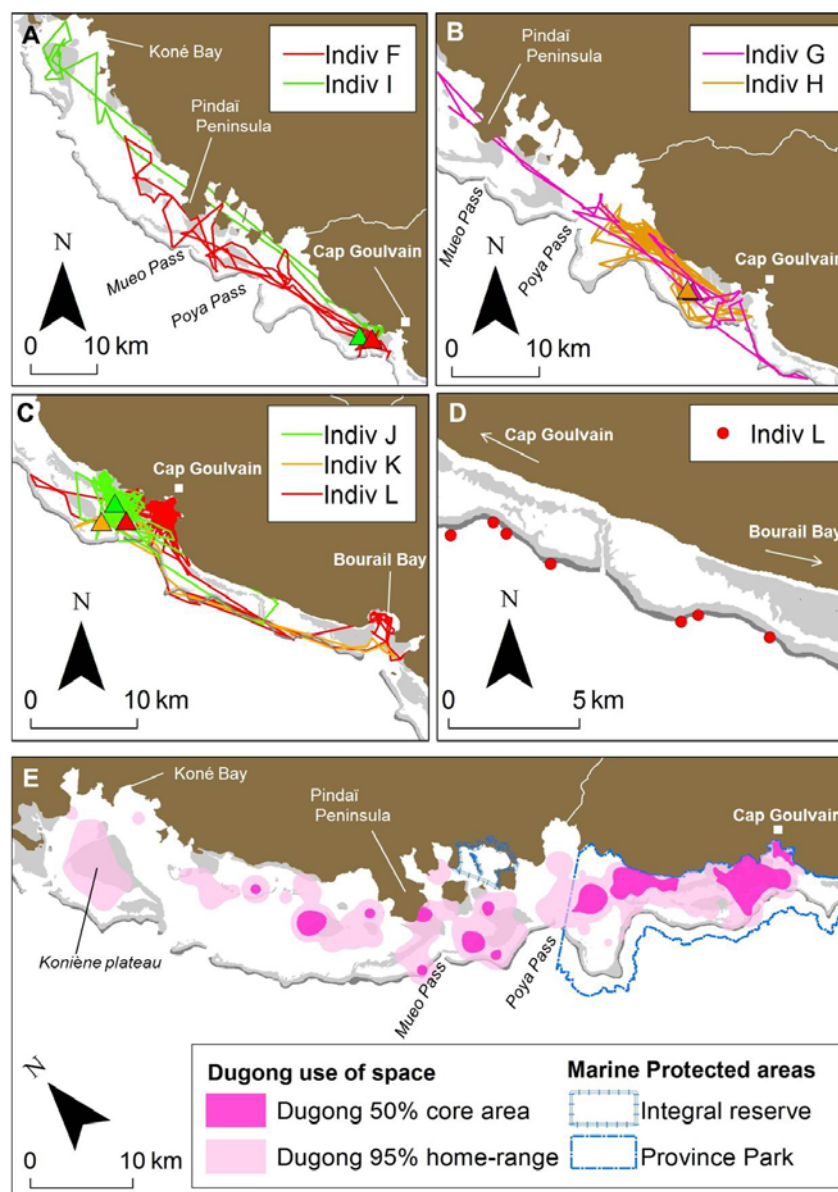
Figure 4.4: Details of the movement patterns and use of space by dugongs captured in Cap Goulvain using the total tracking period of each tracked individual. Figures A, B and C show the movement patterns of the seven dugongs tracked in the Cap Goulvain region. The maps were separated to aid visual representation. Triangles display the capture location of each individual. Figure D shows the GPS-QFP location fixes of individual L that moved from Cap Goulvain to Bourail Bay using the fore reef shelf outside the lagoon. Figure E shows the combined 50% core areas and 95% home-ranges of six of the seven dugongs captured in Cap Goulvain (Individual G's tracking duration was regarded as a too short tracking period to undertake meaningful analysis of home-range). These 50% core areas and 95% home-ranges were not weighted for the tracking period of each tracked dugong as the aim of the figure was to provide an indication of the combined area used by dugongs in the region. Note that light brown represents the land, dark grey represents the barrier reef, and light grey represents reefs inside the lagoons.

Ouano

Two dugongs were captured and satellite tagged in the Ouano region. One dugong (A) mainly used three adjacent bays, Moindou, Ouaraï and Chambeyron Bays (Figure 4.5A). The second dugong (B) was more mobile, remaining for five days in the vicinity of the Moindou Bay where it was captured, making brief daily return excursions to the reef complexes adjacent to the inner side of the barrier reef, hereafter back reef (Figure 4.5A). On its fourth trip out of Moindou Bay, this dugong undertook a 10-day loop heading 38km southward through the Chambeyron Bay down to near Tenia Islet located 20km south of Ouano and came back to its capture location.

Individual A had a 95% home-range area of 35.8km^2 and a 50% core area of 5.3km^2. Individual B had a larger 95% home-range of 117.4km^2 and 50% core area of 17.40km^2 (Figure 4.7 and Table 4.2). The sizes of the 95 % home-ranges and 50% core areas of these two dugongs were similar to those of dugongs in Cap Goulvain (Figure 4.7). The areas most intensively used by these two dugongs were located near the coast near in the Moindou, Ouaraï, and Chambeyron bays, and offshore near the barrier reef between the Coupée Mara Pass and the Ouarai Pass and adjacent to the Isie Pass (Figure 4.5B).

Figure 4.5: Details of the movement patterns and use of space by dugongs captured in Ouano using the total tracking period of each tracked individual. Figure A shows the movement patterns of the two dugongs tracked in the Ouano region. Triangles display the capture location of each individual. Figure B shows the combined 50% core areas and 95% home-ranges of the two dugongs captured in the Ouano region. These 50% core areas and 95% home-ranges were not weighted for the tracking period of each tracked dugong as the aim of the figure was to provide an indication of the combined area used by dugongs in the region. Note that light brown represents the land, dark grey represents the barrier reef, and light grey represents any reef within the lagoons.
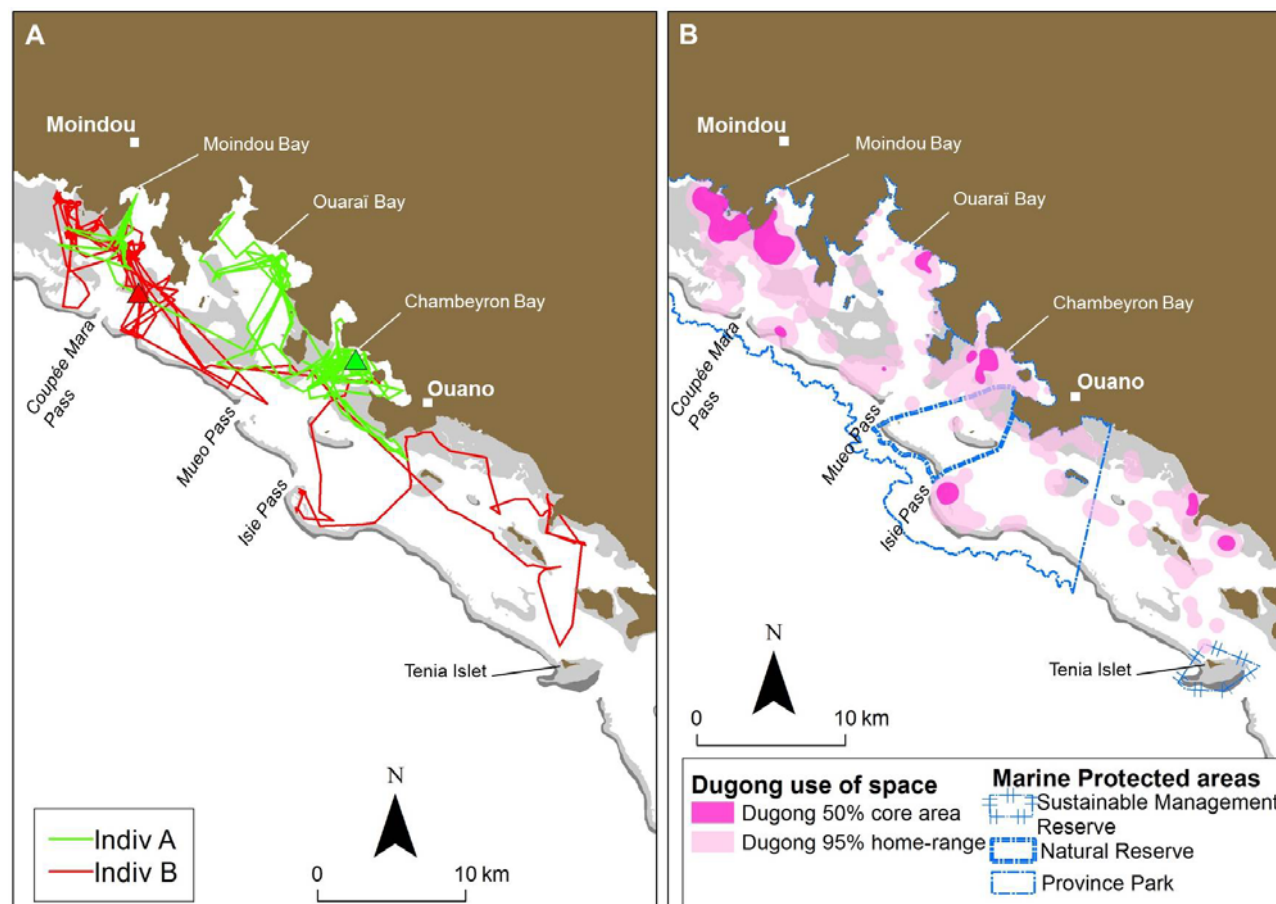
Nouméa

Three dugongs were captured and satellite tagged in the Nouméa region. The movements of the tracked dugongs were also individualistic. One dugong (D) undertook three trips in three different areas of the Nouméa region (Figure 4.6A). On its first trip, individual D undertook a five-day loop to Plum Bay located south of Nouméa and then returned to its capture location. One day after its return to its capture location this dugong undertook a three-day loop to Ndié Islet, then Ndue Islet and Mba Islet before swimming back to Maître Islet. Finally, a day after its second return to its capture location individual D headed south and remained north of Amédée Islet over a day before swimming back to Maître Islet. Individual E commuted twice between the area near Maître Islet and Puen Islet where it spent most of its tracking time (Figure 4.6A). Individual C swam southward and very close to the coast (mean distance from coastline 0.53km ± SD 0.53) during two days before its satellite tag stopped transmitting.

The home-ranges of individuals D and E were substantially greater than those of dugongs tracked in Cap Goulvain and Ouano (Figure 4.7 and Table 4.2). Individual D used a 95% home-range of 455.8km^2 and a 50% core area 47.2km^2 (Figure 4.7). The 95% home-range of individual E was 250.3km^2 and its 50% core area was 12.3km^2. The areas most used by the tracked dugongs were located at their capture site Maître Islet, in the Plum Bay, near Amédée Islet, and adjacent to Puen Islet approximately 60km north of Nouméa (Figure 4.6B).

Figure 4.6: Details of the movement patterns and use of space by dugongs captured in Nouméa using the total tracking period of each tracked individual. Figure A shows the movement patterns of the three dugongs tracked in the Nouméa region. Triangles display the capture location of each individual. Figure B shows the combined 50% core areas and 95% home-ranges of two dugongs captured in the Nouméa region (Individual C's tracking period was regarded as a too short for meaningful analysis of its home-range). These 50% core areas and 95% home-ranges were not weighted for the tracking period of each tracked dugong as the aim of the figure was to provide an indication of the combined area used by dugongs in the region. Note that light brown represents the land, dark grey represents the barrier reef, and light grey represents any reef within the lagoons.
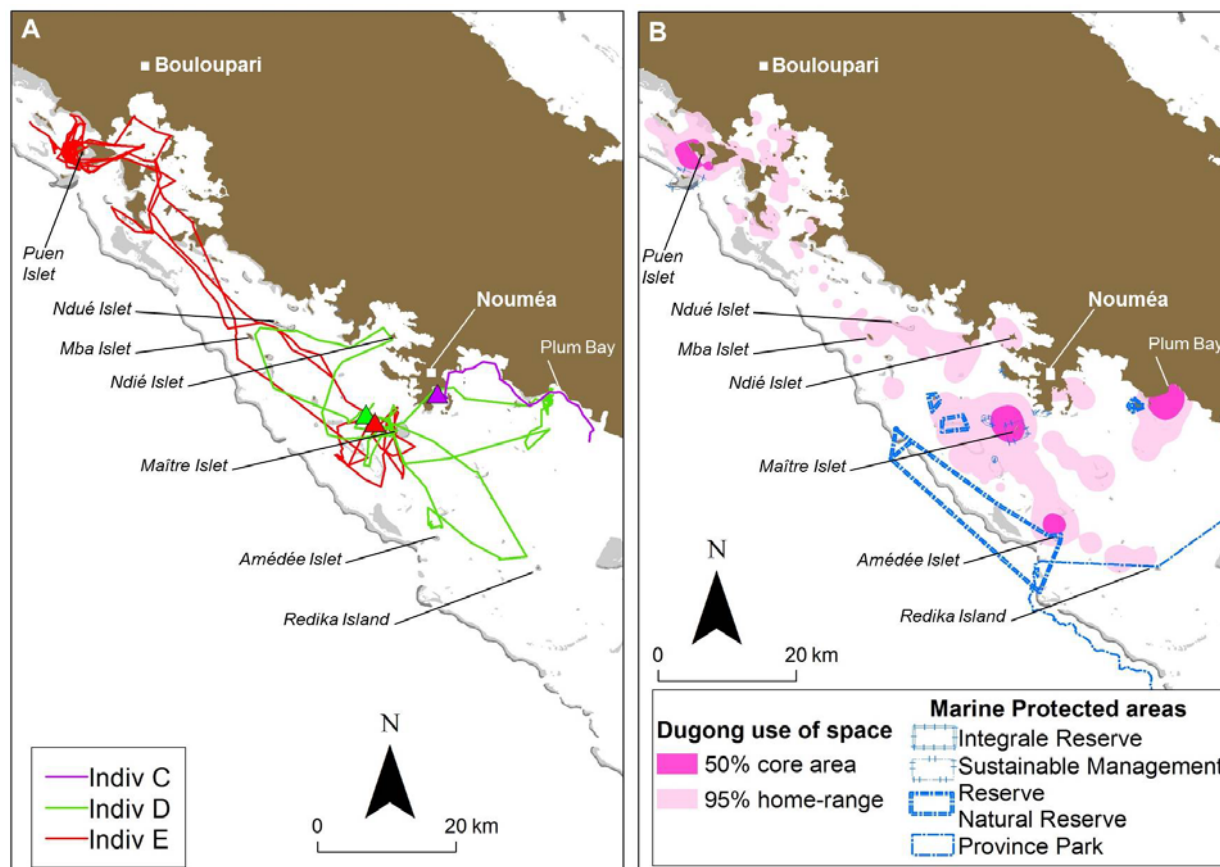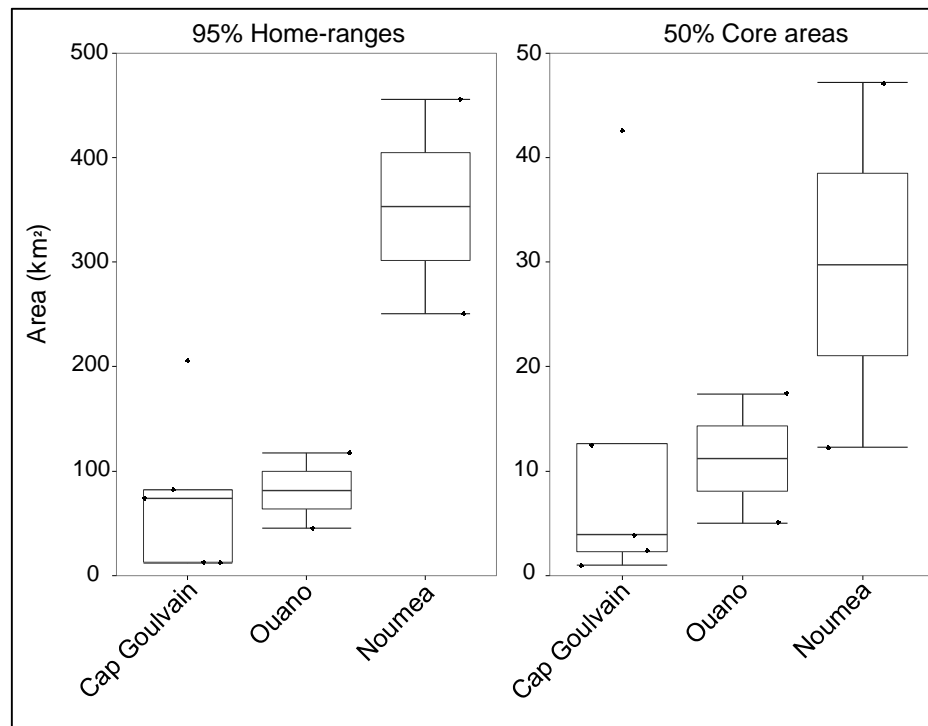
Figure 4.7: Difference between capture locations in the home-range and core area sizes of dugongs tracked in New Caledonia. The lines within boxes represent the median, boxes represent interquartile range, whiskers represent the minimum and maximum values, and dots indicate values for each individual. Note differences in scale of y axes between the two figures. Black dots represent the values of home-range and core area sizes for each tracked dugong.

Diurnal comparisons

There was no overall trend in differences in the size of dugong 95% home-ranges and 50% core areas between day and night in any of the three study regions (Figure 4.11A-C. The dugongs' Utilisation Distribution Overlap Indexes ranged from 0.9 to 4.66 (Table 4.2) indicating that they did not show major diurnal differences in the geographic locations of their home-ranges and core areas.

Seagrass and depth zone distribution

In all the three study areas, a high proportion of the dugongs' range was located over areas where seagrass has not been confirmed (Figure 4.8A-C). For example, in the Nouméa region, where the lagoon is deeper than in the two other study regions, over 90% of the 95% home-range and over 85% of the 50% core areas of the tracked dugongs were located in such areas (Figure 4.8C). This pattern was also observed in the Cap Goulvain and Ouano region where most of the dugongs' 50% core areas did not overlap with known shallow seagrass beds (Figure 4.8A, B respectively).

The dugongs tracked in Cap Goulvain and Ouano used depth zones in a similar fashion (Figure 4.9). The animals' 95% home-ranges and 50% core areas were mostly over shallow water areas with depths less than 5m with > 70% of the individuals' ranges within these depths. In contrast, the 95% home-ranges and 50% core areas of the dugongs captured in the Nouméa region were more evenly distributed across deeper zones than the dugongs from Cap Goulvain and Ouano.

Use of Marine Protected Areas

The tracked dugongs spent little time within the boundaries of the marine protected areas that provide high levels of restriction from anthropogenic activities (see Chapter 3). Six of the seven dugongs captured in Cap Goulvain and the two dugongs tracked in Ouano spent over 70% of their tracking time within the boundaries of the west coast Province Park (IUCN II); (Figure 4.10). Dugongs captured and tracked from Nouméa spent > 90% of their tracking time outside the boundaries of any MPA (Figure 4.10).

Figure 4.8: Relationship between the activity spaces of dugongs captured in the (A) Cap Goulvain, (B) Ouano, and (C) Nouméa regions and the known seagrass habitats (Andréfouët *et al.* 2010). The three figures show the combined 50% core areas and 95% home-ranges of dugongs captured in each study region. Pie charts represent the proportions of 95% home-ranges (outer ring) and 50% core areas (inner ring) of dugong areas where: (1) the presence of seagrass has been confirmed (in green) or (2) is unknown (in grey).
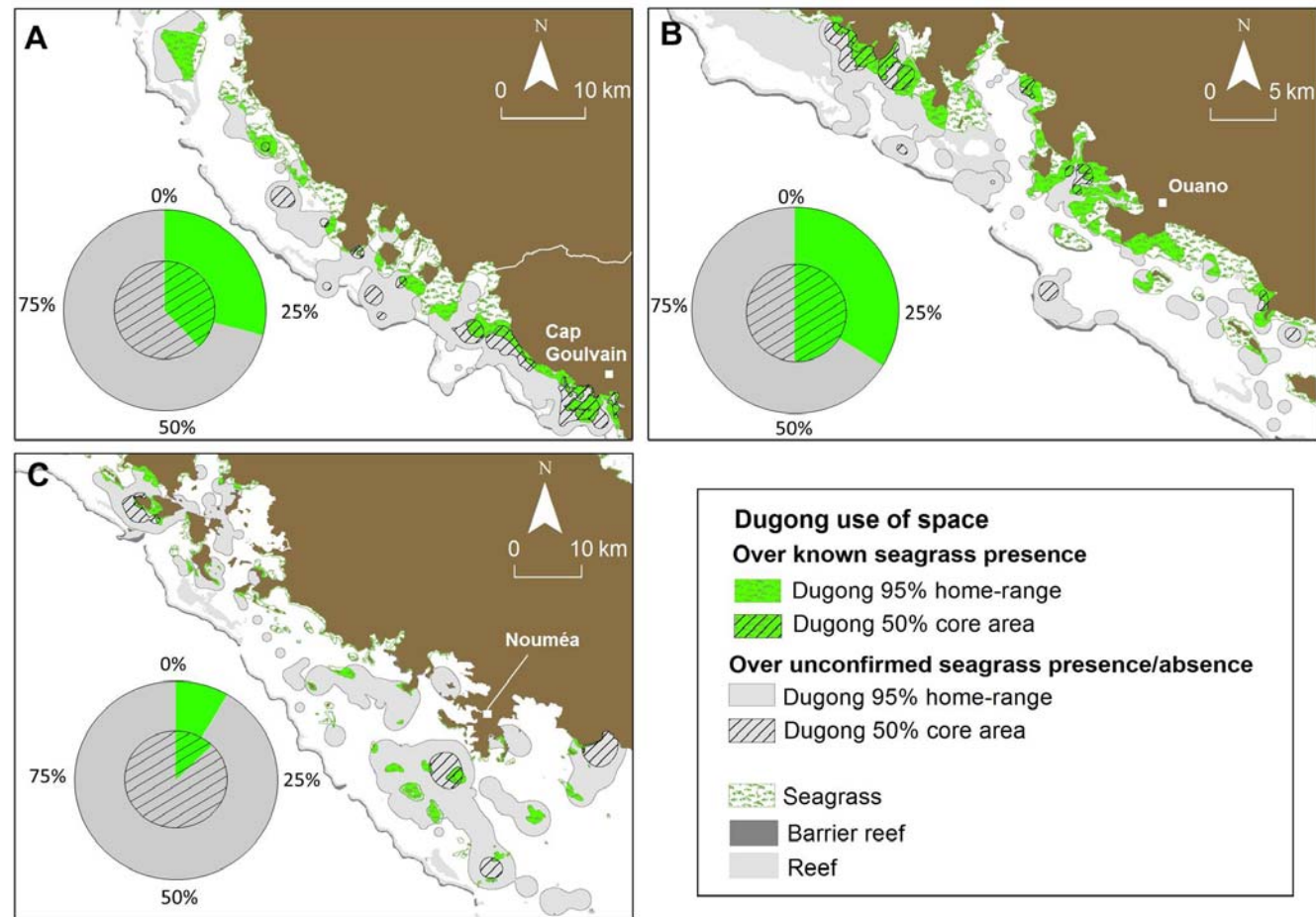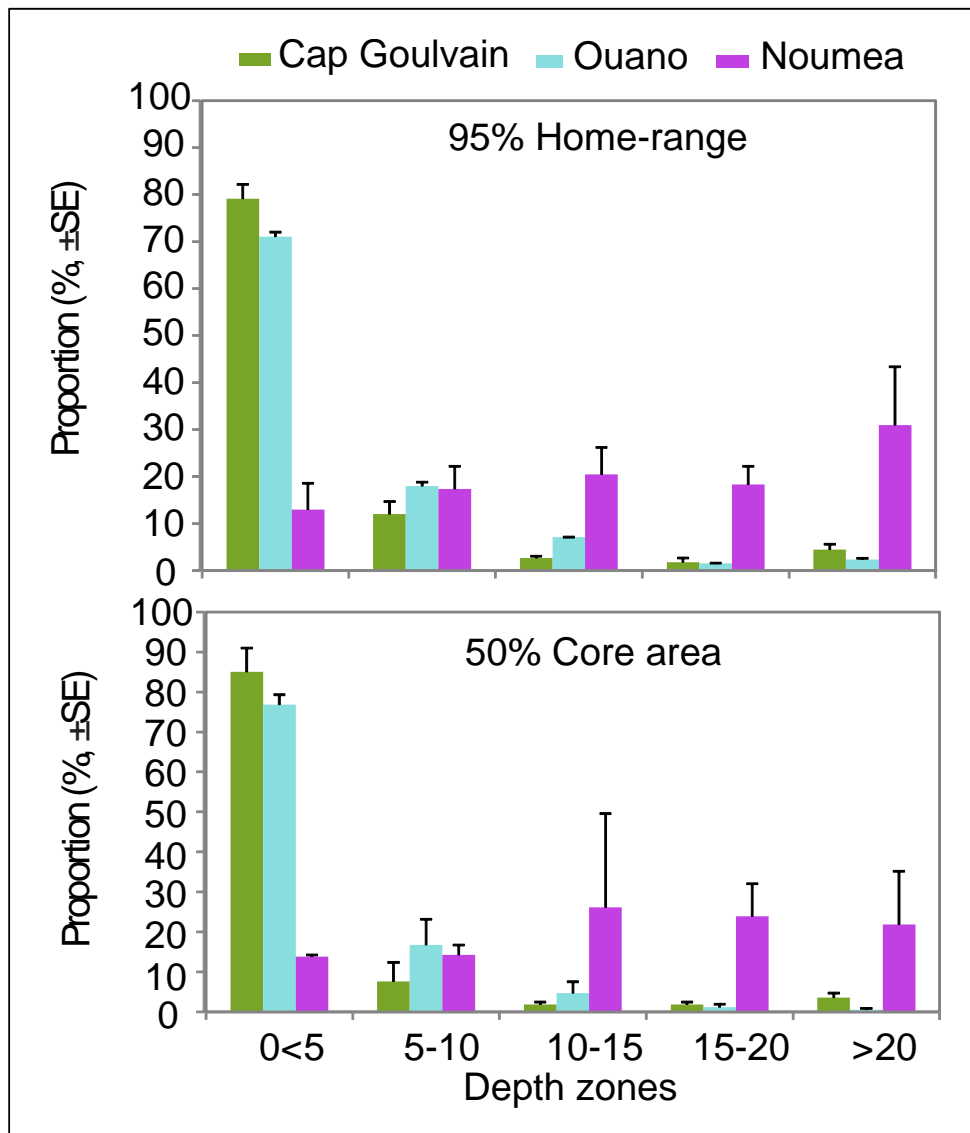
Figure 4.9: Proportion of the 95% home ranges and 50% core areas of dugongs across depth zones in New Caledonia.
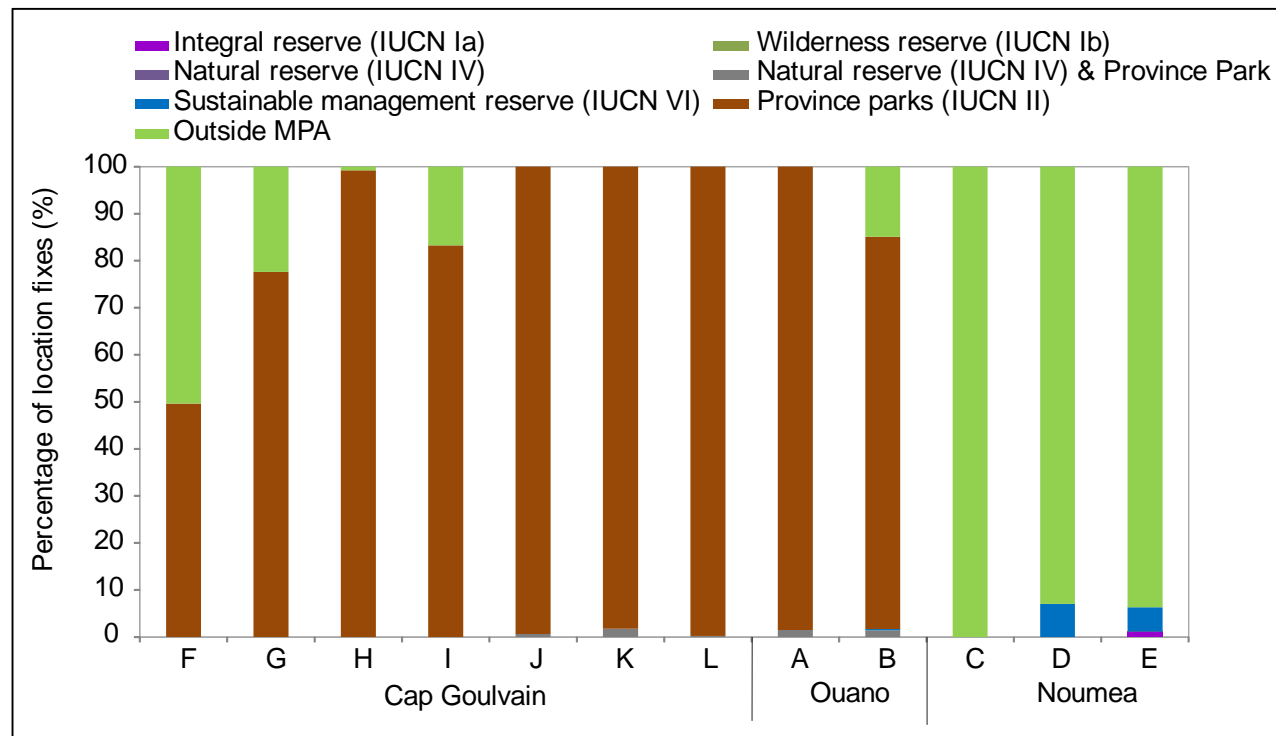
Figure 4.10: Presence of the tracked dugongs in each type of marine protected area (MPA) in New Caledonia. A category merging natural reserves (IUCN IV) and Province parks (IUCN II) was created because these two types of MPAs overlap in some regions of New Caledonia and were used by the tracked dugongs. Natural reserves that do not overlap with Province Parks were not represented as they were only used for 0.2% of the time of one tracked dugong (E). Wilderness Reserves (IUCN Ib) are not represented in this figure because no location fix was recorded in these reserves.

Figure 4.11: Visual comparison of diurnal differences in the locations of the 95% home-range and 50% core areas of dugongs captured in the (A) Cap Goulvain (e.g., individual J), (B) Ouano (e.g., individual A), and (C) Nouméa regions (e.g., individual D). There was no overall trend in differences in the size of dugong 95% home-ranges and 50% core areas between day and night in any of the three study regions.
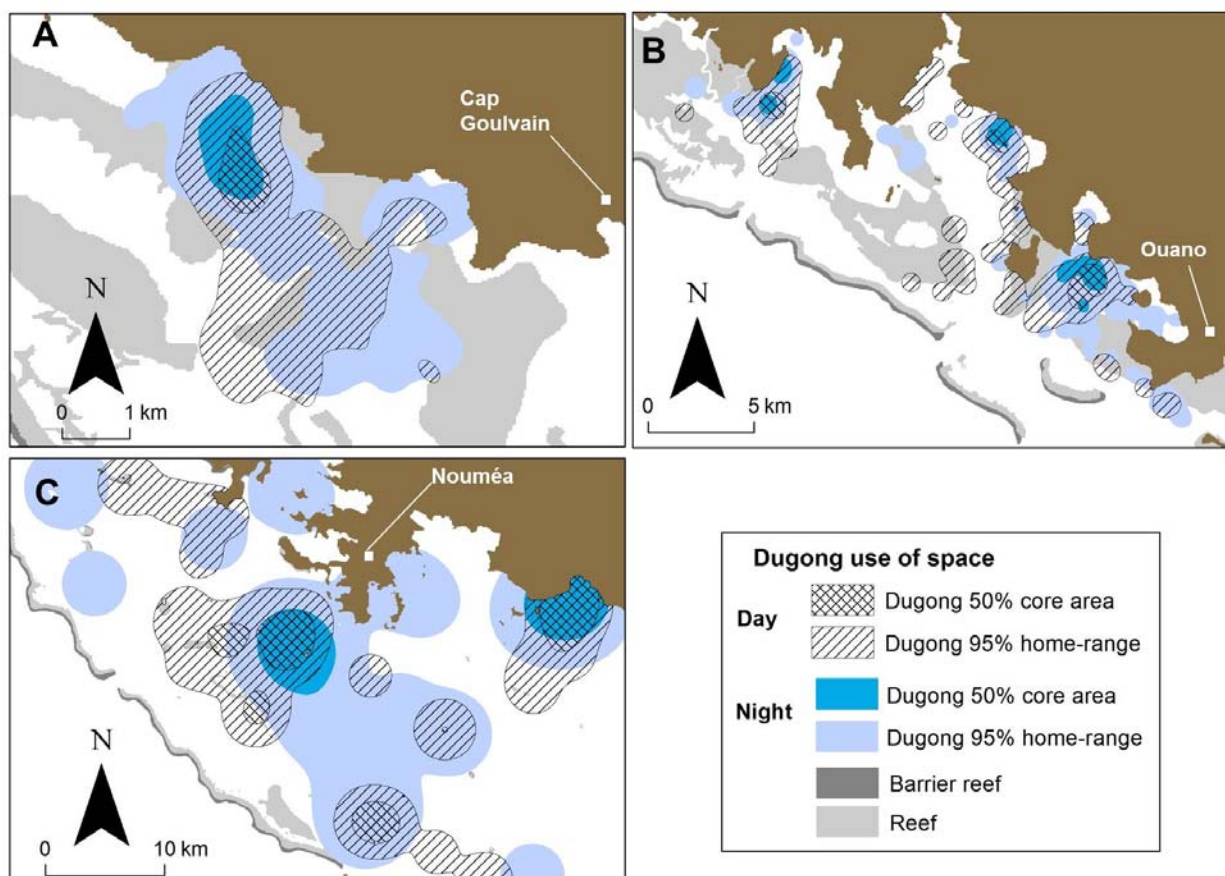
4.4   Discussion

Tracking of dugongs in New Caledonia confirmed that they display a high variability in the movement patterns, as observed in other regions (Marsh and Rathbun 1990; De Iongh *et al.* 1998; Holley 2006; Sheppard *et al.* 2006; Gredzens *et al.* 2014). All but one tracked dugong returned to their capture site after undertaking a trip. Some dugongs crossed Provincial boundaries. Dugongs swam within as well as outside the lagoon to transit between important habitats. Collectively, these results show that dugongs present a management challenge in New Caledonia because of the complexity of their movement behaviours across several spatial scales (see Chapter 6).

Individuality and scale of movements

The dugongs I tracked for this study all exhibited individualistic movements. Whereas some animals displayed sedentary behaviour, others swam over large distances and moved up to 70km from their capture site (Table 4.3). In sub-tropical and tropical waters of Queensland and the Northern Territory in Australia dugongs also exhibited heterogeneous movements ranging from small scale commuting movements (< 15km, n = 26 individuals) to large scale moves (> 15km, n = 44 individuals; Sheppard *et al.* 2006). Small scale commuting movements versus exploratory large scale movements were also reported in Torres Strait (Gredzens *et al.* 2014). In the tropical Lease Islands in east Indonesia, dugongs exhibited similar heterogeneous movement patterns ranging 17-65km from their capture sites (De Iongh *et al.* 1998).

All the large scale movements of the satellite-tracked dugongs that I studied involved animals of both sexes. In contrast, a dugong pedigree analysis across several bays along the east coast of Australia based on a much larger sample size (n = 1002 dugongs) suggests that male dugongs move between populations more than females (Cope *et al.* 2015). My sample size is too small to test whether this phenomenon also applies in New Caledonia.

Some of the movement of the tracked dugongs may be attributable to flight responses. For example, Individuals K and I (captured in the Cap Goulvain region) undertook large scale movements less than a day after they were captured. In contrast, individual L swam from Cap Goulvain to Bourail Bay using the fore reef shelf 110 days after it was captured, suggesting that not all movements can be explained by flight responses a result consistent with other dugong satellite tracking studies (Sheppard *et al.* 2006; Gredzens *et al.* 2014; Zeh *et al.* in review).

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Regional comparisons

The sizes and depth distribution of the tracked dugongs' home-ranges differed among the three study regions with dugong ranges in the Nouméa region being several times larger than those in Cap Goulvain and Ouano in the mid-west lagoon (mean range in Nouméa = 353.1km^2, Ouano mean = 81.5km^2, Cap Goulvain mean = 77.5km^2). Dugongs in the Nouméa region used deeper waters (> 10m) with 70% of the tracked individuals' 95% home-ranges located in such waters. Substantial regional differences in dugong range sizes and water depth use have also been observed in Australia. For example, the range of dugongs in Torres Strait, a vast dugong habitat (see Figure 5.1A), was much higher (median = 942.6km^2) than the range of dugongs along the east coast (Shoalwater Bay, median = 60.6km^2; Gredzens *et al.* 2014).

The lagoon in the Nouméa region is wide and provides large subtidal areas of relatively deep water (> 10m) with shallow-water areas (< 10m) accounting for only a small proportion of the region primarily restricted to reef tops around islets (Bonvallot *et al.* 2012). Most seagrasses in Nouméa are subtidal (Garrigue 1995) although small reef tops and shallow inshore areas also support dense seagrass pastures (Hily *et al.* 2010). The tracking data show that whereas the dugongs tracked in the Nouméa region used reef tops (e.g., reef surrounding Maître Islet) and shallow inshore waters adjacent to the city, they mostly remained in deeper subtidal areas. In contrast, the Ouano and Cap Goulvain regions are characterised by much narrower lagoons and seagrasses are mostly found in shallow inshore areas or over elevated reef flats. Differences in the size and geomorphology of the lagoon and seagrass distribution may explain the smaller range sizes of the dugongs tracked in Cap Goulvain and Ouano in comparison to the dugongs tracked in the Nouméa region.

Use of deeper areas by dugongs in the Nouméa region may also be a response of anthropogenic disturbance. There is evidence of dugongs killed by watercraft in front of Nouméa (ESCAL and A2EP 2011; Claire Garrigue pers. comm.) but the frequency of such collisions is unknown. Boat strike is responsible for the death of dugongs in many other parts of the dugong's range especially in regions where anthropogenic coastal activities are high (Marsh *et al.* 2012). For example, in Moreton Bay which is adjacent to Brisbane -one of the largest cities in Australia- dugongs are struck by boats typically in areas where both animals and boats are constrained to narrow channels at low tide. Hodgson (2004) and Hodgson and Marsh (2007) studied the response of dugongs to approaching boats. One of the primary responses of dugongs to the sound of an approaching boat is to move towards deeper water. In Burrum Heads, north of Hervey Bay, dugongs use deep subtidal waters during the day. Sheppard *et al.* (2007) suggested that dugongs were discouraged from foraging close to the shore during the day because of the high density of recreational boating traffic.

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Spatial heterogeneity in the use of space

The distribution of dugongs generally coincides broadly with that of seagrass beds (Marsh *et al.* 2002, 2012). The patchy nature of seagrasses mapped in the lagoons of New Caledonia partly explains how dugongs used space during their tracking period. However, dugongs also intensively used some areas where seagrasses have not been mapped but are likely to occur. For example, the area around Maître Islet in front of Nouméa was intensively used by two tracked dugongs. Seagrass was reported to be present in this area in early studies of the macrophyte associations on the benthic habitats in the south-west lagoon (Garrigue 1995). But dugongs also make intensive use of areas where seagrass is unlikely to be present including reef complexes adjacent to the inner side of the barrier reef in Cap Goulvain and Ouano. The reasons for dugongs to use such habitats are further investigated in Chapter 5.

Movement corridors

Sheppard *et al.* (2006) suggested that dugongs have evolved to cope with unpredictable and patchy seagrass abundance by making directed movements to alternative areas. My findings support this hypothesis and suggest that dugongs maintain a spatial memory of specific habitat hotspots which may include patches of seagrass food resources that they visit periodically. I identified directed dugong movements with no evidence of stopping. For example, individuals J, K, and L tagged in Cap Goulvain used the fore reef shelf, a non-seagrass coral reef habitat located outside the lagoon, to make return trips to the Bourail Bay. In the Nouméa region, individual E captured near Maître undertook two return trips using very similar routes to visit the area near Puen Islet approximately 60km away. This dugong bypassed areas that were identified as important dugong habitats by aerial survey data (Chapter 3). Similar patterns of dugong movements with no evidence of stop overs to feed have been reported in Australia. For example, two dugongs undertook one day return 'visits' from Hinchinbrook Island to Cleveland Bay located 150km to the south without exploring any known seagrass meadows *en route* (Sheppard *et al.* 2006). Another two dugongs moved from Hervey Bay to Great Keppel Island and Clearview respectively, bypassing Rodds Bay an area of high seagrass density (Sheppard *et al.* 2006).

Although there is no evidence that dugongs show long-term social structure, the use of distinct movement pathways and bypassing other habitats may reflect matrilineal transmitted learned behaviours and spatial memory (Sheppard *et al.* 2006; Marsh *et al.* 2012). This hypothesis is reinforced by tracking studies conducted on Florida manatees that showed that manatee calves exhibited strong fidelity to areas frequented by their mothers (Deutsch *et al.* 2003). Interestingly, most captive-raised Florida manatees released as sub-adults along the Atlantic

coast did not undertake seasonal migrations, despite migratory behaviour occurring in over 87% of the wild population (Deutsch *et al.* 2003).

Movements of dugongs across large distances and using distinctive pathways also suggest great capacity for orientation and navigation. I did not find any diurnal patterns in the movement and home-ranges of dugongs in New Caledonia. For example, dugongs that transited between Cap Goulvain and Bourail Bay swam during both day and night over the fore reef shelf. Recent dugong movement studies in Moreton Bay (Zeh *et al.* 2015) and Torres Strait (Gredzens *et al.* 2014) obtained similar results.

The sensory modalities used by sirenians to navigate are unknown. But the limitations on vision (Bauer *et al.* 2003) and a lack of active echolocation (Mann *et al.* 2005) suggest that other sensory modalities play an important role in spatial orientation (Reep *et al.* 2002; Reep and Sarko 2009; Reep *et al.* 2011). The tactile sensory modality is highly developed in sirenians (Reep and Sarko 2009), especially their orofacial hair system. Reep *et al.* (2011) found that the detection threshold levels of hydrodynamic stimuli of manatees using facial or post-facial vibrissae were similar with the lateral line systems of some fish, a theory originally proposed by Reynolds in 1980 (Reynolds pers. comm.). Facial and post-facial vibrissae of sirenians may play a similar role as the lateral line system in fish (Dijkgraaf 1963; Bleckmann 1986) by aiding them to detect conspecifics, water currents, tidal flows, and to explore the environment.

Manatees are known to have an exceptional acoustic sensitivity (Hartman 1979; Popov and Supin 1990; Gerstein 2002). Coral reefs are associated with high levels of biological sound generated by organisms such as shrimps and fishes in the range 0.4-4kHz (Cato 1978; Radford et al. 2010). This range falls within the hearing capacity of manatees, ranging from about 200Hz to 35-40kHz and presumably of dugongs which produce sounds in the range of 0.3kHz to 18kHz (Anderson and Barclay 1995). Thus, it is reasonable to hypothesize that dugongs may use auditory cues while travelling, especially at night, in coral reef environments. Sirenian tongues possess developed tastebuds which are more abundant than other marine mammals, suggesting that tastebuds may function as receptors for chemical cues from the environment (Levin and Pfeiffer 2002). However, navigation in dugongs remains largely unexplored and requires further investigation.

Movements of dugongs between Cap Goulvain and the Bourail Bay may be limited by a combination of geomorphological characteristics. The lagoon between Cap Goulvain and the Bourail Bay is the narrowest (average width = 2km) and the shallowest (< 5m) around the main island of New Caledonia. This lagoon is characterised by reticulated reef formations (Andréfouët *et al.* 2004), which may impede movement of large animals like dugongs especially

at low tide (see Chapter 5). There may be a risk of dugongs being ambushed by predators in reticulated reef areas (see Chapter 5). These factors may explain why dugongs use the fore reef shelf to commute between bays in this particular region.

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4.5   Conclusion

Dugongs in New Caledonia use diverse environments, from large and deep lagoons to areas where the lagoon is too narrow and shallow, requiring the use of outer lagoon areas to commute between bays. My findings that dugongs move across large spatial scales in New Caledonia, have implications for conservation and management at a range of scales. My results strengthen the aerial survey evidence for management and monitoring at ecological scales that cross jurisdiction and for a required improvement the efficacy of MPAs to protect dugongs in the region. Given the heterogeneity in the environment across regions in New Caledonia my results cannot be applied at the population level. Larger sample sizes are required to further inform this evidence-based approach because. Seasonal change in the distribution and movement patterns of dugongs could not be examined because the tracking time was too short. Alternatively, insight into seasonal changes in habitat use by dugongs can be obtained at a local scale using aerial survey techniques (Chapter 5).

4.6   A critical evaluation of my approach

My results showed that dugongs in the western lagoons of New Caledonia are capable of moving across large distances (> 15km) in a matter of days. Whereas the analysis conducted in Chapter 2 did not suggest movement of dugongs across the aerial survey blocks it is likely that dugongs move at least within blocks and across transects. Movements of dugongs across transects during the long interruptions of all the aerial surveys conducted in New Caledonia may have led to double counting of animals. However, it is impossible to estimate how many animals were double counted during the surveys. Thus, as highlighted in Chapter 2, decision rules should be developed to decide when a specific region needs to be completely re-surveyed in order to improve population estimates and enhance the information provided to management.

Although the dugong satellite tracking study I conducted provides important insights into the dugong movement patterns and use of space in the lagoons of New Caledonia my analyses were limited by a small sample size typically due to costs constraints, a short tracking period limited to the warm season due to the quick detachment of the satellite tag harnesses, and the limited information on key dugong habitats such as the distribution of seagrasses in depth greater than five metres at appropriate spatial scales. Overcoming these issues will be essential to increase our understanding of dugong habitat use in the lagoons of New Caledonia. Retrieving 11 out of the 12 tags provides opportunities to conduct further studies on dugong movement behaviour in

New Caledonia at a reasonable cost because the tags I used can be redeployed after their batteries are changed.

As expected, many GPS satellite tags remained attached to dugongs for only a short period of time in New Caledonia because of the high likelihood of the tracking equipment entangling in the coral reefs. The size of the tags currently used to track dugongs may partly explain why the attachment apparatus gets easily entangled. Collaborative work with a wildlife tracking company is underway to decrease the size of the tags and hence increase the chances of tracking dugongs for longer periods.

I captured dugongs in high dugong density areas to increase my chances of capturing animals. In Chapter 3, I highlighted that these high dugong density areas were poorly covered by MPAs that provide high levels of restriction from anthropogenic activities. Thus, it was not unexpected to find that the tracked dugongs spent little time within the boundaries of highly restrictive MPAs. Nonetheless it would be very difficult to capture dugongs in MPAs with high levels of restriction from anthropogenic activities because dugongs occur only in low densities in these areas.

4.7   Chapter summary

- Understanding the use of space in marine megafauna species has profound implications for their conservation. The use of space by dugongs in coral reefs is poorly understood. Thus investigating use of space by dugongs in the lagoons of New Caledonia enhances understanding of dugong ecology in coral reef systems and informs the conservation and management of the species in the region.
- I used modern GPS satellite telemetry to examine the scale and heterogeneity in the use of space by dugongs in the lagoons of New Caledonia by capturing 12 individuals in three locations of high dugong conservation value.
- My findings confirmed that dugongs display great variability in movement patterns and range as established in other regions.
- Dugongs moved as far as 70km from their capture location. Three of the seven dugongs captured in Cap Goulvain crossed Provincial boundaries.
- Dugongs swam within the lagoon as well as over the fore reef shelf outside the lagoon to transit between bays. This is the first study documenting movements of dugongs on the external edge of a barrier reef.
- I found regional differences in the sizes and depth distribution of the tracked dugongs' home-ranges with dugong ranges in the Nouméa region being several times larger than those

in Cap Goulvain and Ouano in the mid-west lagoon (mean range in Nouméa = 353.1km^2, Ouano mean = 81.5km^2, Cap Goulvain mean = 77.5km^2). Dugongs in the Nouméa region used deeper waters with 70% of the tracked individuals' 95% home-ranges located in waters deeper than 10m.

- There was no overall trend in differences in the size of dugong 95% home-ranges and 50% core areas between day and night in any of the three study regions, indicating that dugongs did not show major diurnal differences in the geographic locations of their home-ranges and core areas.

Chapter 5: Seasonal changes in the abundance and habitat use of dugongs in the coral reefs of Cap Goulvain

Chapter 1
General introduction

Objective 1
Assess the temporal changes in dugong abundance and conservation strategies in New Caledonia

Chapter 2
Temporal changes in the relative abundance of dugongs

Chapter 3
The spatial coverage of dugongs by marine protected areas

Objective 2
Enhance understanding of spatial ecology of dugongs in coral reef environments

Chapter 4
Dugong movement heterogeneity in the coral reef of New Caledonia

Chapter 5
Seasonal changes in the abundance and habitat use of dugongs in the coral reefs of Cap Goulvain

Objective 3
Integrating scientific research conducted on dugongs as part of this thesis to inform decisions relating to dugong conservation and management regionally and internationally.

Chapter 6
General discussion

In this chapter, I investigate seasonal changes in the abundance and habitat use of dugongs in Cap Goulvain, on the mid-west coast of New Caledonia. I selected Cap Goulvain because: (1) this region was identified as one of the most important dugong and seagrass habitats in New Caledonia in Chapter 3, and (2) the environment in Cap Goulvain differs from overseas regions where dugong habitat use studies have been conducted. Fine-scale aerial surveys were conducted to document the abundance and distribution of dugongs across a range of habitats in different seasons and at different tides. These data were then combined with opportunistic dugong sightings from transit flights to investigate the spatial and temporal patterns of dugong herds in the region. Finally, I used aerial and underwater videos to explore the behaviour of the dugongs forming herds outside the lagoon in Cap Goulvain.

5.1   Introduction

An important component of ecology attempts to explain the restricted and generally patchy distribution of species. This endeavour is at least as challenging with respect to marine mammals as it is for other taxa. A number of factors affect the distribution of marine mammals. Bowen and Siniff (1999) grouped them as follows: (1) environmental- including the type of substrate, temperature, salinity and bathymetry; (2) biological – including productivity, the distribution and abundance of predators, competitors, and food resources; (3) demographical – including population size, age, sex, and reproductive status; (4) species adaptations, including morphological, physiological, and behavioural; and (5) human effects, including disturbance and pollutants. Combinations of factors are generally responsible for observed distribution and abundance patterns.

Like other vertebrates, many marine mammal species exhibit seasonal changes in distribution and habitat use (Jefferson *et al.* 1993). These changes generally reflect the differing requirements for feeding and reproduction, the need to avoid predation, and response to changes, such as water temperature, in the physical environment (Bjørge 2001). In principle, 'K-strategists' such as marine mammals are adapted to stable environments, however, they can survive intermittent periods of unfavourable conditions because they have the capacity to delay breeding in adverse conditions. For example, Arctic marine mammals have survived repeated periods of cooling or warming over evolutionary time scales (Harrington 2008). Nonetheless, seasonal changes in habitat use can be radical. Pinnipeds must periodically abandon the sea, their foraging area, and return to land or ice to give birth, rear their offspring, and moult (Marcotte 2006). Some species of marine mammals also shift to solid substrate to escape predators, for thermoregulatory purposes, and/or to rest (Gaspari 1994; Norris and Kunz 2012). In coastal upwelling areas, habitat variability has been shown to influence the temporal changes in abundance and assemblages of species of cetaceans (Benson *et al.* 2002). These requirements result in seasonal changes in distribution and abundance as it is unusual for a single region to provide all of the resources needed by a species. Understanding these changes is important to predict the distribution of marine mammals and therefore successfully manage them.

The general distribution of sirenians is now well known (Marsh *et al.* 2012). However, with the exception of the Florida manatee, the fine-scale habitat use and seasonal changes in this use are generally not well understood. The range of the dugong extends from the tropical and subtropical coastal and island waters of the Indo-West Pacific from east Africa to Vanuatu and Okinawa (Japan). Throughout this vast range the dugong's distribution globally reflects that of its main food resource, seagrass. Seagrasses are marine flowering plants that grow in photic

environments (Dawes 1998). Seagrass communities exhibit high spatial heterogeneity at a range of scales (Coles *et al.* 2011). Thus, seagrass meadows form both continuous and fragmented landscapes of varying nutritional quality interspersed with non-vegetated substrate (Hemminga and Duarte 2000; Robbins and Bell 2000). As seagrass community specialists, dugongs have presumably adapted their foraging strategies to cope with the spatial variability in their food resource (Sheppard *et al.* 2007, 2009, 2010). However, little is known about how dugongs have adapted to environments where seagrasses occur only in relatively small intertidal patches accessible only at high tide.

Comprehensive studies designed specifically to examine dugong habitat use have mainly been conducted in Australia, in regions where seagrass meadows are distributed over vast intertidal and subtidal areas, often associated with coral reefs. In eastern Queensland, where most of the studies of the interaction between dugongs and their habitats have been conducted, the shallow (< 15m) seagrasses are distributed over more than 5,000km^2 and it is expected that approximately 40,000km^2 of the seafloor in the Great Barrier Reef World Heritage Area deeper than 15m supports some seagrass (Coles *et al.* 2007). In Torres Strait (Figure 5.1A) immediately to the north of the Great Barrier Reef region and home of the world's largest dugong population (Marsh *et al.* 2012), Coles *et al.* (2003) estimated that there was least 13,000km^2 of seagrass distributed in the intertidal and subtidal zones. Taylor and Rasheed (2010) subsequently discovered the largest recorded single continuous seagrass meadow in Australia (8,752km^2) to the west of this region in 2010.

The environment is very different in other parts of the dugong's range. For example in Okinawa (Japan), Palau, Mayotte, Madagascar, and the Pacific Islands such as New Caledonia, dugongs are observed in locations where the width of the continental shelf is narrow (i.e., tens of kilometres). In these regions, seagrasses are found on coral reef flats in lagoons protected by tropical barrier reefs (Short *et al.* 2007). The width of these lagoons ranges from a few kilometres to tens of kilometres (Pinet 2011). How dugongs have adapted to these environments especially where lagoons are narrow and seagrasses located on top of reefs are available only at high tide has not been studied.

Studies at both the eastern and western southern limits to the dugong's range in Australia, Moreton Bay in South-east Queensland and Shark Bay in Western Australia indicate that several environmental variables are associated with changes in dugong distribution and habitat use. In Moreton Bay, Preen (1992) used aerial survey data to explore the environmental variables associated with the distribution and abundance of dugongs. During winter, dugongs were more likely to be in waters warmer than 19°C than in areas where water temperatures were lower and in areas with easy access to deep water rather than in areas where deep water was

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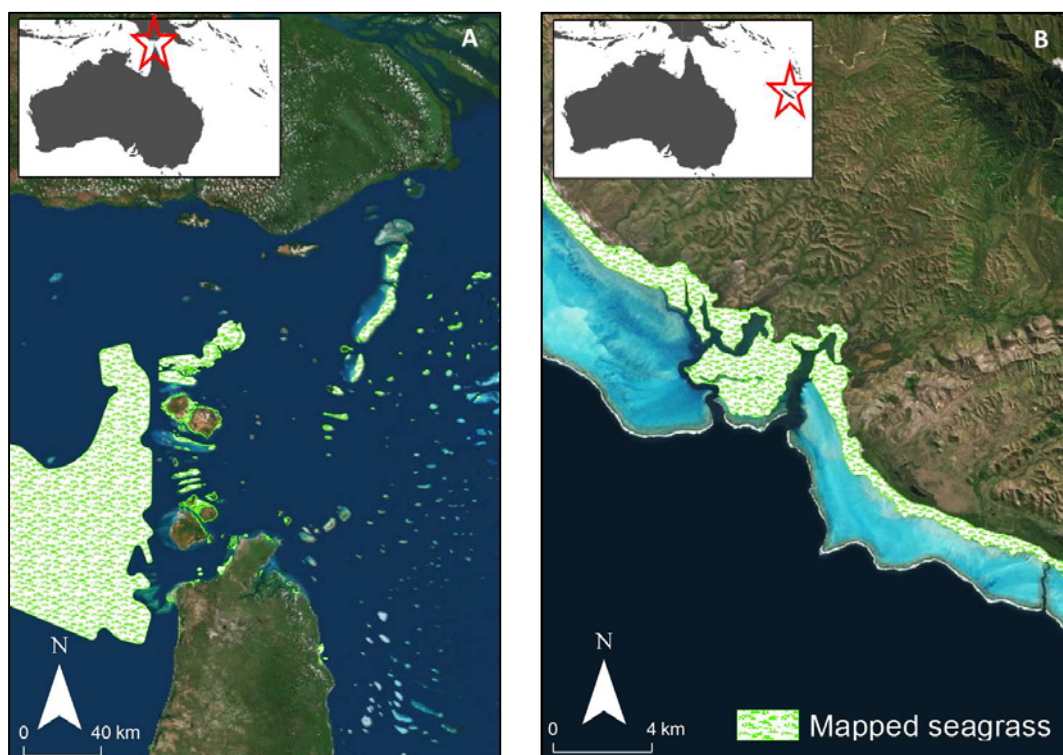
Figure 5.1: Torres Strait, north of Australia (A) and Cap Goulvain on the mid-west coast of the main island of New Caledonia (B), both important dugong areas comprising seagrass communities associated with coral reefs with very different environments. Torres Strait is a very important seagrass habitat that includes intertidal seagrass meadows on top of reef flats and the largest single continuous seagrass meadow in Australia (8,752km^2; Taylor and Rasheed 2010) whereas in Cap Goulvain the 17.4km^2 intertidal seagrass meadow is distributed over small coral reef plateaus and space is limited by a narrow lagoon. Note (1) differences in scale between the two figures; and (2) that the extent of the seagrass communities in Torres Strait is vastly underestimated in Figure (A). Satellite images source: in software ARCGIS 10.2 (ESRI 2013).

further away, presumably to facilitate escape from large sharks. Dugongs were generally more likely to be associated with seagrass meadows dominated by species of *Halophila* except in winter when habitats dominated by *Zostera capricorni*, channels and the area immediately outside South Passage leading into the Bay were preferred. The distribution of dugongs did not vary among years and was not affected by the presence of boats. In Shark Bay, dugong distribution also varied seasonally apparently in response to water temperature (Anderson 1986; 1994; Holley 2006; Holley *et al.* 2006). At finer spatial scales, changes in habitat use by dugongs in the eastern Gulf of Shark Bay were attributed to the risk of predation from tiger sharks (*Galeocerdo cuvier*) by Wirsing *et al.* (a-d). The potential influence of water temperature on the fine-scale habitat use of dugongs was dismissed by Wirsing *et al.* (2007d) based on the

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fact that dugongs were sighted with some regularity in the study area even when water temperatures were below the proposed lower physiological threshold for dugongs (i.e., 19°C); (Anderson 1986). This explanation did not consider the possible energetic advantages of behavioural thermoregulation (Cossins and Bowler 1987; Terrien *et al.* 2011). Nonetheless, these findings collectively suggest that the use of seagrass habitats by dugongs is influenced by factors other than the prevalence and community structure of seagrass *per se* including water temperature and the risk of predation.

Located on the mid-west coast of the main island of New Caledonia, Cap Goulvain is home to one of the largest intertidal seagrass meadows (17km^2) and highest densities of dugongs in New Caledonia (Payri *et al.* 2005; also see Chapters 2 and 3). In this region, the lagoon is narrow (up to 4km) and accessibility to intertidal seagrasses is restricted by tides, forcing dugongs to use adjacent non-seagrass coral reef habitats at low tide.

There are a variety of non-seagrass coral reef habitats adjacent to the seagrass beds in Cap Goulvain. One such habitat is the fore reef shelf, a flattened coral reef area, located outside the lagoon between the fore reef crest and the reef slope connecting to the deep open ocean waters. During the first dugong aerial survey conducted during the cool season in 2003 an aggregation of over 45 dugongs was observed in this habitat, (Chapter 2; Garrigue *et al.* 2008). There are similar reports of dugongs aggregating (i.e., forming groups sizes of ≥ 10 individuals sensu Lanyon 2003) in warm oceanic water near the high latitude limits of their range in winter. For example, dugongs aggregating in the oceanic area outside South Passage in Moreton Bay (up to 10km offshore from Moreton and North Stradbroke Islands) were described by Marsh and Sinclair (1989b), Preen (1992), and Lanyon (2003). Anderson (1986) described dugongs aggregating in warm tongues of oceanic water during winter in Shark Bay. In the Arabian Gulf, Preen (2004) observed a large dugong aggregation, estimated to contain some 670 individuals in two main groups. Preen (2004) suggested that the herds were located near warm water sources but this was not verified. Whereas the possible causes of dugong aggregations over inshore seagrass meadows have received attention (Preen 1992; Hodgson 2004), the reasons why dugongs aggregate in oceanic waters where seagrass is absent have not been formally investigated.

The goal of this chapter is to investigate seasonal and tidal changes in abundance, aggregation patterns and habitat use of dugongs in the lagoon of Cap Goulvain. Aerial surveys were conducted over 18 months at both low and high tide to document the seasonal and tidal changes in the distribution and number of dugongs found in seagrass and non-seagrass coral reef habitats. I then used the resultant dataset and other opportunistic dugong herd sightings to explore the spatial and temporal occurrence of dugong herds in Cap Goulvain. Finally, I used

aerial and underwater videos to explore the behaviour of dugongs aggregating over the fore reef shelf.

5.2   Methods

Study area

As explained in Chapter 1, the lagoons around the main island of New Caledonia encompass some of the world's most diverse reef structures, especially on the west coast of the main island where a mosaic of habitats from shallow inshore seagrasses to deep channels and a wide range of reef forms occur (Andréfouët *et al.* 2004).

The lagoon in Cap Goulvain has been identified as one of the most important dugong and seagrass habitats in New Caledonia (Payri *et al.* 2005; Cleguer *et al.* 2015; Chapter 3 Figure 3.1). The lagoon in Cap Goulvain is approximately four kilometres wide, much narrower than the lagoons on the northern and southern part of New Caledonia's west coast, which reach 15-30km width respectively (Bonvallot *et al.* 2012).

Habitat identification was based on the Atlas of the New Caledonian Coral Reefs (Andréfouët *et al.* 2004) and a generic map of shallow (< 5m) seagrass produced from Landsat images, the best available dataset on seagrass at the scale of the study (Andréfouët *et al.* 2010). Habitat area was calculated by importing the habitat layers into ArcGIS® 10.2 (ESRI 2013) and summing the area of each habitat (km^2). I identified four main habitats (Table 5.1). Three habitats are located inside the lagoon: (1) intertidal seagrass meadows ($17km^2$), (2) reticulated reef flats ($20.5km^2$), and (3) deep water channels ($5.6km^2$); and one habitat outside the lagoon: (4) the fore reef shelf ($14.2km^2$) on the seaward edge of the barrier reef, between the fore reef crest and the reef slope leading to the deep open ocean waters (Figure 5.2 and Table 5.1; Andréfouët *et al.* 2004; Payri *et al.* 2005; Andréfouët *et al.* 2010). Seagrasses are absent from the fore reef shelf and the reticulated reef flats, and are likely to be extremely scarce or inexistent in the channels where the water is deep (i.e., up to 86m) and turbid (Hily *et al.* 2010).

Table 5.1: Details on the size, depth and presence/absence of seagrass in the four habitats found at Cap Goulvain.

Habitat type	Size (km²)	Depth (m)[b]			Presence/absence of seagrass[a]
		Mean (± SD)	Median	Max	
Seagrass meadows	17.4	0.98 (1.99)	0.3	4.7	Six seagrass species represented, dominated by *Cymodocea serrulata*
Reticulated reef flats	20.5	1.8 (2.57)	1.5	20.3	Absent
Channels	6.8	27.4 (15.8)	29.9	86.0	Likely scarce
Fore reef shelf	14.2	29.17 (14.75)	29.2	97.3	Absent

[a] Source Payri *et al.* (2005).

[b] Depth values from the bathymetric model developed by Lefevre *et al.* (Institut de Recherche pour le Développement; unpublished).
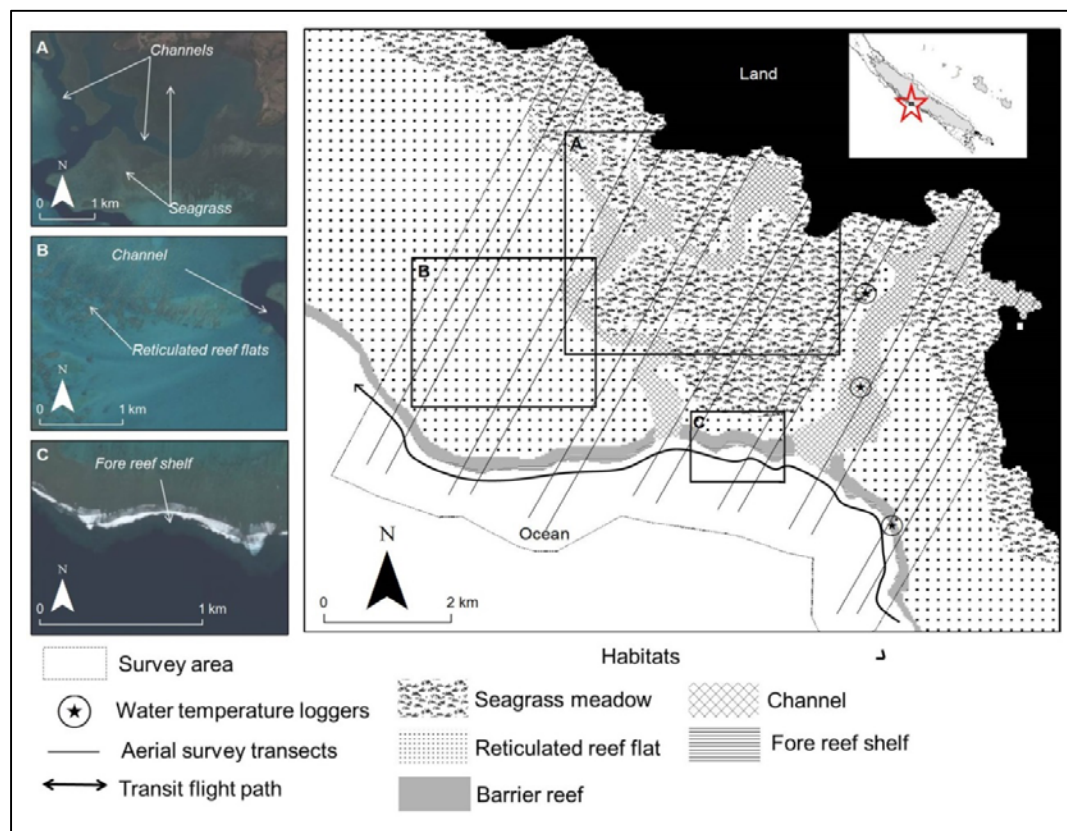
Figure 5.2: The design of the dugong aerial survey and water temperature sampling in Cap Goulvain. Side figures show satellite images of: (A) seagrass meadows and channels, (B) reticulated reef flats, and (C) the exit of the northern channel, the barrier reef and the fore reef shelf. Satellite images source: in software ARCGIS 10.2 (ESRI 2013).

Environmental variables

A water temperature logger (Sea-Bird SBE56 V0.96, accuracy ± 0.002°C) was deployed at each of the following sites: (1) the southern edge of the main seagrass meadow at a depth of two meters; (2) the southern channel at 17m and (3) over the fore reef shelf in the southern part of the study area at 20m (Figure 5.2). The temperature loggers were deployed on 15 August 2012 and recorded temperature every ten minutes for a year.

Tidal dynamics of the lagoons of New Caledonia are generally dominated by semi-diurnal tides (e.g., two high tides each day). The tidal range does not vary substantially diurnally or seasonally (Bonvallot *et al.* 2012).

Aerial surveys

Transect surveys

Sixty-two dedicated transect surveys were conducted over Cap Goulvain, from mid-February 2012 to mid-August 2013 to record the number of dugongs and temporal changes in their habitat use. Twenty-nine surveys were conducted during the warm season as defined by Météo-France (Météo-France 2014) including 15 surveys at high tide and 14 surveys at low tide (Appendix D Table D.1). Thirty-three surveys were conducted during the cool season (*sensu* Météo-France 2014); 16 at high tide and 17 at low tide.

The surveys required an observer to be available every two weeks during 18 months. Given the co-tutelle arrangements of my PhD candidature, I could not be available for such a time period. Thus prior to the start of the study in Cap Goulvain, I trained two observers using an 8-seater Cessna 210/Centurion plane available in Nouméa. I then conducted two trial surveys in Cap Goulvain with the pilot who was hired for the entire survey period to ensure that the predefined transects were appropriately followed using a strict flight protocol. The surveys were conducted using a two seater Fly Synthesis Storch ultra-light aircraft. A trained observer sat on the starboard side next to the pilot. To limit potential observer bias, the same observer conducted most of the surveys. Five of the 62 surveys were conducted by a second trained observer.

Surveys were conducted at a constant ground speed of 60 knots. In order to meet New Caledonia safety requirements of a single engine aircraft over water, flights were conducted at 900 feet (274m). Flying at this altitude also enabled the observer to identify the limits of and count large groups of dugongs (Marsh and Sinclair 1989a, b). These ultra-light surveys were flown at approximately two week intervals (mean interval between surveys = 16.2 days, ± SE = 1.4) and took an average of 46.6 min each (± SE = 0.68) excluding aircraft transit times to and from the airport. If possible, surveys were conducted at slack low and high tides on each survey day and in calm weather with wind speeds of less than 20km/h; and cloud cover less than 6 oktas to minimise sighting bias caused by poor visibility in bad weather.

The survey design and procedures were a variant of the protocols of Marsh and Saalfeld (1989) and Marsh and Sinclair (1989a); coloured tape was attached to the starboard wing strut of the aircraft to delineate a transect 400m wide on the water surface on the starboard side of the aircraft (see Chapter 2 Figure 2.3). This transect width delimited the zone in which dugongs were counted. Habitats inside the lagoon and the fore reef shelf (total of 60km^2) were covered by 14 non-overlapping transects (Figure 5.2). Transects were paired because observer coverage was limited to the starboard side of the aircraft. Within pairs, transects were spaced at intervals

of 350m; the inter-pair transect distance was 1km. This design allowed the survey to intensively cover the study area with a 59% sampling intensity while limiting the risks of double counting dugongs. The 14 transects were flown in all survey sessions, hence there was no variation in sampling effort during the study. All dugong and large shark (> 2m) sightings and their associated habitats were recorded onto an audio-recorder. In all habitats other than the channels the bottom was visible from the aircraft.

Transiting flights

I examined the data from 41 flights transiting over the fore reef shelf in Cap Goulvain for sightings of more than 10 dugongs forming a distinct aggregation (dugong herds *sensu* Lanyon 2003). These flights were conducted by teams of aerial survey observers transiting to the north of New Caledonia to conduct dugong surveys in other areas. The flight altitude was adjusted to 900 feet (274m) when passing over the fore reef shelf of Cap Goulvain in order to maximise dugong sightings.

Aerial and underwater video footages

Some aerial video footage of dugong herds over the fore reef shelf was available for analysis. The videos were taken from a photographer of the Province Sud Resource Department from a helicopter (Martial Dosdane pers. comm.). Seven videos were taken on 7 July 2011 and four on 16 July 2012. An underwater video, taken by local sea-rangers snorkelling over the fore reef shelf on 18 April 2011 was also available for examination (Romain Laigle pers. comm.; Appendix D Table D.2).

Data analysis

Habitat use

I explored monthly and tidal variation in the numbers of dugongs observed. The response was the total number of dugongs observed in each month-tide combination divided by the corresponding number of surveys.

The interaction between the total counts of dugongs for each of the four habitat types (seagrass meadows, channels, reticulated reef flats, fore reef shelf), season and tide was assessed using log-linear regression via generalized linear models (GLM) with a Poisson distribution (McCullough and Nelder 1989). The size of each habitat was accounted for using the logarithm to the base e of habitat area as an offset in the models. I tested the null hypothesis that there was

no three-way interaction between habitat, tide and season. The dataset was subsequently divided
into season-tide categories (i.e., cool season-low tide, cool season-high tide, warm season-low
tide, warm season-high tide) and the proportion of dugongs sighted across habitats in each
season-tide category was calculated. The resulting values were binned into four classes of
dugong sightings (i.e., 0-25, 25-50, 50-75, 75-100%). These classes were coloured and assigned
to their relevant habitat layer within each season-tide category in ArcGIS® 10.2 (ESRI 2013) to
enable better visual representation of the results.

Dugong herds

I explored the occurrence of dugong herds: (1) spatially - inside or outside the lagoon; and (2)
temporally - by month. Dedicated transect survey and transiting flight data were combined for
the analysis of the dugong herd observations outside the lagoon but not for the analysis of the
dugong herd observation inside the lagoon because the transiting flights were conducted only
outside the lagoon. I then examined the correlation between water temperature changes and the
spatial and temporal patterns of dugong herding. I calculated the mean minimum monthly water
temperature difference between the fore reef shelf - outside the lagoon, and the seagrass
meadow - inside the lagoon during the transect surveys. A Spearman rank correlation test (Zar
1998) was conducted to assess the correlation between the probability of seeing at least one
dugong herd and the mean minimum water temperature difference between outside and inside
the lagoon. I chose to focus on the minimum water temperatures, which I assumed likely to
trigger a change in the spatial and temporal pattern of dugong herding. The association between
the proportions of dugong herd observations by tides was tested using a Fisher's exact test
(Upton 1992). I examined whether sharks were observed during the same dedicated transect
survey as the dugong herd observations. Hodgson's (2004) behavioural protocol was used for
the analysis of the video footages in order to identify the behaviour of dugongs in the herds
located on the fore reef shelf (Appendix D Table D.3).

5.3   Results

Water temperature

The changes in water temperature in Cap Goulvain were concordant with the definition of seasons used by Météo France (2015); (Chapter 1). The cool season started in April when water temperature decreased in all three monitored habitats. The warm season extended from October to March. During the cool season the mean minimum monthly water temperature was significantly higher over the fore reef shelf outside of the lagoon, than in the channel or over the seagrass meadows (Tukey multiple comparisons tests, $p < 0.0001$, Table 5.2). The difference between the mean minimum monthly water temperature over the fore reef shelf and in the southern channel became positive in April and peaked in May at 1.9°C (Table 5.2). A similar pattern was observed between the fore reef shelf and the seagrass meadow with the mean minimum monthly water temperature being warmer over the fore reef shelf from May through October (water temperature difference ranging 0.1-1.1°C). During the warm season, the spatial differences in water temperature reversed: the mean minimum monthly water temperature was significantly higher in the channel (up to 1.1°C difference; Tukey multiple comparisons tests, $p < 0.0001$) and over the seagrass meadow (up to 0.8°C Tukey multiple comparisons tests, $p < 0.0001$) compared with the fore reef shelf (Table 5.2).

Table 5.2: Mean minimum monthly water temperature (°C, ± SD) on the fore reef shelf, on the seagrass meadow and on the southern channel between mid-August 2012 and mid-August 2013.

Survey month	Fore reef shelf[a]	Southern channel[a]	Seagrass meadow[a]	Mean minimum monthly water temperature difference	
	Mean min	Mean min	Mean min	Fore reef shelf – Seagrass meadow	Fore reef shelf – Southern channel
January	24.5 (0.9)	25.6 (1.2)	25.3 (0.9)	-0.8	-1.1
February	26 (0.4)	26.5 (0.9)	26.2 (0.4)	-0.2	-0.5
March	25.6 (0.7)	26.0 (1.0)	25.8 (0.7)	-0.2	-0.4
April	25.0 (0.8)	25.0 (1.0)	25.2 (0.7)	-0.2	0.0
May	24.8 (0.6)	22.9 (1.0)	23.7 (0.8)	1.1	1.9
June	23.6 (0.2)	22.1 (0.6)	22.7 (0.4)	0.9	1.5
July	22.9 (0.3)	21.2 (1.4)	21.9 (1.2)	1.0	1.7
August	22.6 (0.2)	21.1 (1.0)	22.0 (0.5)	0.6	1.5
September	22.4 (0.1)	21.3 (1.0)	22.0 (0.5)	0.4	1.0
October	22.8 (0.4)	22.7 (1.2)	22.7 (0.7)	0.1	0.1
November	23.7 (0.5)	24.2 (1.2)	23.8 (0.6)	-0.1	-0.5
December	24.6 (0.6)	25.5 (0.9)	24.6 (0.7)	0.0	-0.9

[a] Water temperature loggers were deployed at depth of: (1) two meters in the southern edge of the main seagrass meadow; (2) 17m in the southern channel; and (3) 20m over the fore reef shelf in the southern part of the study area at (Figure 5.2).

Seasonal and tidal patterns in the number of dugongs observed per survey

The number of dugongs observed per survey varied seasonally. Substantially fewer dugongs were sighted during the warm season, between October and March (n = 172 dugongs over 29 surveys, median = 5, Figure 5.3 and Appendix D Table D.1) than during the cool season, between April and September (n = 599 dugongs over 33 surveys, median = 18), (Mann-Whitney U test, p < 0.01). The number of dugongs observed per survey was three times higher during the cool season (ñ = 18.4 dugongs per survey) than during the warm season (ñ = 5.6 dugong per survey, Figure 5.3). The lowest numbers of dugongs observed per survey was in February (ñ = 5 dugongs per survey) and December (ñ = 7 dugongs per survey). Dugongs were observed in large numbers during the cool months of June (ñ = 50 dugongs per survey), July (ñ = 41 dugongs per survey) and August (ñ = 40 dugongs per survey).

Dugong herds

Dugong herds (e.g., Figure 5.4) were observed in Cap Goulvain on 27 of 103 (26%) flights and the proportion of dugong herd sightings was not significantly different between the dedicated transect surveys and the transit flights (X^2 = 1.153, df = 1, p = 0.283). Six observations of dugong herds were made inside the lagoon and 21 outside the lagoon. There was a noticeable seasonal difference in the location of the dugong herds (Figure 5.5): dugong herds were sighted inside the lagoon from the end of the cool season to the end of the warm season between August and March whereas dugong herds were sighted outside the lagoon during the cool season only between April and September.

The probability of seeing at least one dugong herd outside the lagoon ranged between 0.12 at high tide and 0.38 at low tide and inside the lagoon between 0.03 at high tide and 0.17 at low tide (Appendix D Table D.4). These variations did not differ significantly across tides, neither outside the lagoon (Fisher's exact test, p = 0.29) nor inside the lagoon (Fisher's exact test, p = 0.29). On four occasions, dugong herds were sighted at the same location on the same day but at different tidal times (Appendix D Table D.5). For example, a herd of 57 dugongs was sighted at the peak of the low tide on the fore reef shelf during a transect survey on 14 May 2012. A smaller herd of 20 dugongs was sighted at the same location during the transect survey on the following high tide peak six hours later.

Between April and September the mean minimum water temperatures on the fore reef shelf at 17m depth was up to 1.9°C warmer than the mean minimum water temperature in the southern channel at 20m depth (Table 5.2). There was a strong positive correlation between the

proportion of dugong herd sightings in a month on the fore reef shelf and the difference in the mean minimum monthly water temperatures on the fore reef shelf and in the southern channel (Spearman Rank correlation coefficient, n = 12, r = 0.858, p < 0.01).

Sharks were never observed in the vicinity of a dugong herd (Appendix D Table D.5). However, sharks were occasionally observed on the same flight as a dugong herd but in a different habitat. For example, a shark was observed over the seagrass meadow at low tide on 27 June 2013 when two dugong herds were approximately 2.5km away (straight line distance) on the fore reef shelf.

During the dedicated transect surveys, the only time the observer could interpret the behaviour of dugongs in herds was on 13 November 2012, when a herd was sighted over the seagrass meadow inside the lagoon. The dugongs were creating feeding plumes.
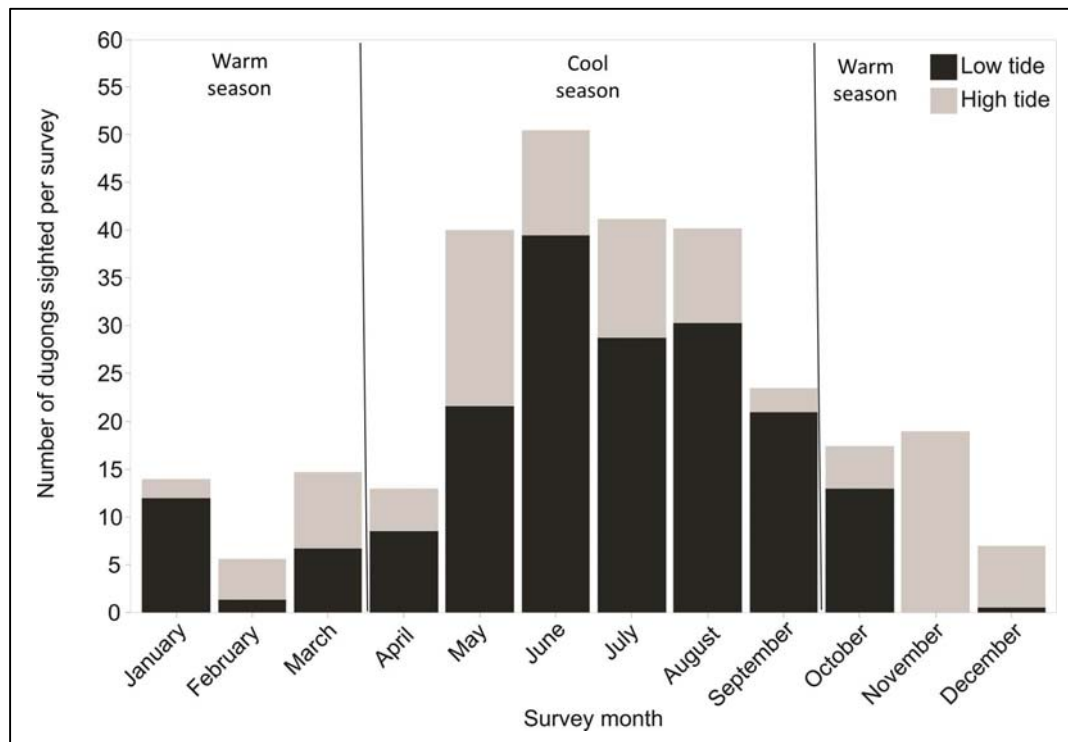
Figure 5.3: Number of dugongs observed per aerial survey in each survey month at high and low tide in Cap Goulvain.

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Figure 5.4: A herd of 69 dugongs over the fore reef shelf outside of the lagoon in Cap Goulvain on 22 June 2011. Note high proportion of animals apparently basking at the surface.
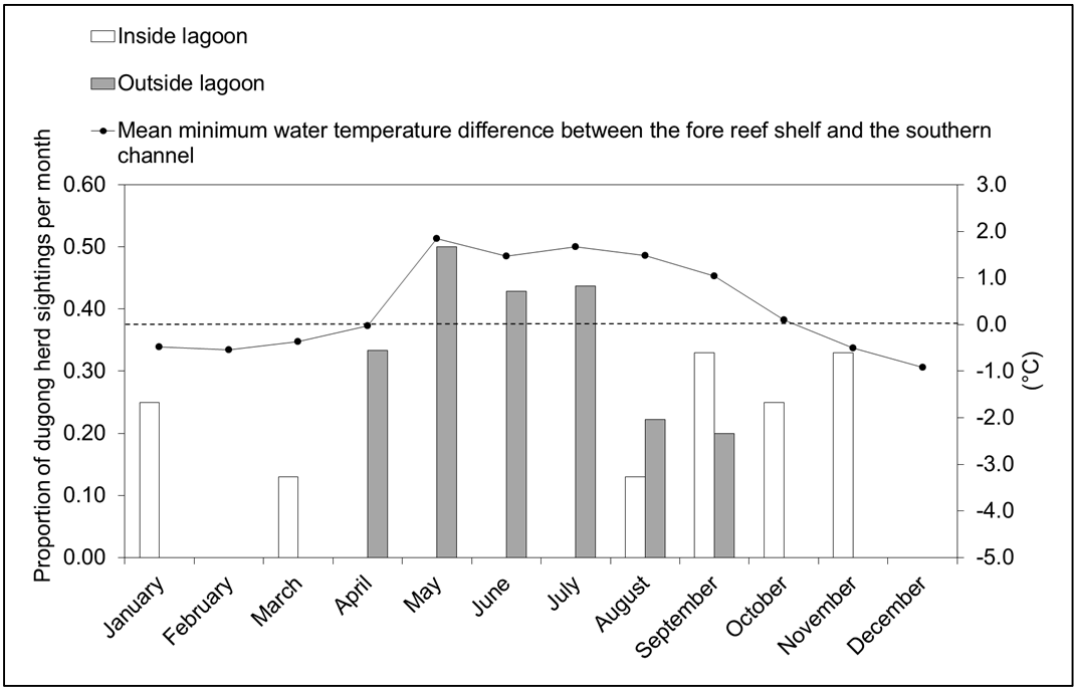
Figure 5.5: Proportion of dugong herd sightings per month outside the lagoon (grey columns) and inside the lagoon (white columns) in Cap Goulvain in relation to the mean minimum monthly water temperature difference between the fore reef shelf, outside the lagoon and the southern channel, inside the lagoon. The dotted black line is a reference point to enable the reader to see when the water temperature becomes warmer (positive temperatures) or cooler (negative temperatures) on the fore reef shelf compared to the southern channel.

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Behaviour of individuals within herds

In the videos of the dugong herds located over the fore reef shelf, I examined if any of the behaviours listed by Hodgson (2004) were displayed by the individuals forming the herds. I identified the behavioural states of resting, rolling, surfacing, socializing and feeding. The videos were too short (i.e., the longest video lasted for 24 min) and moving too much across the herds to conduct comprehensive focal follow examinations (Appendix E). Travelling was not observed. Feeding behaviour was limited to calves suckling from their mother's teats. Dugongs rested at the surface and in the mid-water column. Calves rested on their mother's back or side. The social events (*sensu* Hodgson 2004) displayed were 'close pass by', 'join' and 'swim away'. Dugongs were also observed swimming at very slow speed with changes in direction or immobile basking at the water surface. The mother and calf pairs were swimming together with the calf on the side or over the back of their mother. There was no evidence of pre-copulatory behaviours or mating.

Habitat use

More dugongs were observed per survey at low tide than at high tide in all months of the cool season (Figure 5.3). During the warm season there was no tidal pattern in the number of dugongs observed per survey: dugongs were mostly seen at high tide in November, December, February and March while in January and April most of the dugongs were observed at low tide.

The distribution of dugongs across the four habitats varied with season and tides (Table 5.3). The log-linear model revealed a significant three-way interaction in the counts of dugongs between habitat, season and tide ($G^2 = 68.5$, df = 4, p < 0.0001; Appendix D Table D.6) and significant two-way tide-habitat ($G^2 = 372.68$, df = 4, p < 0.0001), tide-season ($G^2 = 35.17$, df = 1, p < 0.0001) and season-habitat interactions ($G^2 = 107.70$, df = 4, p < 0.0001). To compare habitat use by dugongs in each season-tide category, I split the dataset into season-tide categories to interpret the interaction (Table 5.3).

At high tide, the highest percentage of dugongs was sighted over the seagrass meadow during both the cool and the warm seasons (Figure 5.6 and Table 5.3). However, this percentage changed seasonally and was more than twice as high in the warm season than in the cold season. The seagrass meadow that was used by dugongs was mostly exposed and not available to dugongs at low tide. Use of the fore reef shelf was virtually limited to the cool season and more than twice as frequent at low tide than at high tide (Figure 5.6 and Table 5.3). Dugongs were mostly sighted over the reticulted reef flat at low tide during the warm season and at high tide

during the cool season and used the channels mostly at low tide, especially in the warm season (Figure 5.6 and Table 5.3).

Table 5.3: Percentage of dugong sightings in each habitat for each season-tide category.

Tide-season	Habitat			
	Seagrass	**Reticulated reef flat**	**Channels**	**Fore reef shelf**
Low – Cool	3	7	31	59
Low – Warm	0	23	73	4
High – Cool	36	28	14	22
High – Warm	79	6	16	0
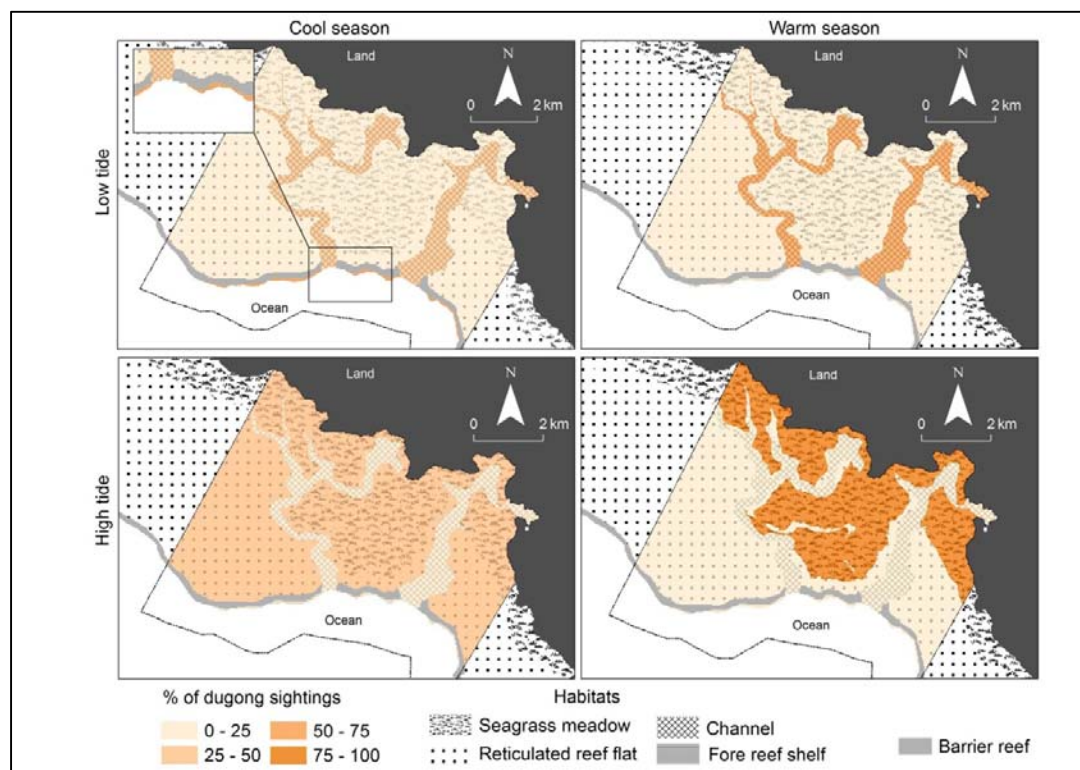
Figure 5.6: Percentage of dugong sightings in each habitat for each season-tide category. Sampling intensity was constant within and across each season-tide category.

5.4   Discussion

I found strong seasonal and tidal patterns in dugong abundance, behaviour and habitat use in Cap Goulvain. The number of dugongs observed per survey was three times higher during the cool season than during the warm season. There was a noticeable seasonal difference in the location and behaviour of the dugong herds. Aggregations of dugongs inside the lagoon were generally sighted in the warm season and resting aggregations outside the lagoon during the cool season between April and September. In addition, there were strong seasonal and tidal changes in the way dugongs used habitats in Cap Goulvain. Not unexpectedly, dugongs were sighted in higher numbers over the intertidal seagrass meadows at high tide than in any other habitat regardless of the season. But when tides restricted access to the seagrass meadows there was a seasonal variability in the way dugongs were distributed over the non-seagrass coral reef habitats. During the cool season at low tide, a higher percentage of dugongs was sighted on the fore reef shelf than in any other habitat. During the warm season at low tide, dugongs appeared to remain in the lagoon, particularly in the channels. The reticulated reefs were used by dugongs at low tide during the warm season and at high tide during the cool season.

During the cool season the water temperature on the fore reef shelf, outside the lagoon, was higher than the water temperature on the seagrass meadow and in the southern channel inside the lagoon. This difference reversed during the warm season. Collectively, these results suggest that behavioural thermoregulation may have played a key role in the seasonal changes in number and behaviour of dugongs in Cap Goulvain as well as in the way animals used their habitats in the region. Below I evaluate the evidence supporting this hypothesis while considering other possible explanatory factors, which are not mutually exclusive.

Behavioural thermoregulation

Thermoregulation is a key feature in the maintenance of homeostasis in mammals (Cossins and Bowler 1987; Terrien *et al.* 2011). Thermoregulatory capacities are strongly related to energy balance and animals constantly seek to limit the energy costs of normothermia (Terrien *et al.* 2011). Many mammals use behavioural mechanisms to reduce the energy costs of thermoregulation (Cabanac *et al.* 1970; Baldwin 1974; Gordon 1985; Flouris 2011). For example, in Australia, wild pigs inhabiting river systems in the semi-arid rangelands reduce the cost of thermoregulation by seeking refuge under continuous cover associated with riverine woodlands. The need to access riverine woodlands when temperatures are high constrains the foraging behaviour and habitat use of wild pigs where the landscape topography limits access to this habitat (Choquenot and Ruscoe 2003).

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Thermoregulation is a particular problem for marine mammals because they spend all or a greater part of their lives in water, a medium with conductivity 25 times greater than air and with temperatures generally lower than their body temperature (Pabst *et al.* 1999; Rosen *et al.* 2007; Satinoff 2011). Marine mammals regulate their body temperature through both morphological (fur, subcutaneous body fat, changes to anatomy of the blood supply to the integument) and behavioural adaptations. For example, sea otters keep their highly vascularized paws out of the cold water to stay warm (Morrison *et al.* 1974; Costa and Kooyman 1982). Seals and sea lions commute up and down the tidal zone on the beach to cool off or warm up (White and Odell 1971; Odell 1974).

Sirenians feed on low energy food relative to the food of carnivorous marine mammals (Aragones *et al.* 2012). They have a relatively low metabolic rate, poor thermal conductance (although see Horgan *et al.* 2014) compared to cold-water marine mammals and limited scope for increasing their metabolic rate to counter heat loss (Gallivan and Best 1980; Irvine 1983). Thus sirenians modify their behaviour to reduce the energy lost by thermal conductance. This phenomenon has been extensively studied in Florida where winter water temperatures can be lethal to manatees after cold fronts (Bossart *et al.* 2003, 2004). Manatees respond to cold water temperatures in Florida by seasonal migrations and local movements between warm water springs and industrial warm-water sources during winter (Laist and Reynolds 2005; Deutsch *et al.* 2006). In areas where temperature-inverted haloclines result in the water temperature being higher at the bottom than at the surface, manatees tend to spend more time at the bottom (Stith *et al.* 2011).

Both aerial surveys and tracking suggest that the movement patterns of dugongs are associated with changes in water temperature at the higher latitude limits of their range even though the water temperatures are much higher than the temperatures that cause cold induced movements in manatees. Marsh and Rathbun (1990) found that a radio-tagged dugongs travelled more than 100km to warmer waters coincident with the onset of cold weather. Six dugongs tracked in Hervey Bay, eastern Australia, undertook meso-scale 80km movements across the bay in winter from the 19-20°C coastal waters to the 21-22°C waters off Sandy Cape despite the apparent lack of seagrass meadows in the Sandy Cape area (Sheppard *et al.* 2006). Preen (1992) reported movements in and out of Moreton Bay over a temperature gradient of less than two degrees between offshore and inshore areas (i.e., 17.7°C inside the bay versus 19.4°C recorded outside the bay). Holley (2006) concluded that seasonal drops in temperature caused individual dugongs to move from the inner to outer regions of Shark Bay. Sighting records and aerial surveys at three high latitude limits to the dugong's range indicate that most dugongs avoid waters lower in temperature than about 18°C: Moreton Bay in Queensland (Marsh and Sinclair 1989b; Preen

1992), Shark Bay in Western Australia (Anderson 1986, 1994; Marsh *et al.* 1994; Preen *et al.*
1997; Gales *et al.* 2004; Holley *et al.* 2006), and the Arabian/Persian Gulf (Preen 1989).
Sighting records of live dugongs along the New South Wales coast in south-eastern Australia
are limited to summer (Allen *et al.* 2004). These behavioural adjustments along with insulation
provided by the integument may help dugongs to live year-round at sub-tropical latitudes
(Horgan *et al.* 2014). Nonetheless, Wirsing *et al.* (2007b) sighted some dugongs in Shark Bay in
waters below 15°C, and Lanyon *et al.* (2005) reported seeing dugongs in Pumicestone Passage
in the Moreton Bay region year round, despite water temperatures below 18°C from June to
August, and down to 15.4°C in June. It is not known whether these were repeated sightings of
the same dugongs.

The seasonal changes in the distribution and number of dugongs at low tide in non-seagrass
coral reef habitats of Cap Goulvain were correlated with the differences in water temperature
between the outer and the inner-lagoon areas, even though the lowest mean minimum monthly
water temperatures recorded (21.1°C) were much higher than 18°C. A similar difference in
water temperature between inshore areas and areas closer to oceanic waters has been
documented in other regions on the west coast of New Caledonia where the lagoon is wider than
in Cap Goulvain including the southwest lagoon in the Nouméa region (i.e., up to 35km from
coastline to barrier reef; Le Borgne *et al.* 2010).

Nonetheless the ~2°C temperature difference between the dugongs spending low tide on the
fore reef shelf rather than in the subtidal sections of the lagoon in the cool season could
significantly reduce the heat transfer to the dugong's body core to the skin as illustrated by this
simplistic application of Newton's law of cooling (Davidzon 2012):

$H = Ak\ (Tc\text{-}Ta)$

where

H = heat produced, transferred from the core to the surface via the circulation; A =
surface area; k = heat transfer coefficient; and Tc = deep body temperature and Ta =
water temperature.

Assuming that A and k are constant and that the dugong's deep body temperature Tc = 37°C,
moving from the channel temperature of 22.9°C (coolest mean minimum monthly water
temperature recorded in May) during the cool season at low tide to the fore reef shelf (24.8°C;
mean minimum monthly water temperature in May) would reduce heat transfer by 13.5%
(37°C - 22.9°C /37°C - 24.8°C). These energy savings would be reversed in the warm season
when it is warmer in the lagoon than on the fore reef shelf.

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More dugongs were sighted in Cap Goulvain during the cool season compared with the warm season. The increase in the number of dugongs in Cap Goulvain during the cool season could be a strategy to reduce the energy cost of accessing warm waters. The lagoon in Cap Goulvain is narrower than other regions on the west coast where seagrass meadows are extensive. For example, Nepoui and Poya Bays, the closest bays north of Cap Goulvain that support extensive seagrass meadows are up to 10km wide. Similar distances separate inshore seagrasses to oceanic waters in Moindou located south of Cap Goulvain. Thus the energy cost of dugongs commuting from their seagrass feeding grounds to warm water at Cap Goulvain is potentially lower than in other regions where the lagoon is wider.

At low tide during the warm season, dugongs were mainly sighted in the channels and on the reticulated reef flats than over the fore reef shelf. During this period, the water temperature inside the lagoon and the channels was warmer than the water temperature outside the lagoon, supporting the hypothesis that dugongs may seek the warmest habitat while resting to maintain their core body temperature.

Dugongs sighted outside the lagoon were always observed in the proximity of the passes which constitute the main access to the inshore seagrass resources. Proximity to the passes may help dugongs to minimise their energy cost to commute to the seagrass meadow. The dugong aggregations were observed during the cool season coinciding with the increase in dugong abundance. Therefore the herds observed on the fore reef shelf in the cool season may have simply reflected an inevitable increase in density associated with the increase in abundance. I conclude that the increase in the number of dugongs in Cap Goulvain combined with the need to use a habitat as warm as possible with easy access to food resources is a plausible explanation or why dugongs aggregate on the fore reef shelf at Cap Goulvain during the cool season.

Reducing the risk of predation

As long-lived slow breeding marine mammals, dugongs need to maximise survival by minimising the risk of predation. The evidence of direct attacks on dugongs from sharks summarised by Marsh *et al.* (2012) indicate that there is a risk of dugongs being attacked by large sharks, particularly tiger sharks despite being protected from shark attack by their large size, generally good auditory and tactile perception, thick skin, stout rib cage, and fusiform body shape with minimal constriction or appendages that can be easily grasped by predators (Marsh *et al.* 2012).

Dugongs also minimise predation through behaviour by: (1) reducing the risk of encountering a predator by using a refuge; and (2) decreasing the consequences of the encounter by increasing

the likelihood of escape (Wirsing *et al.* 2007a). These strategies are likely to fail if dugongs are ambushed in the reticulated reef flats and channels in Cap Goulvain. The reticulated reef flats are subtidal but shallow (< 10m) formations with the potential to limit the movements of large vertebrates (Andréfouët *et al.* 2004). During the 2003 aerial survey described in Chapter 2, Garrigue *et al.* (2008) observed an animal tentatively identified as a dugong being attacked by 10 tiger sharks and 20 other smaller sharks. The dugong could not escape the barrier created by the reef and pursuit lasted only a few minutes before the sharks attacked it. Shark attacks of live dugongs in the reticulated reef flats of the west coast of New Caledonia have also reported by sea rangers during boat patrols (Bruno Manach. pers. comm.). Adjacent to the reticulated reef flats, the channels provide access to deep water to escape from predation. Wirsing *et al.* (2007 a-d) suggested that dugongs overuse deep areas as a refuge when sharks are abundant even though these areas may offer little food. However, the channels in Cap Goulvain are deep and turbid, possibly limiting the dugongs' capacity to detect shark attacks from below. Predation from below is more likely to be fatal than attacks from above because the dorsum and sides of dugongs are protected by the rib cage (Marsh *et al.* 2012). The fore reef shelf located outside the lagoon provides access to deep oceanic waters. Studies on dugong-shark interactions suggest that dugongs use habitats that provide an easy access to deep waters to escape from shark attacks if sharks are present (Wirsing *et al.* 2007 a-d). During our surveys the dugongs sighted over the fore reef shelf were sighted in clear waters where the bottom is visible. Thus, predation from below may be more easily detected when dugongs are on the fore reef shelf than in the channels.

However, at least 22% and up to 96% of dugongs were sighted in the reticulated reef flat or in the channels during our surveys in the four season-tide combinations (Table 5.3). Even at low tide in winter, 38% of dugongs were in these areas. It is difficult to reconcile these observations with the hypothesis that use of the fore reef shelf in the cool season being primarily a strategy to limit the risk of shark attack. Further investigation on the seasonal changes in abundance and habitat use of sharks in Cap Goulvain is required to evaluate the influence of shark predation on dugongs in this region.

Rotational cropping of seagrass

The seasonal pattern in the number of animals sighted in Cap Goulvain presumably results from dugong movements in and out of the study area (see Chapter 4). However, my capacity to explain why such movements may have occurred is limited.

Herbivory in some reef environments, particularly lagoon environments can significantly alter seagrass productivity (Unsworth *et al.* 2007; Coles *et al.* 2011), which in turn can affect the

distribution and abundance of the herbivores that rely on it for food. Seagrass grazing by dugongs influences microbial processes, plant biomass and productivity, community structure and composition, food quality and associated benthic animals such as marine invertebrates (see review by Marsh *et al.* 2012). The time scale of recovery of seagrass beds from dugong feeding varies with time of year and location (McMahon 2005). For example recovery times ranged from months for species of *Zostera, Cymodocea* and *Halophila* in tropical north Queensland to more than a year in a monospecific meadow of *Halodule uninervis* at another site in the same general area (Aragones and Marsh 2000). Short shoots of *Halodule wrightii* and *Syringodium filiforme* showed significant recovery within one growing season after Florida manatees intensively fed on them for the three winter months of the year (Lefebvre *et al.* 2000). The growing season recovery of these plants enabled manatees to migrate again to the same area during the next winter. It is therefore reasonable to hypothesize that the seasonal change in dugong abundance at Cap Goulvain results from rotational grazing with some (but not all dugongs) using the area as a seasonal feeding ground only and then moving to allow the seagrass to recover during the warm season. However, I have no evidence to reject or support this hypothesis, which is not mutually exclusive of the behavioural thermoregulation hypothesis discussed above.

Social interactions

Social interactions seem an unlikely explanation for the seasonal changes in the distribution of dugongs at Cap Goulvain. The (admittedly limited) video footage available for analysis indicated that the dugongs forming herds on the fore reef shelf were resting. I did not identify any distinct social interaction between dugongs except for the females nursing their calves. Hodgson (2004) conducted the most comprehensive study on the behaviour of dugongs forming herds using a blimp-mounted video system in Moreton Bay. She concluded that dugongs were not forming herds to facilitate social interactions, rest or reduce the risk of predation. Rather their aggregations stimulated the growth of pioneer seagrass species with high quality foliage (Preen 1992, 1995; Hodgson 2004). However these interpretations of the function of herding in dugongs in Moreton Bay may have been biased by the focus of the observations, which were mostly conducted over seagrass meadows. The situation at Cap Goulvain is very different because there is no doubt from the videos that the dugongs sighted on the fore reef shelf were resting and this habitat is devoid of seagrass. Thus although rotational cropping may be part of the reason for the increase in the abundance of dugongs at Cap Goulvain during the cool season, it cannot explain the formation of herds on the fore-reef shelf.

Reducing the risk of anthropogenic disturbance

The behavioural responses of dugongs to boat traffic have only been formally investigated in Moreton Bay, a region with relatively high and increasing boating activity (Hodgson and Marsh 2007). This study showed limited behavioural responses of dugongs from boat traffic. How dugongs react to boat traffic in more remote areas where they may be less familiar to this type of disturbance is unknown. Acoustic playback experiments were conducted to assess the behavioral responses of Florida manatees to watercraft approaches. Manatees markedly responded to vessel approaches, especially to fast personal watercrafts (Miksis-Olds et al. 2007). Disturbance from human activities is unlikely to have influenced the distribution of dugongs at Cap Goulvain as very little activity was recorded in the region during the surveys. Ten boats observed over the 62 surveys were the only evidence of human activity detected.

5.5   Conclusion

This chapter highlights that season (presumably water temperature) and tides strongly influence the number and distribution of dugongs in Cap Goulvain and that both seagrass and non-seagrass habitats are important for this species. Behavioural thermoregulation may be a key driver in the seasonal changes in number and behaviour of dugongs in Cap Goulvain as well as in the way animals used their habitats in the region. Nonetheless, further investigation on the effect of seasonal changes in food availability and quality and predation from sharks is required.

The fore reef shelf is a key non-seagrass habitat for dugongs not only to transit from one bay to another (see Chapter 4) but also to rest during the cool season. The ecological importance of this habitat has also been identified for species of reef fish in the tropical Atlantic (Olavo *et al.* 2011) and reef sharks in the Great Barrier Reef in Australia (Rizzari *et al.* 2014).

5.6 Chapter summary

- Little is known about dugong habitat use in coral reef environments where seagrasses occur only in relatively small intertidal patches that are not accessible at low tide.

- I investigated seasonal and tidal changes in abundance, aggregation patterns and habitat use of dugongs in the lagoon of Cap Goulvain using data obtained from fine-scale aerial surveys. I then used aerial and underwater videos to explore the behaviour of dugongs aggregating over the fore reef shelf outside the lagoon.

- There were strong seasonal and tidal patterns in dugong abundance, behaviour and habitat use in Cap Goulvain.

- Substantially fewer dugongs were sighted during the warm season, between October and March (n = 172 dugongs over 29 surveys, median = 5) than during the cool season, between April and September (n = 599 dugongs over 33 surveys, median = 18).

- Aggregations of dugongs inside the lagoon were generally sighted in the warm season and aggregations outside the lagoon during the cool season between April and September.

- Aerial and underwater videos clearly showed that the dugongs aggregating over the fore reef shelf were resting. There was no tidal pattern in the occurrence of these outer reef herds in Cap Goulvain.

- Dugongs were sighted in higher numbers over the intertidal seagrass meadows at high tide than in any other habitat regardless of the season.

- When tides restricted access to the seagrass meadows there was a seasonal variability in the way dugongs were distributed over the non-seagrass coral reef habitats. During the cool season at low tide, a higher percentage of dugongs was sighted on the fore reef shelf than in any other habitat. During the warm season at low tide, dugongs appeared to remain in the lagoon, particularly in the channels. The reticulated reefs were used by dugongs at low tide during the warm season and at high tide during the cool season.

- The intensive use of the outer lagoon area coincided with a positive difference in the water temperature between the fore reef shelf, outside the lagoon, higher by up to ~2°C than the water temperature on the seagrass meadow and in the southern channel inside the lagoon.

- I hypothesised that behavioural thermoregulation may have played a key role in the seasonal changes in number and behaviour of dugongs in Cap Goulvain as well as in the way animals used their habitats in the region. Nonetheless, further investigation is required to evaluate the influence of other possible non-mutually explanatory factors including seasonal variation in the abundance of sharks and in seagrass availability and quality.

Chapter 6: General Discussion

Chapter 1
General introduction

Objective 1
Assessing the status of dugongs in New Caledonia

Chapter 2
Temporal changes in the relative abundance of dugongs

Chapter 3
Dugong distribution and Marine Protected Areas

Objective 2
Enhance understanding of spatial ecology of dugongs in coral reef environments

Chapter 4
Dugong movement heterogeneity in the coral reef of New Caledonia

Chapter 5
Seasonal changes in the abundance and habitat use of dugongs in the coral reefs of Cap Goulvain

Objective 3
Integrating scientific research conducted on dugongs as part of this thesis to inform decisions relating to dugong conservation and management regionally and internationally.

Chapter 6
General discussion

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6.1 Opportunities to enhance the conservation and management of dugongs in New Caledonia

In response to increasing worldwide biodiversity loss, the United Nations Environment Programme (UNEP) developed the Convention on Biological Diversity (CBD) with the intent, in part, of "enabling the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of benefits from using genetic resources" (Balmford *et al.* 2005). The conservation of dugongs is congruent with the aim of this convention.

Dugongs are important components of tropical and subtropical coastal ecosystems. The status of most of these ecosystems is of great concern and affects dugongs throughout most of their range in the Indo-West Pacific (Marsh *et al.* 2012). The scope for the survival of dugongs from disturbance should be higher in countries of Very High Human Development Index (HDI) because the capacity to implement effective conservation actions and tackle wildlife conservation issues should be greater than in less developed countries (Marsh *et al.* 2012).

New Caledonia is one of the richest countries in Oceania (ISEE 2014). New Caledonia receives financial transfers from Metropolitan France, which has a Very High HDI, plus the European Union, and its mining activities are booming. The capacity of New Caledonia to implement research and conservation initiatives to enhance the conservation of dugongs should be higher than any other dugong range state in Oceania with exception of Australia. As explained in Chapters 1 and 2, standardized dugong aerial surveys were conducted in 2003 and in 2008 (Garrigue *et al.* 2008, 2009). The dugong population estimate that resulted from the 2008 survey was much lower than that for the 2003 survey, triggering local concerns. Hence local managers decided to underwrite further investigation including research on the basic ecology of dugongs in New Caledonia to assess the size and status of the dugong population and of the conservation strategies in place. This thesis is the result of that investment.

Initiating new conservation strategies and/or enhancing current actions to protect dugongs require spatial-ecological information about the population. The generic information on the spatial ecology of dugongs is substantial and reflects more than 30 years of extensive scientific research mostly conducted in Australia (Marsh *et al.* 2012). Some of this science is relevant to informing the conservation of the dugong throughout its range. However, further research on the spatial ecology of dugongs was required in New Caledonia because the environment is very different from that in the countries where dugong research has been carried out. Very little is

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known about the spatial ecology of dugongs in tropical coral reef environments. Obtaining this information is critical to ensure that future conservation plans in New Caledonia are adequately developed and managed as the pressure on the coastal environment continues to increase (David *et al.* 2010). This thesis is an important first step to address this gap. The aim of my thesis was to provide an evidence-base to inform the conservation and management of dugongs at several spatial and temporal scales in New Caledonia by: (1) assessing the temporal changes in the dugong population size and the capacity of the current marine protected areas (MPAs) to protect dugongs at the scale of New Caledonia; (2) investigating the spatial ecology of dugongs in the lagoons and coral reefs of New Caledonia by studying their movement patterns and habitat use at local scales. I briefly review my findings below; and (3) integrating scientific research conducted on dugongs as part of this thesis to inform decisions relating to dugong conservation and management regionally and internationally.

6.2   Review of findings

In Chapter 2, I investigated the temporal variation in a standardised index of dugong relative abundance in New Caledonia. As explained in Chapters 1 and 2, the two surveys conducted prior to my study occurred in the cool season of 2003 and the warm season of 2008 and there were justified concerns that seasonal differences may have influenced the results. I addressed this concern by conducting one survey in each of the cool and warm seasons of both 2011 and 2012. I did not detect any significant seasonal differences in dugong abundance. The 2011 and 2012 estimates of dugong relative abundance in New Caledonia were similar to the 2008 estimate but significantly lower than the 2003 estimate. I explored the evidence for several possible explanations for this result including: (1) an actual reduction in the size of the dugong population between 2003 and 2008; (2) temporary migration within the survey area leading to double counting in 2003; or (3) unaccounted biases associated with detection probability. Although my results show that the discrepancy in dugong population estimates may be caused by several factors, I could not come to a definite conclusion. Furthermore, my research highlighted the importance of conducting replicate baseline surveys to enable robust interpretation of temporal variation in subsequent population size estimates and in turn improve the management of dugongs and marine mammals in general.

Dugongs were not explicitly considered in the design of the network of MPAs in New Caledonia, despite being one of the region's World Heritage values. In Chapter 3, I assessed the capacity of the New Caledonia MPA network to protect dugongs from anthropogenic hazards. My analysis demonstrated a spatial mismatch between locations that support high densities of dugongs and the MPAs that provide the greatest protection from anthropogenic activities. My

spatially-explicit model of dugong distribution and relative density in New Caledonia identified important dugong areas in regions highly exposed by human activities including the Nouméa and the Voh-Koné-Pouembout regions. I provided guidance on how these shortcomings can be avoided in New Caledonia and other regions.

The understanding of the fine scale movement heterogeneity and use of space of animals of conservation concern has the potential to provide information that complements the spatially-explicit models of distribution that are widely used in conservation planning. Advances in telemetry now provide robust and detailed information on the daily and seasonal movement patterns of tracked animals including locations that may not be evident from models based on survey results alone. In Chapter 4, I used fast-acquisition GPS satellite telemetry technology to study the movement patterns and activity spaces of 12 dugongs, using for the first time a Personal Watercraft (PWC) to safely and quickly capture 12 dugongs in shallow areas over reef flats, where boat access is difficult and can be dangerous.

Individual dugongs were tracked for between 3-192 days (mean = 35.9 days, ± SE = 15.31 days during the warm season). The tracked dugongs displayed great variability in their movement patterns. Some animals moved > 15km whereas others remained in the vicinity of their capture locations. All but one tracked dugong subsequently returned to their capture site. Some dugongs crossed provincial boundaries. None spent tracking time in the MPAs that significantly restrict anthropogenic activities, confirming the results obtained in Chapter 3. Dugongs swam both within and outside the lagoon to transit between bays. For example, all the dugongs tracked in the Ouano and the Nouméa regions swam within the lagoon whereas in the Cap Goulvain region three dugongs exited the lagoon and used the fore reef shelf as a corridor to transit between Cap Goulvain and Bourail Bay.

The sizes of the tracked dugongs' home-ranges were several times larger in the Nouméa region than in the Cap Goulvain and Ouano regions. No dugong exhibited major diurnal differences in home-range and core area. My analysis of the use of seagrass patches by dugongs was limited to depths less than five metres because seagrasses have not been mapped at depths greater than five metres at the spatial scale of New Caledonia. Nonetheless, my spatially-explicit model of dugong distribution and relative density and the distribution of the core areas of the tracked dugongs suggest that dugongs spend a significant amount of time in areas including subtidal areas where seagrass meadows in New Caledonia are probably much more extensive than indicated by the current maps of seagrass distribution.

I investigated the seasonal changes in abundance and habitat use of dugongs in the coral reefs of Cap Goulvain, one of the most important dugong and seagrass habitats in New Caledonia

(Chapter 5). I also explored the behaviour of dugongs aggregating over the fore reef shelf outside the lagoon. I found strong seasonal and tidal patterns in dugong relative abundance, behaviour and habitat use at Cap Goulvain. Substantially fewer dugongs were sighted during the warm season, between October and March, than during the cool season, between April and September. Aggregations of dugongs inside the lagoon were generally sighted in the warm season; those outside the lagoon during the cool season. Aerial and underwater videos clearly showed that the dugongs aggregating over the fore reef shelf were resting. The intensive use of the outer lagoon area during the cool season coincided with the water temperatures being up to 2°C higher on the fore reef shelf than over the seagrass meadow and in the southern channel inside the lagoon, suggesting that behavioural thermoregulation plays a key role in the seasonal changes in number and behaviour of dugongs in Cap Goulvain. Nonetheless, the influence of other explanatory factors including seasonal variation in the abundance of sharks and in seagrass biomass and quality cannot be ruled out.

6.3   Management considerations

Managing at multiple spatial scales

The management agencies responsible for dugong conservation in New Caledonia operate at provincial scales. I showed that important dugong habitats occur in both Province Nord and Sud and that dugongs cross these jurisdictional boundaries (Chapter 4). Thus management needs to be coordinated at an ecological scale relevant to the dugong by developing cross-jurisdictional management arrangements between the government of New Caledonia and the Province Nord and Sud of New Caledonia. As pointed out by Sheppard (2008) "the dugong population of any one bay should be considered not as an isolated entity but as a fluctuating component of a spatially dynamic metapopulation".

My findings indicate the need to implement dugong conservation actions at local scales also. I selected Cap Goulvain as a local scale case study (Chapter 4 and 5) because it is an important dugong and seagrass habitat (Chapter 3). The tracking data indicated that dugongs made intensive use of the Cap Goulvain region. My time series of fine-scale aerial surveys further indicated that the number of dugongs in the Cap Goulvain region varied seasonally and that the dugongs used habitats differently according to the season and tide. Human activity in Cap Goulvain was very low at the time of my study. However, this situation is about to change. Construction of a large beach resort ten kilometres south of Cap Goulvain has recently been completed. The hotel should attract a large number of tourists to the region and it is designed to make the lagoon one of its main attractions. Strategies to mitigate the potential risk of

anthropogenic impact to dugongs in this important habitat are critical and should be addressed as soon as possible in collaboration with key stakeholders.

In addition, given the high cultural value of the dugong to the indigenous and Caledonian communities of New Caledonia (Dupont 2015), these communities should be consulted about their desire to participate in community-based management. In Australia, community-based management of dugongs has catalysed more generic co-management in regions where indigenous stakeholders are interested in managing the traditional sea country of their clan group (Havemann *et al.* 2005; Marsh *et al.* 2012; Butler *et al.* 2012).

Enhancing the capacity of New Caledonia's Marine Protected Areas to protect dugongs

As explained above, analysis of the time-series of dugong aerial surveys in New Caledonia indicated that there is a spatial mismatch between locations that support a high density of dugongs and marine protected areas (MPAs) that provide the greatest protection from anthropogenic activities. The use of space by the tracked dugongs matched the spatially-explicit model of dugong distribution and relative density (e.g., Appendix F Figure F.1), reinforcing this conclusion. The tracked dugongs spent little time within the boundaries of highly restrictive MPAs. In addition, the use of the Quick Fix Pseudoranging (QFP) technology has provided important information on the movement of dugongs between important habitats. For example, some of the apparently directed movements of tracked dugongs were close to the shore where there may be a risk of dugongs entangling in nets. All the tracked dugongs in my study stayed within 8km of land with the mean individual distance from land ranging from 0.49km (± SD = 0.44) to 2.74km (± SD = 1.42). Zeh *et al.* (in review) found that four out of the 30 dugongs they captured in Moreton Bay travelled over 200km north to Hervey Bay, three of them moving along and very close to the coast (< 5km). Dugongs tracked by Sheppard *et al.* (2006) stayed mostly within 7km of the coast but were often found up to 20km away from the coast (whether this last result is real or an artefact of the technology is unknown).

The risks that dugongs face by ranging close to the coast vary with location. For example, between Moreton Bay and Hervey Bay in Australia, shark nets for bather protection are located immediately offshore from several beaches and 39 dugongs were recorded drowned in shark nets in this region between 1989 and 2011 (Meager *et al.* 2013). A similar result has been reported for a dugong moving between the Gladstone and Hervey Bay regions (Marsh unpublished data). In the Great Barrier Reef World Heritage Area, an extensive series of Dugong Protection Areas and marine park zones have been established to protect relatively high

density dugong areas in the World Heritage Area (Marsh and Lawler 2000; Dobbs *et al.* 2008; Grech and Marsh 2008). Mesh netting has been banned from areas close to major headlands to protect dugongs travelling between bays in the Great Barrier Reef Marine Park (GBRMPA 2007) and from some dugong movement corridors in the Great Sandy Marine Park (Sheppard 2008). Similarly, the information I obtained on the key areas and movement corridors used by dugongs on the west coast of New Caledonia should be used by local management agencies to ensure that netting effort will be reduced in these areas to reduce the risk of dugong from entanglement. Tracking additional dugongs in New Caledonia is needed to inform the protection of dugong movement corridors in other regions of New Caledonia.

The inadequacy of the current MPAs to protect dugongs could constitute the basis of new discussions among managers, planners, scientists and sea-users towards the rezoning of the MPAs in New Caledonia. In Chapter 3, I provide guidance to inform these discussions. In Australia, the review of a section of the Great Barrier Reef Marine Park (GBRMP) indicated that the no-take protected areas were inadequately distributed to ensure protection of the entire range of marine biodiversity in the park. Consequently in 2004, the GBRMP was rezoned to increase the representation of key biodiversity features and improve the MPA's capacity to protect its World Heritage Values. To do this the Great Barrier Reef Marine Park Authority (GBRMPA) followed a planning sequence with negotiated objectives, principles, targets and feedback loops (Fernandes *et al.* 2005). Such a structured approach would likely be appropriate in New Caledonia at the scale of the main island if the MPAs were rezoned.

Spatial management of the risks to dugongs from anthropogenic activities

Dugongs are long-lived slow breeding mammals and hence require very high and stable levels of adult survival to maintain numbers and can sustain only very low levels of mortality from human causes (Marsh *et al.* 2012). Thus understanding the importance of the hazards that directly impact dugong adult survivorship is essential.

If spatial information on the distribution of hazards is available, the exposure of dugongs to these hazards can be rapidly assessed in a geographic information system (GIS) to identify areas of conservation priority. Grech and Marsh (2008) used a spatial risk assessment approach in geographical information systems (GIS) to rapidly assess the risk to dugongs from multiple anthropogenic activities in the Great Barrier Reef World Heritage Area.

Based on interviews with environmental managers from Province Nord and Province Sud, Bordin (2009) listed the potential hazards to dugongs in New Caledonia and suggested that

illegal hunting and interactions with vessels were the most serious direct hazards. I have spatially assessed the exposure to dugongs from hunting and bycatch in fishing nets at the scale of the main island; and the risks of collision with vessels in the Nouméa region to identify areas that should be prioritized for dugong management in New Caledonia. In the two sections below I briefly explain the rationale for, methodology used and results of these analyses.

Risk to dugongs from hunting and catch in fishing nets

In New Caledonia, especially in remote regions, illegal hunting still occurs despite the current quasi-ban on dugong take. Exceptions to the ban require a special permit to be granted in Province Nord (which has not occurred since 2004). Interviews conducted in 2005 (Harris 2005) in the Province Nord and in 2006 (TNS 2005) in the Province Sud estimated that respectively 55% and 20% of households had consumed dugong in the year prior to the interview, mostly during family dinners and customary feasts. Since these interviews were conducted, several lines of evidence indicate that illegal hunting still occurs. This evidence includes cases of dugong stranding resulting from poaching attempts (e.g., dugong found shot dead on the shore) and witnesses of dugong hunting and consumption (anonymous pers. comm.). During my fieldwork, I saw dugong meat stored in the house of a local fisherman.

It was impossible for me to quantify the level and spatial occurrence of intentional harvest of dugongs given its illegality. Information on informal fisheries is likely to be the most appropriate proxy because opportunistic encounters between dugongs and fishermen are likely to result in a hunting attempt (resource managers of Province Nord and Sud, pers. comm.). The likelihood of a dugong interacting with a fisherman in an area typically increases with the number of dugongs and the number of fishers using gear that catches dugongs (e.g., fishing nets).

I used the approach developed by Grech and Marsh (2008) to rapidly assess the exposure to dugongs from hunting or bycatch in fishing nets at the scale of the lagoons of New Caledonia. I used the spatially-explicit model of dugong distribution and relative density that I developed in Chapter 3 and overlaid it with a layer of local fishing activity zones (i.e., locations of fishing activities using nets) collected from interviews conducted throughout the main island of New Caledonia by a local audit company and compiled by Pilcher *et al.* (2014) see Appendix F Figure F.2. For ease of interpretation, I merged the high and very high dugong relative density classes because very high dugong relative density was detected in only one location (Cap Goulvain). I then binned the fishing activity into three categories based on their frequency distribution: low fishing (no fishing zones drawn), medium fishing (1-3 overlaps in fishing zones), and high fishing (4-10 overlaps in fishing zones). I then intersected the spatially-explicit

model of dugong distribution and relative density with the layer of fishing activity and evaluated the level of exposure of dugongs to hunting and bycatch in fishing nets by qualitatively assessing each dugong relative density class against each the fishing activity categories.

My results suggest that exposure of dugongs to hunting and bycatch in fishing nets occurs mostly on the west coast of New Caledonia and include the Nouméa region, several bays between Boulouparis and Ouano, Cap Goulvain, the Voh-Koné-Pouembout region and Koumac (Figure 6.1 and 6.2). On the east coast, the only area of high exposure of dugongs to hunting and bycatch in fishing nets is likely to be in front of Pouebo. These 'hotspots' should be a priority for conservation action to mitigate the risk to dugongs from hunting and fishing. The assessment I conducted could be refined if more data on hunting and fishing become available.
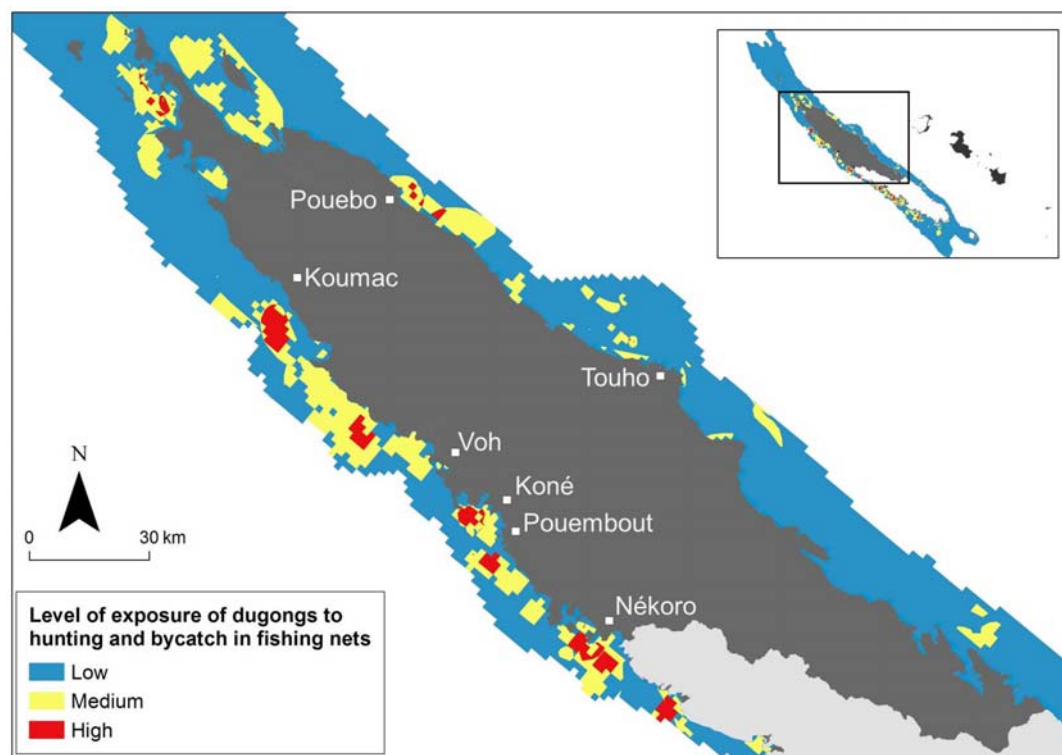
Figure 6.1: Spatial assessment of the exposure of dugongs to hunting and fisheries bycatch in fishing nets in Province Nord based on: (1) the spatially-explicit model of dugong distribution and relative density obtained from the time series of aerial surveys conducted in New Caledonia (Chapter 3); and (2) the layer of fishing activity compiled by Pilcher *et al.* (2014). Note that this map shows Province Nord only to assist in visual representation of the results. As explained in this chapter, management of the risks to dugongs should be developed at multiple spatial scales including cross-jurisdictional scale.
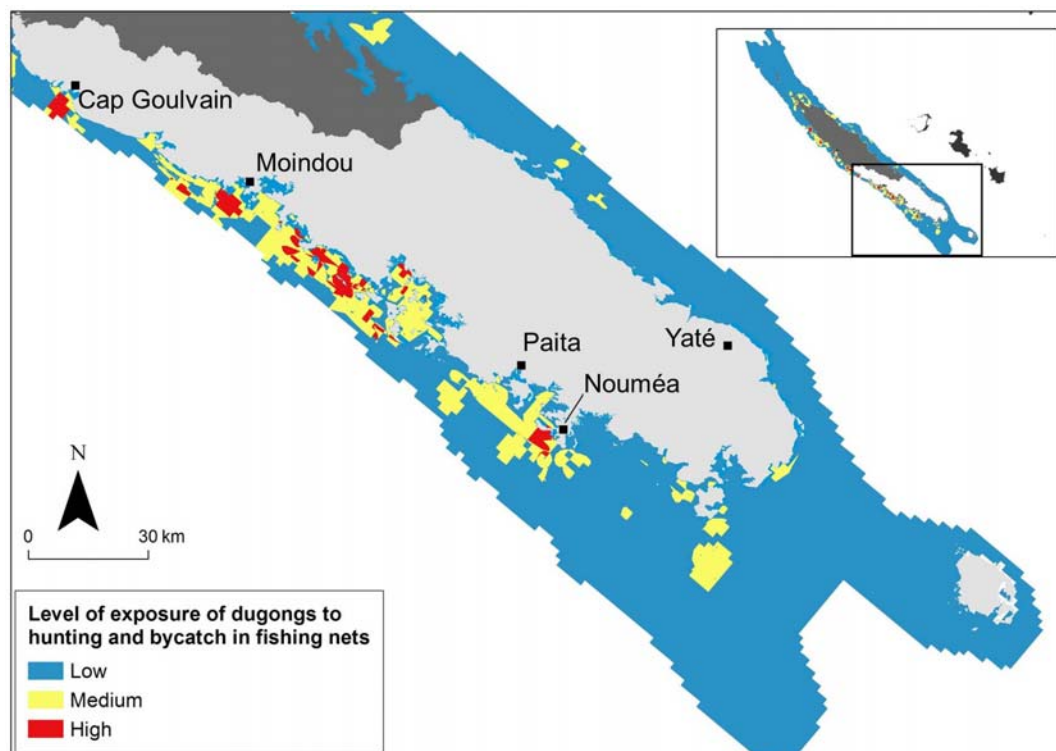
Figure 6.2: Spatial assessment of the exposure of dugongs to hunting and fisheries bycatch in fishing nets in Province Sud based on: (1) the spatially-explicit model of dugong distribution and relative density obtained from the time series of aerial surveys conducted in New Caledonia (Chapter 3); and (2) the layer of fishing activity compiled by Pilcher *et al.* (2014). Note that this map shows Province Sud only to assist in visual representation of the results. As explained in this chapter, management of the risks to dugongs should be developed at multiple spatial scales including cross-jurisdictional scale.

Risk to dugongs from boat strike

Although dugong deaths from vessel strike occur in many range states including Australia, Thailand, Malaysia and New Caledonia (Marsh *et al.* 2012), the hazard is mainly confined to areas close to ports, especially where both dugongs and vessels occur in high density and in shallow waters (typically < 5m), which constrain the animal's capacity for vessel avoidance (Maitland *et al.* 2006; Hodgson and Marsh 2007). The limited data available suggest that the risk of collision between dugongs and vessels is positively correlated with vessel speed. Hodgson (2004) provided qualitative evidence that dugongs have a greater opportunity to avoid vessels travelling below planning speed. Slower boat speeds also significantly reduce the risk of

boat strike for Florida manatees (Glaser and Reynolds 2003; Laist and Shaw 2006; Calleson and Frohlich 2007).

Transit lanes that by-pass shallow areas of high dugong density or Go-Slow zones where speed limits apply have been used to reduce the risk of vessel strike. In New Caledonia, stranding information collected between 2004 and 2008 and interviews with local stakeholders confirmed that collisions between dugongs and boats occur in the urban region of Nouméa but have been avoided in Voh-Koné-Pouembout (ESCAL and A2EP 2011). I identified the areas where dugongs are most at risk from vessel collision based on two criteria: dugong density and bathymetry. I focused on two regions where boat traffic is intense: the Nouméa and the Voh-Koné-Pouembout regions. Given the lack of information on the intensity of vessel traffic at adequate spatial scales (although see Jollit *et al.* 2010), I simplistically assumed that boating activity was constant across each region. I assumed that dugongs had fewer escape options in shallow areas (< 5m at low tide).

Exploratory analysis showed that there are no shallow water areas supporting high dugong relative densities in the Voh-Koné-Pouembout region, a plausible explanation for the apparent absence of dugong vessel strikes. I therefore focused my analysis on the Nouméa region, intersecting the spatially-explicit model of dugong distribution and relative density that I developed in Chapter 3 with a bathymetric layer (Lefevre *et al.* unpublished). I then identified the sites that encompassed over 95% of areas where dugongs occur in high densities over shallow areas as candidate Go-Slow zones: adjacent to the shore and city of Nouméa; between Maître Islet, Sèche Croissant Reef Cay, and Larégnère Reef; and north of Nouméa around the Mba Islet (Figure 6.3).
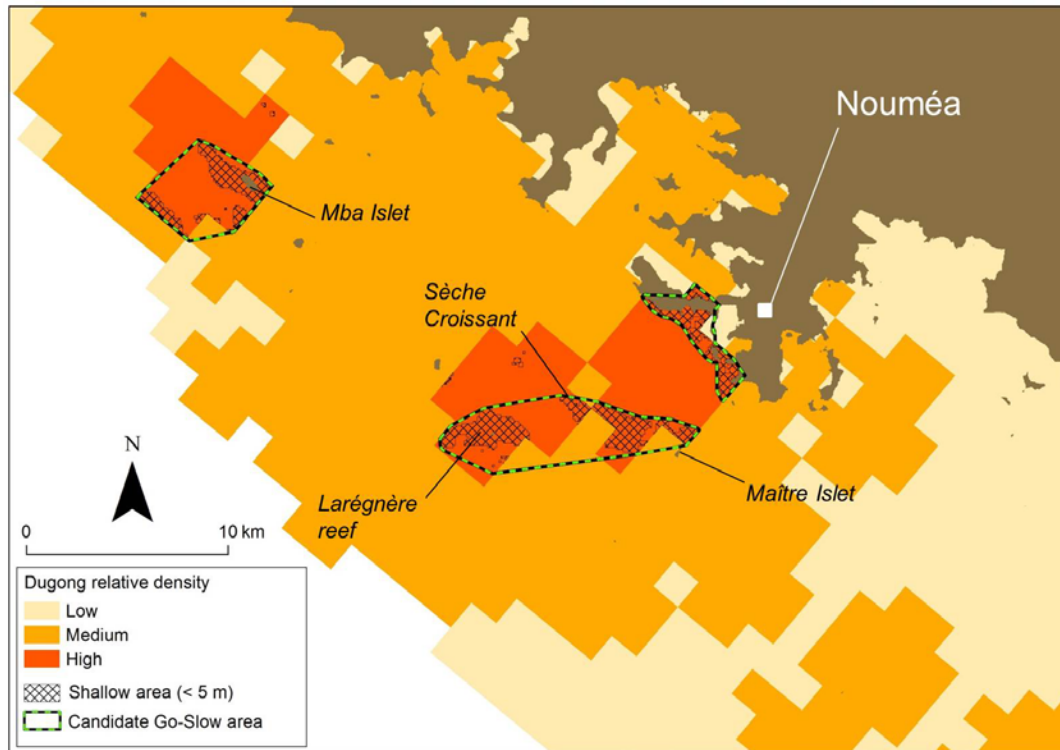
Figure 6.3: Suggested candidate Go-Slow zones to reduce the risk to dugongs from vessel collision in the Nouméa region based on: (1) the spatially-explicit model of dugong distribution and relative density obtained from the time series of aerial surveys conducted in New Caledonia (Chapter 3); and (2) bathymetry (Lefevre *et al.* unpublished).

Legislation and compliance

One of the primary goals of the Dugong Action Plan for New Caledonia is to increase awareness that dugong hunting is illegal. An enlarged Dugong Action Plan (DAP) Committee which includes teachers and local associations for environmental education is currently focusing on this issue. Funding has been allocated and the enlarged committee is currently developing culturally appropriate outreach materials (e.g., TV advertisements, calendars with drawings from schools kids, educational books). Nonetheless, a recent social survey conducted in the north-east and in the mid-west coastal regions of New Caledonia indicates that people are aware that killing a dugong in New Caledonia without a valid permit is against the law (Dupont 2015). In the conservation context, non-compliance is common; it is one of the largest illegal activities in the world, degrading social, environmental and economic goals (Haken 2011). Thus, understanding and managing compliance is key for ensuring effective conservation of natural resources. Social surveys are the simplest method of studying compliance, but the responses are likely to be biased because non-compliance is perceived as clandestine behaviour and the likelihood of deceitful responses is high. Methods for studying compliance have recently been reviewed by Arias (2015). These methods should be investigated along with understanding fundamental cultural values and changing those values and consequent behaviour, to enhance understanding of non-compliance with dugong hunting regulations in New Caledonia with a view to implementing them more effectively.

Environmental regulations are difficult to implement in New Caledonia (Sourisseau *et al.* 2010). The division of responsibilities between the French government, the government of New Caledonia, and the provinces is one of the factors that impede the effective application of regulations. For example, marine fisheries and coastal MPA regulations are the responsibility of the provincial authorities but the New Caledonia government is in charge of monitoring and enforcement. Patrolling and enforcement are weak because the provinces have limited capacity to control human activities at the spatial scale of the large lagoons of New Caledonia. The challenge is for local authorities to work out an effective way enforcing environmental laws in New Caledonia. Allocating sufficient funding and staffing to ensure that existing laws are enforced will be critical.

Dugong population monitoring

As discussed in Chapter 2, detecting trends in dugong and other marine mammal species abundance in a management time frame when animals occur at low densities is very difficult unless changes are very large (Taylor and Gerrodette 1993; Marsh 1995; Taylor *et al.* 2007).

Nonetheless, dugong aerial surveys in New Caledonia have been very useful to show that there was no seasonal effect in the dugong population size estimates (Chapter 2) and for identifying important dugong habitats (Chapter 3). Continuing to conduct regular aerial surveys for dugongs in New Caledonia will allow spatial and temporal changes in the important dugong habitats in the region to be monitored. It will be important to reach agreement about the optimum time between surveys and the timing of the surveys based on: (1) power analysis of their capacity to detect trends (Gerrodette 1987); (2) the need to retain corporate memory of the methodology; (3) the lessons from my experience and analysis (Chapter 2).

Given the uncertainties that remain in the dugong relative abundance estimates and the lack of robust information on the number of dugongs killed by anthropogenic activities in New Caledonia, it is difficult to conclude whether this level or removal of dugongs is sustainable or not. A comprehensive record of dugong mortality in New Caledonia could help to identify areas where conservation should be prioritized and enable the relative importance of the various causes of anthropogenic mortality to be estimated. This approach will be very difficult to implement given that most hunting is illegal. However, involving local communities in a stranding network across New Caledonia should be logistically possible and more widely acceptable than monitoring mortality *per se*, and have the added advantage of increasing understanding of the demography and biology of other marine mammals and marine turtles in the region.

6.4 Future research on dugong and seagrass ecology

Mapping subtidal seagrasses

Seagrass habitats are reported to be declining worldwide (Waycott *et al.* 2009). Various anthropogenic activities potentially harm seagrasses: dredging, coastal development, damage associated with over exploitation of coastal resources, recreational boating activities and nutrient and sediment loading from adjacent land catchments (Cambridge and McComb 1984; Short and Wyllie-Echeverria 1996; Coles *et al.* 2003; Orth *et al.* 2006; Waycott *et al.* 2009). In New Caledonia, the increase in coastal human population density and resource developments in mining and agriculture, especially on the west coast is inevitably placing pressures on the adjacent marine environment and seagrass ecosystems (Hily *et al.* 2010). Local resource managers in New Caledonia are aware of the importance of seagrasses to the maintenance of

coastal ecosystems and they have classified seagrasses as an 'Ecosystem Heritage' (Province Nord 2008; Province Sud 2009).

The shallow seagrasses (< 5m) of New Caledonia have been mapped using remote sensing (Andréfouët *et al.* 2010). I used this map in Chapters 4 and 5 to provide an indication of the use of shallow seagrass meadows by dugongs at different spatial scales in New Caledonia. The resolution and information provided by the map of seagrass I used is not appropriate for fine-scale analysis of the seagrass use by dugongs in New Caledonia. Although seagrasses present in waters deeper than five metres are unlikely to occur at high density (Hily *et al.* 2010), they may be used by dugongs when intertidal seagrass are unavailable. Australian studies show that dugongs also routinely use subtidal seagrass habitats (Holley *et al.* 2006; Sheppard *et al.* 2007, 2009), a result concordant with my tracking data. Locating and protecting seagrass habitats that are important to dugongs is critical to the maintenance of both. The spatially-explicit model of dugong distribution and relative density I developed in Chapter 3, the dugong movements and home-range analysis conducted in Chapter 4, and the local seasonal and tidal use of habitats in Cap Goulvain (Chapter 5) provide an excellent basis for using dugongs as indicators to design a program to map the distribution of subtidal seagrasses in the lagoons of New Caledonia for subsequent ground-truthing as was done in the Northern Great Barrier Reef and Torres Strait in Australia (Helene Marsh pers. comm.). An accurate map of the subtidal seagrasses in the lagoons of New Caledonia combined with dugong telemetry data could improve the evidence-base for conserving dugongs and their seagrass habitat in this region. For example seagrass maps in the south-west lagoon near Nouméa could be developed using multibeam sonars and supporting ground-truth data (e.g., Kenny *et al.* 2003; Komatsu *et al.* 2003).

Knowledge on the nutritional ecology of herbivores is central to understanding their activity patterns, demography, and distribution (Choat and Clements 1998). The diet of sirenians has traditionally been studied through gut, mouth, and faeces content analysis (see Marsh *et al.* 2012 for review). These methods provide snapshots of the food recently eaten by individual sirenians. Measurement of the ratio of stable isotopes from various tissues can provide information on the average dietary intake of individuals over a long period of time and has been used in Florida manatees (Alves-Stanley and Worthy 2009; Alves-Stanley *et al.* 2010). In New Caledonia, there are few opportunities to collect dugong stomach contents (Claire Garrigue pers. comm.). Nonetheless, the collection of soft tissues is now substantial and could be used in isotopic analyses to provide information on the food selection of dugongs in New Caledonia.

Christophe Cleguer

Dugong spatial ecology

In Chapter 4, I provided insights into the movement heterogeneity and home-range of dugongs in the lagoons of New Caledonia. The inferences from my study are limited by sample size and time of tracking (i.e., warm season). A complementary study could determine whether dugongs use space differently during the cool season. For example, tracking dugongs at the start of the cool season in Cap Goulvain could improve understanding of how individual dugongs commute across habitats in this region and provide further evidence to evaluate the behavioural thermoregulation hypothesis suggested in Chapter 5. Tagging more dugongs in Cap Goulvain or other regions where the lagoon is narrow would also provide further information on the use of the fore reef shelf as a resting as well as a transiting platform.

The Quick Fix Pseudo Ranging (QFP) technology enabled me to identify previously unknown movement corridors used by dugongs to commute between bays. Such information is difficult to obtain from aerial surveys and provides supplementary information relevant to the conservation of important dugong habitats. Tracking more dugongs with QFP technology could reveal dugong movement corridors of dugongs in other regions. For example, the development of a mining complex in the Voh-Koné-Pouembout region is resulting in significant human and economic developments; and fishing pressure on local reef fish resources is likely to increase (Guillemot *et al.* 2009). Fine-scale data on the movement patterns of dugongs in this region could inform local spatial management actions (e.g., implementation of netting closures in areas intensively used by dugongs). In the Nouméa region, my tracking information is based on only three dugongs, one of which was tracked for only three days. Inferences about the dugongs' use of space in the Nouméa region would be stronger if more dugongs were tracked.

6.5   Collaborative research

My dugong satellite tracking study provided an opportunity to collect skin and faeces samples across different regions. These samples have been used by Oremus *et al.* (2015) to conduct a study on the conservation genetics and evolutionary history of dugongs in New Caledonia.

I deployed time depth recorders (TDRs, MK9 Wildlife Computers) on the 12 dugongs I captured in New Caledonia. Nine recorders were retrieved and are now being used by Dr Rie Hagihara, from James Cook University to explore the dive patterns of the dugongs tracked in New Caledonia with a view to improving the estimates of dugong population size estimates in the region.

6.6   Concluding remarks

In New Caledonia, the management of the dugong population has been hampered by a lack of scientific information. My research tackled this issue by providing an evidence-base for the conservation and management of dugongs in New Caledonia at several spatial and temporal scales. Future research should be directed at understanding why illegal hunting occurs in New Caledonia and how compliance with the law could be increased. Further investigating the fine-scale interaction between seagrasses and dugongs in New Caledonia would also greatly enhance our understanding of dugong and seagrass ecology in tropical lagoons and coral reefs more generically.

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Appendix A

Table A.1: Details of the survey design used for the dugong relative abundance and density analysis.

Block	Area covered (km^2)	Distance between transects (NM)		Sampling Intensity (%)		Number of transects surveyed	
		Jun 2003-Jan 2008	Jun & Nov 2011-2012	Jun 2003-Jan 2008	Jun & Nov 2011-2012	Jun 2003-Jan 2008	Jun & Nov 2011-2012
1	1841	2.50	2.50	16.04	16.82	22	22
2	1300	2.50	1.25	16.92	34.00	32	63
3	1948	2.50	2.50	15.92	16.88	24	24
4	1749	2.50	2.50	15.23	17.35	23	23
Total	6838	-	-	-	-	101	132

Table A.2: Availability probability estimates (SEs) for various strata of survey depths and turbidities calculated from data on artificial dugong models and the individual dive profiles of telemetered wild dugongs. (Extracted from Pollock et al. 2006).

Water quality	Depth range	Visibility of sea floor	Maximum depth of visibility of models[a] (m)	Depth zone of visibility (m)[b] to calculate p_a	p_a (SE)
Optimal sea state					
Clear	Shallow	Clearly visible	Bottom	All	1
Variable	Variable	Visible but unclear	2.44	2.5	0.65 (0.0452)
Clear	>5m	Not visible	4.32	4.0	0.46[d] (0.057)
Turbid	Variable	Not visible	1.23	1.5[c]	0.47 (0.0525)
Marginal sea state					
Clear	Shallow	Clearly visible	Bottom	Bottom	1
Variable	Variable	Visible but unclear	1.21	1.5[c]	0.47 (0.0525)
Clear	>5m	Not visible	0.69	1.5[c]	0.30[d] (0.0724)
Turbid	Variable	Not visible	1.43	1.5[c]	0.47 (0.0525)

[a] Average for models 2.0 and 2.5 m long.
[b] Maximum depth used to calculate p_a from the telemetered animals.
[c] Based on minimum dive depth detectable on 15 telemetered wild dugongs. (See text for explanation.)
[d] Based on records from 4 dugongs with mean, median, and modal maximum dives of >6 m and a corresponding subset of the data from 1 dugong that spent considerable time in water >5 m deep. (See text for explanation.)

Table A.3: Details of the number and proportion of transects for which no dugongs have been sighted in any surveys in New Caledonia for the four blocks used in the dugong relative abundance and density analysis.

Number of occasions a zero value was recorded	Number of transects	Percentage (%)
1	9	6.8
2	11	8.3
3	24	18.2
4	36	27.3
5	24	18.2
6	28	21.2
Total	**132**	-

Table A.4: Comparison of the standardized estimates of dugong relative abundance and standard errors (±SE) obtained using the Pollock *et al.* (2006) methodology for the dugong aerial surveys conducted in New Caledonia between 2003 and 2012. Details of the counts of dugong groups, individual dugongs, dugong per transect, and calf sightings are also included.

	Block	Survey year					
		Jun 2003	Jan 2008	Jun 2011	Nov 2012	Jun 2012	Nov 2012
No. groups	1	31	20	14	14	18	16
	2	18	3	16	9	16	18
	3	19	4	8	8	16	15
	4	11	7	6	5	7	4
	Total	**79**	**34**	**44**	**36**	**57**	**53**
No. dugongs	1	52	27	14	14	24	16
	2	30	4	26[a]	9	21	26
	3	23	9	14	11	25	18
	4	17	10	7	8	10	4
	Total	**122**	**50**	**61**	**42**	**80**	**64**
No. dugongs	1	2.36	1.23	0.63	0.63	1.10	0.73

	Block	Survey year					
		Jun 2003	**Jan 2008**	**Jun 2011**	**Nov 2012**	**Jun 2012**	**Nov 2012**
per transect	2	0.94	0.12	0.41B	0.14	0.33	0.41
	3	0.96	0.37	0.58	0.46	1.04	0.75
	4	0.74	0.43	0.30	0.35	0.43	0.17
	Total	**1.21**	**0.49**	**0.46**	**0.32**	**0.6**	**0.48**
No. calves (%)[b]	1	3 (5.8%)	3 (11.1%)	0	0	1 (4.2%)	0
	2	1 (3.3%)	0	6 (23.1%)	0	3 (14.3%)	2 (7.7%)
	3	1 (4.3%)	2 (22.2%)	4 (28.6%)	3 (27.3%)	4 (16.0%)	1 (5.6%)
	4	4 (23.5%)	2 (20.0%)	1 (14.3%)	3 (37.5%)	2 (20.0%)	0
	Total	**9 (7.4%)**	**7 (14.0%)**	**11 (18.0%)**	**6 (14.3%)**	**10 (12.5%)**	**3 (4.7%)**
Population estimate (SE)	1	919 (414)	435 (181)	250 (128)	243 (132)	417 (162)	261 (132)
	2	401 (219)	Tfs[c]	220 (82)	75 (56)	203 (74)	225 (83)
	3	380 (223)	Tfs[c]	233 (112)	213 (113)	484 (225)	338 (156)
	4	326 (192)	170 (85)	107 (68)	117 (70)	123 (75)	73 (71)
	Total	**2026 (553)**	**606 (200)**	**881 (201)**	**649 (195)**	**1227 (296)**	**898 (231)**
Coefficient of variation		**0.27**	**0.33**	**0.24**	**0.30**	**0.25**	**0.22**

[a] In addition, one herd of 69 dugongs (including 5 calves) was sighted and added to the final population estimate as explained in chapter 2.

[b] Excluding calves sighted in herds,

[c] too few sightings to estimate dugong abundance (< 5 dugong group sightings).

Table A.5: Details of group sizes of dugongs sighted during the aerial surveys conducted between 2003 and 2012 in New Caledonia and used for the dugong relative abundance and density analysis.

Dugong group size	Block	Survey year					
		Jun 2003	**Jan 2008**	**Jun 2011**	**Nov 2011**	**Jun 2012**	**Nov 2012**
Mean	1	1.7	1.4	1	1	1.3	1
Median		1	1	1	1	1	1

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Max		5	3	1	1	4	1
Mean		1.7	1.3	1.6[a]	1	1.3	1.4
Median	2	1	1	1	1	1	1
Max		7	2	4	1	2	5
Mean		1.2	2.3	1.8	1.4	1.6	1.2
Median	3	1	1.5	1	1.5	1	1
Max		3	5	4	2	3	3
Mean		1.5	1.4	1.2	1.6	1.4	1
Median	4	1	1	1	1	1	2
Max		3	2	2	2	4	1

[a] Dugong herd of 69 individuals excluded from the table.

Table A.6: Count (A) and zero-inflation (B) model coefficients with Negative Binomial distribution of dugong relative density across survey years and blocks. The reference level for year is 2003 and 1 for block.

(A) Count model coefficients					
	Estimates	**Std. Error**	**Z value**	**Pr(> |z|)**	**Sig.**
(Intercept)	-0.5009	0.1864	-2.687	0.00721	**b
year2008	-0.5431	0.2496	-2.176	0.02959	*
year2011	-0.8622	0.2132	-4.043	5.27E-05	***
year2012	-0.7409	0.204	-3.633	0.00028	***
block2	0.6623	0.218	3.038	0.00238	**
block3	0.3827	0.1921	1.992	0.04637	*
block4	-0.2597	0.2173	-1.195	0.23207	
(B) Zero-inflation model coefficient					
	Estimates	**Std. Error**	**Z value**	**Pr(> |z|)**	**Sig.**
(Intercept)	-3.23253	0.34439	-9.386	< 2e-16	***
year2008	0.47777	0.36533	1.308	0.190947	
year2011	0.44278	0.32027	1.383	0.166815	

year2012	0.05114	0.31755	0.161	0.872063	
block2	2.61628	0.32954	7.939	2.03E-15	***
block3	1.06889	0.3129	3.416	0.000635	***
block4	1.21574	0.35717	3.404	0.000664	***

[a] estimated from corrected counts with area of transect as an offset

[b] significance codes: < 0.001 = ***; 0.001 to < 0.01 = ** ;0.01 to $\leq$ 0.05 = *

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Table A.7: Results of (A) log-linear analysis and (B) general linear hypotheses and multiple comparisons to compare the interactions between blocks in the proportion of dugong calves.

A				
	Estimate	**Std. Error**	**z value**	**Pr(> |z|)**
(Intercept)	-2.6295	0.5008	-5.25	< 0.0001
block2	0.8749	0.4908	1.783	0.087461
block3	1.2925	0.4684	2.76	< 0.01
block4	1.6645	0.4899	3.398	< 0.001
Jun-03	-0.7586	0.5301	-1.431	0.17295
Jun-11	0.18	0.536	0.336	0.74164
Jun-12	-0.2803	0.5308	-0.528	0.60516
Nov-11	-0.1247	0.5935	-0.21	0.83643
Nov-12	-1.3192	0.7143	-1.847	0.0846

Null deviance: 40.433 on 23 degrees of freedom

Residual deviance: 18.125 on 20 degrees of freedom

B				
2 - 1 = 0	0.8412	0.4923	1.709	0.31729
3 - 1 = 0	1.2701	0.4772	2.662	< 0.05
4 - 1 = 0	1.7104	0.505	3.387	< 0.01
3 - 2 = 0	0.4288	0.4128	1.039	0.72519
4 - 2 = 0	0.8692	0.4446	1.955	0.20402
4 - 3 = 0	0.4403	0.4278	1.029	0.73096

Table A.8: Results of log-linear model developed to analyze the relationship between the proportion of dugong sightings and water depth categories and survey year during the time series of dugong aerial surveys in New Caledonia.

Analysis of deviance	Df	Deviance	Residual Df	Residual Deviance	Pr (> Chi)
Null			272	471.84	
Year	5	15.702	267	456.14	0.06231
Depth	4	154.074	263	302.07	< 0.0001
Year x Depth	20	21.044	243	281.02	0.82698

Table A.9: Estimated sustainable levels of mortalities from anthropogenic sources for dugongs in New Caledonia.

Date of Survey	Recovery Factor (R.F.)	N	SE	CV	Nmin	Potential Biological Removal (PBR)				
						Rmax =0.01	Rmax =0.02	Rmax =0.03	Rmax =0.04	Rmax =0.05
Jun-03	0.5	2026	553	0.27	1617	4	8	12	16	20
Jan-08	0.5	606	200	0.33	462	1	2	3	5	6
Jun-11	0.5	881	201	0.23	728	2	4	5	7	9
Nov-11	0.5	649	195	0.30	507	1	3	4	5	6
Jun-12	0.5	1227	898	0.24	1005	3	5	8	10	13
Nov-12	0.5	898	231	0.26	724	2	4	5	7	9
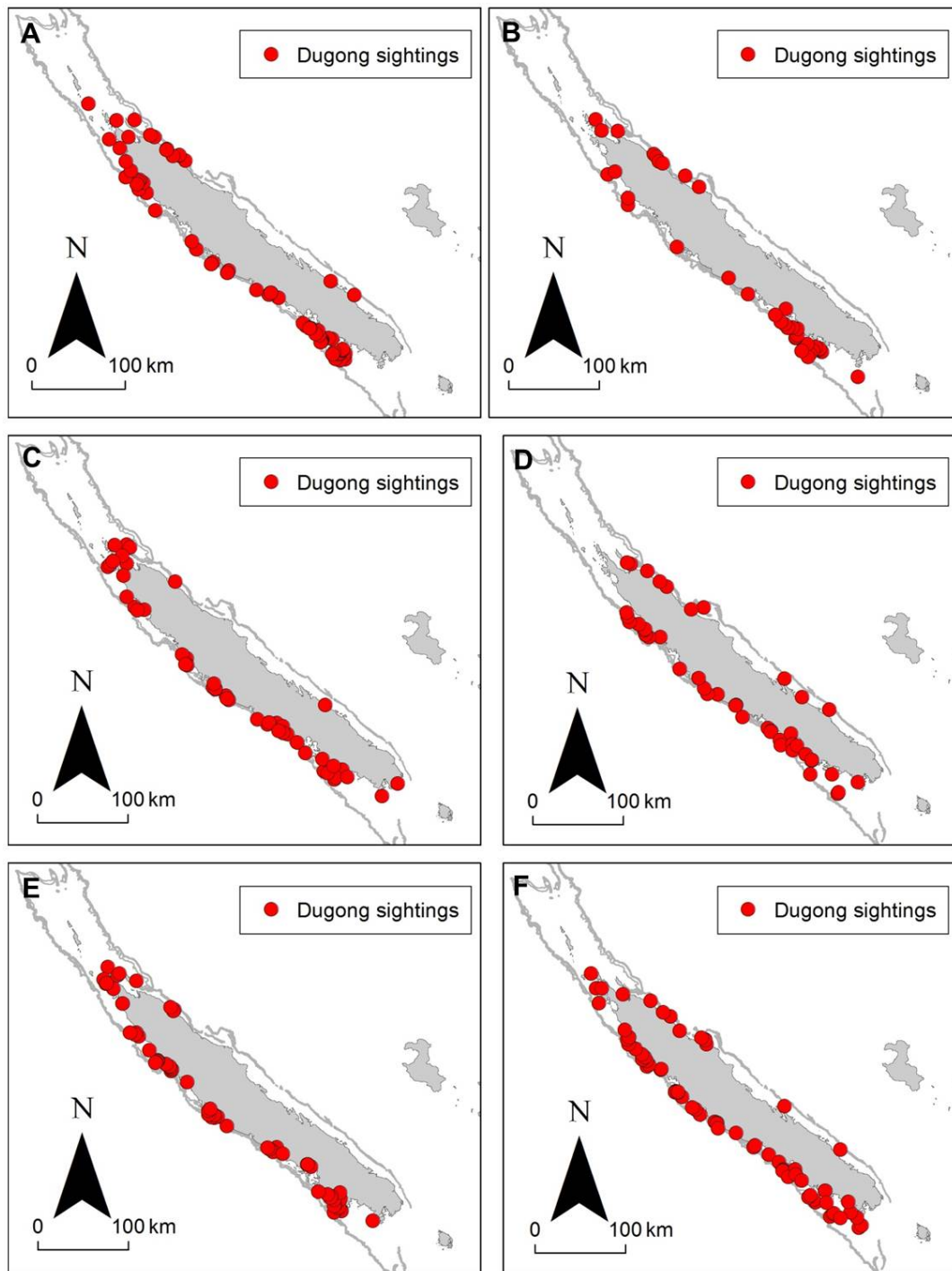
Figure A.1: Map of the raw dugong sightings from the (A) cool season of 2003, (B) warm season of 2008, (C) cool season of 2011, (D) warm season of 2011, (E) cool season of 2012, (F) warm season of 2012.

Appendix B

Satellite tag attachment device for dugong tracking studies

Details of design

Version 1.0, November 2014

Overview

The dugong belt assembly was developed to deploy TMT 462 GPS/ARGOS tags on adult dugongs for tracking purposes. This system allows the tag to float at the water surface when the animal is in shallow waters, increasing the frequency of transmission of signals to passing satellites. The apparatus was developed by Helene Marsh's research group in collaboration with Dr. James Powell (Sea to Shore Alliance, Florida, USA).

The satellite tag is attached to the animal's peduncle near the tail via a three-meter long flexible tether fitted with a padded belt. This belt assembly incorporates: (1) a weak link at the peduncle end of the tether that can be broken by the animal if it becomes entangled in marine obstructions such as coral or mangroves; and (2) a backup corroding link comprised of a zinc bolt in a stainless steel shackle. The weak link breaks when subjected to a force of around 160kg (average adult weight of a dugong is above 300kg and ranges up to 530kg). The breakage point was determined empirically in collaboration with James Cook University engineers. The zinc bolt slowly corrodes in a galvanic reaction in seawater and releases the belt to ensure the satellite tag is eventually detached from the dugong.

Belt

The belt is constructed to prevent any abrasion on the dugong's skin (Figure B.1). The sizes of the belt and silicone tube were determined from field studies and by testing different belt sizes on adult dugongs.
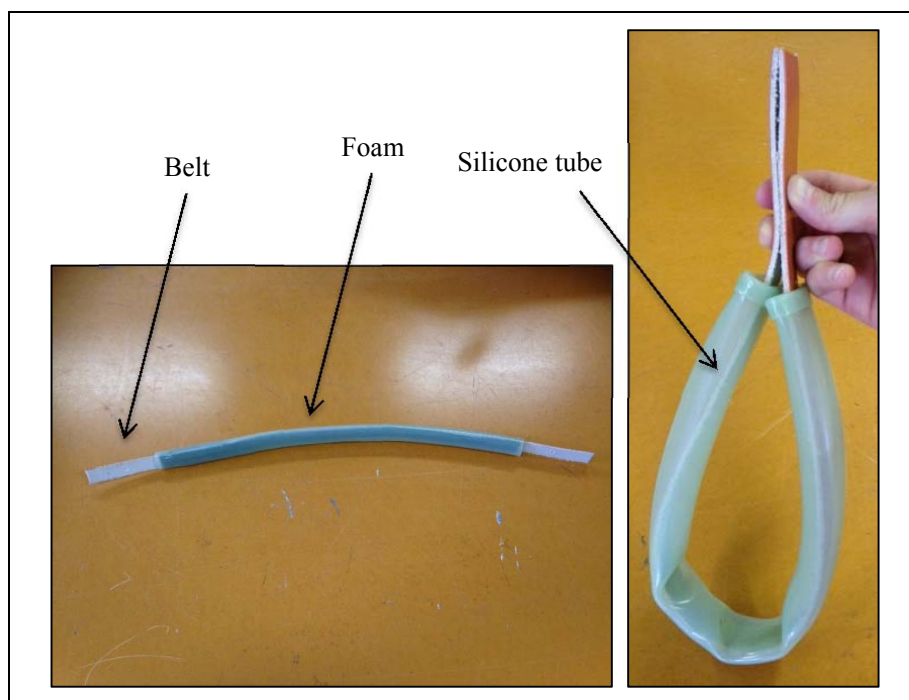
Figure B.1: Belt and silicone tube

The belt is constructed of:

- Machine belting 4mm thick x 23mm wide x 800mm long.
- A strip of foam glued to the belt 23mm wide x 650mm long

Silicone tubing 27mm ID x 30mm OD x 650mm long.

Buckle and corrodible link

The stainless steel buckle (Figure B.2A, B.2B) secures the ends of the belt around the dugong peduncle, which is then fastened in place by the zinc bolt (Figure B.2B, B.2C). This bolt is first hollowed out by a drill then the point is sharpened on a lathe in order to: (1) allow it to cut through the belting as it is tightened into place with a socket wrench until it sits flush with the opposite side of the buckle (Figure B.2D), and (2) help speed up the corrosive reaction. The corrodible link breakpoint timing varies with environmental factors (i.e., water salinity, water

TC) and pressure from the dugong's peduncle. This reaction has taken a minimum of six months to occur in field deployments in Moreton Bay, Australia. After being attached, the buckle is wrapped into a Velcro band to prevent any abrasion onto the dugong's skin (Figure B.2E).
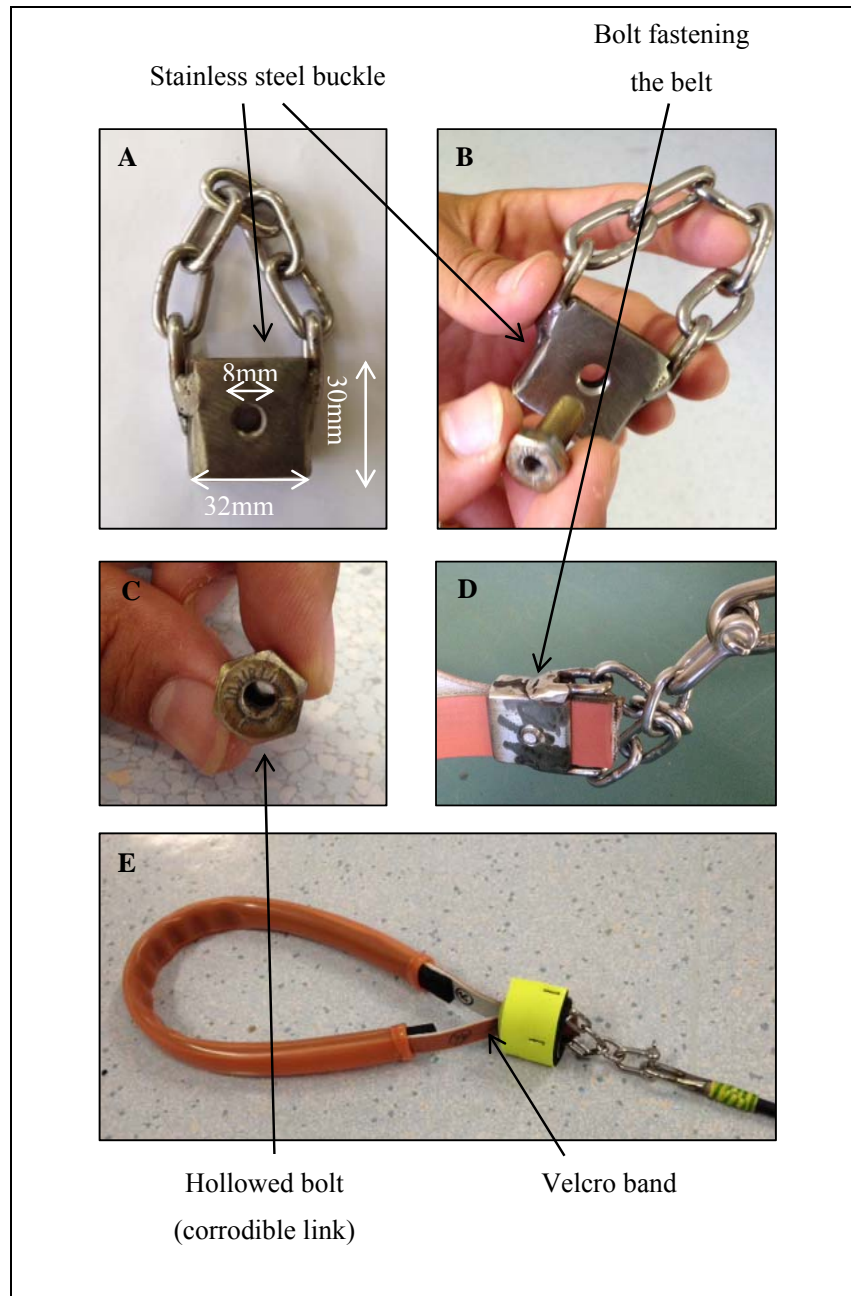
Figure B.2: Stainless steel buckle and corrodible link.

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Joiners, weak link and tether

The tether is an acetal plastic rod (10mm diameter and 3m long). Stainless steel joiners are fastened to each end of the plastic tether using stainless steel blind rivets (3.2mm diameter x 15mm length). These are drilled a minimum of 10mm from the tips of the plastic tether. The peduncle end of the tether incorporates a weak link allowing the dugong to break free if it gets entangled in marine obstructions. The weak link is created by drilling two 9/64*9/64 diameter holes perpendicularly through the tether approximately 20mm from the tip of the belt end of the tether (Figure B.3A). The weak link should be within the stainless steel joiner and not visible. Diameters of the drilled holes determine the strength of the weak link.

The tether is joined to both the satellite tag and the buckle by stainless steel D-shackles (10mm; Figure B.3B). These are firmly tightened in place with a pair of pliers and a small cable tie or stainless steel tie wire to prevent the pin coming loose.
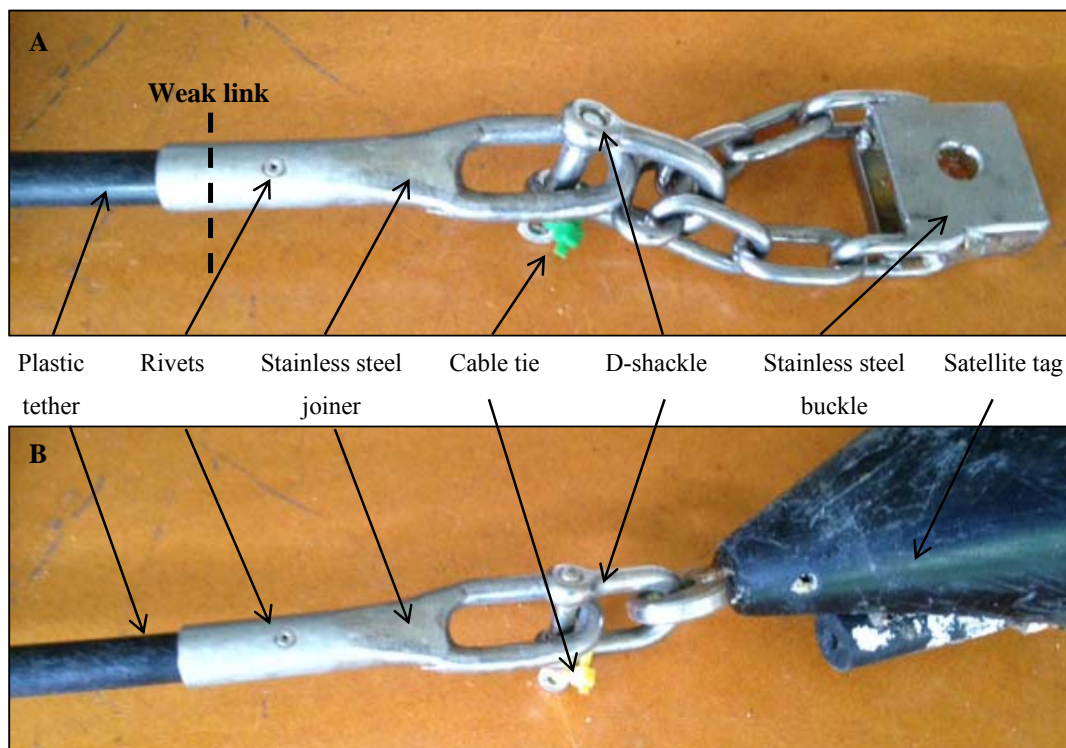
Figure B.3: Joiners and tether

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Appendix C

Dugong (*Dugong dugon*) Monitoring Protocols
for determining pursuit and capture during research

June 2013

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Introduction

The capture of wild sirenia for biological sampling can be a stressful event for the animal involved. These species are at risk of stress-induced morbidity and mortality initiated by pursuit and capture. As such, to minimise risks of adverse events occurring during biological investigations, it is imperative only healthy animals from within the population are sampled and all efforts are made to minimise the restraint period. The caveat to this risk-minimisation strategy is when the sampling of sick or injured animals is required to obtain a disease diagnosis or to provide medical intervention.

The following are external clinical signs for veterinarians and biologists to assess at the start of pursuit to determine whether a dugong should be excluded from capture, requires immediate release during restraint, or requires medical intervention post release. This list is not meant to be exhaustive, rather provide a baseline of indicators that can be developed and further defined for specific locations and environmental conditions.

These clinical signs are used under the assumption the dugong will remain in the water during restraint. For dugongs that are held out of the water during restraint, additional monitoring is required.

Assessment should only be performed by an appropriately qualified veterinarian or senior biologist.

Indicators for exclusion to be assessed at the start of pursuit

Assessment during pursuit should be the first stage of diligence and rapid health assessment.

Biological criteria for exclusion includes:

- Presence of an attendant calf with target animal.
- Target animal is less than 2.2m in length.
- The dugong shows evidence of recent capture (e.g., flagging tape applied to the titanium tag, as is the practice for those caught in Moreton Bay by UQ/ Sea World).

To identify if animals are medically compromised and the cessation of pursuit is required, exclusion criteria should incorporate at least:

- Evidence of overt skin conditions such as lesions, sloughing of skin, hyperkeratosis and depigmentation of the skin;

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- An assessment of body condition including visual estimation of loss of soft tissue mass (predominantly adipose tissue) around the peduncle and neck resulting in the vertebral column appearing more prominent;
- Evidence of abnormal behaviour such as:
  o Accelerated respiration rate
  o Prolonged periods of resting on the bottom of the water column during pursuit and/or
  o Erratic behaviour.

Indicators for immediate release to be assessed during restraint

On capture (restraint), the above criteria should be reassessed by an appropriately qualified veterinarian or senior biologist as the animal is being secured to the vessel. This will minimise the risk of restraining an animal that should have been excluded but was not due to missing indicators during the often-rapid pursuit stage.

In addition, based on ongoing monitoring, restraint should incorporate exclusion criteria of:

- Heart and respiration rates:
  o Heart rate should be between 40-100bpm. Outside of this range is a criterion for release.
  o Development of cardiac arrhythmias.
  o Respiration rate should be between 1-15 breaths every TWO minutes. Outside of this range is a criterion for release.
  o Development of laboured or staccatic respiration.
  o If the heart or breathing stops, this is a medical emergency and veterinary intervention is required immediately.
- Posture:
  o Curling up
  o Lethargy or flaccid (limp- loss of muscle tone) behaviour
  o Inability to maintain buoyancy or position in the water column
- Other key indicators:
  o Muscle tremors
  o Loss of consciousness

Indicators for the need for medical intervention during post-release monitoring

On release, the dugong should be observed to be swimming normally, breathing and actively moving away from the boat until it is out of sight. If there is any evidence of compromise, the

animal should be followed at a safe distance for additional observation with intent and capacity to recapture and administer emergency veterinary care.

Recapture/ further assessment criteria should include:

- Erratic swimming/behaviour or loss of ability to swim away from the boat
- Laboured breathing or signs of difficulty breathing
- Buoyancy disorders (e.g., over inflation of lungs)
- Signs of trauma caused by capture and/or restraint

What if the dugong caught meets the exclusion criteria and is compromised?

If a potentially or confirmed unhealthy dugong is to be caught for treatment or further assessment, in addition to the above considerations, preparations should be made for humane euthanasia and/or transportation by road or sea to an appropriate facility capable of administering triage and medical care.

If the animal is to be returned to the water, the attending veterinarian has a Duty of Care and must make a presumptive diagnosis and, if treatment is required, prescribe appropriately.

All actions on compromised animals should carefully consider all aspects of animal welfare. These decisions should only be made by an appropriately qualified veterinarian or senior biologist.

Checklist

Exclusion criteria for capturing and restraining wild dugong

Red font suggests exclude / veterinary intervention required.

All measurements other than skin condition and body condition should be on-going assessments and therefore multiple records for each criterion should occur for each dugong.

Dugong ID:		**Date:**		**Time:**	
Pursuit					
Biological	< 2.2m long **Y*** N	Attendant Calf **Y** N	Recent tagging **Y** N	
Skin condition	Peeling **Y*** N	Raised **Y** N	Blanched **Y** N	Lesions **Y** N
Body Condition	Peanut head **Y** N	Spine Neck **Y** N	Spine Peduncle **Y** N	
Behaviour	Resp Rate 1-2bpm 3-5bpm **> 5bpm**	Swimming **Resting**	Normal **Abnormal**	
Restraint					
Heart rate	**<40 bpm**	40-100Bpm	**> 100 bpm**	Arrhythmia **Y** N
Respiration Rate	**< 1 per 2 min**	1-15 per 2 min	**> 15 per 2 min**	Laboured **Y** N
Posture	Curling **Y** N	Lethargic **Y** N	Limp **Y** N	Buoyant Y **N**
Other	Tremors **Y** N	Stimuli response Y **N**		
Release					
Behaviour	Swims away Y **N**	Swims straight Y **N**		
Respiration	Laboured **Y** N	Difficulty **Y** N		
Posture	Buoyant Y **N**	Sinking **Y** N	Cannot dive **Y** N	
Trauma	Bleeding **Y** N	Loss of limb use **Y** N		

Appendix D

Table D.1: Number of dugongs observed per habitat, season and tide in Cap Goulvain. Percentages are represented between brackets in the table.

Season	Tide	No. surveys	No. of dugongs observed				
			Fore reef shelf	Channel	Reef flat	Seagrass meadow	Total
Cool	High tide	16	40 (22)	26 (14)	50 (28)	65 (36)	181
	Low tide	17	247 (59)	131 (31)	29 (7)	11 (3)	418
	Total	**33**	**287 (48)**	**157 (26)**	**79 (13)**	**76 (13)**	**599**
Warm	High tide	15	0 (0)	14 (16)	5 (6)	71 (79)	90
	Low tide	14	3 (4)	60 (73)	19 (23)	0 (0)	82
	Total	**29**	**3 (2)**	**74 (43)**	**24 (14)**	**71 (41)**	**172**
Grand total		**62**	**290 (38)**	**231 (30)**	**103 (13)**	**147 (19)**	**771**

Table D.2: Aerial and underwater video footage of dugong herds over the fore reef shelf in the Cap Goulvain region in New Caledonia.

Source of data	Date	No. video footages	Length of video (hh:mm:ss)	
			Min	Max
Province Sud helicopter patrol video footage	7/07/2011	7	00:00:30	00:05:50
	12/07/2012	4	00:01:15	00:24:03
Province Sud underwater video footage	18/04/2011	1	-	-

Table D.3: Extract of the dugong behavioural focal follow protocol developed by Hodgson (2004). Dugong behavioural category and specific behaviour identified from the dugong herds filmed over the fore reef shelf in the Cap Goulvain region are written in bold and italic.

Behavioural category	Specific behaviour			
Feeding	• Horizontal	• At angle	• With plumes	• *Suckling*
Travelling	• Slow	• Cruising	• Fast	• Attempted surface
	• Follow mother	• Halt	• Back track	• Abrupt flee
	• Circling novel stimuli	• Follow on mother's back		
Resting	• *At surface*	• *Mid-water column*	• On substrate	• *On mother's back*
	• *At mother's side*			
Socialising	• Approach	• Rapid approach	• Follow	• Herding
	• *Swim away*	• *Swim away fast*	• Abrupt flee from other	• *Join*
	• Tail swipe sideways	• Tail raised	• Tail swipe raised	• Tail swipe with flip
	• Tails touch	• Swim over	• *Close pass by*	• Note to tail
	• Nose to tail push	• Nose to nose	• Nose to side	• Nose to side push
	• Body rub	• Receiving body rub	• Attempted mount	• Calf retrieval
	• Over back retreat	• Spurt		
Rolling	• Full roll on substrate	• Half roll on substrate	• Full roll mid-water	• *Half roll mid-water*
	• Front rub	• Tail push		
Surfacing	• *Surface*	• *Almost synchronised surface with other individual or mother*	• *Exactly synchronised surface with other individual or mother*	• *Over back surface during ascent or descent or both*

Table D.4: Probability of seeing at least one dugong herd inside and outside the lagoon in across tides in the Cap Goulvain region obtained directly from the dugong sighting data.

		Low	Flood	High	Ebb
Probability of seeing at least one dugong herd	Inside the lagoon	0.17	0.00	0.03	0.00
No. of flights		30	1	29	2
Probability of seeing at least one dugong herd	Outside the lagoon	0.21	0.38	0.12	0.31
No. of flights		34	13	43	13

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Table D.5: Details of dugong herd observations in the Cap Goulvain region in New Caledonia.

Source of data	Date (dd/mm/yyyy)	Habitat type	Time of observation (hh:mm:ss)	Tide	No. dugong herds sighted	Herd size	Presence of shark (Group size)	Location of shark sighting
Dedicated transect surveys	23/03/2012	Reef flat	14:40:59	Low	1	15	No	-
	14/05/2012[1]	Fore reef shelf	09:21:24	Low	1	57	No	-
	14/05/2012[1]	Fore reef shelf	15:09:15	High	1	20	Yes (2)	Reef flat
	29/07/2012	Fore reef shelf	08:49:06	Ebb	1	16	No	-
	13/08/2012	Fore reef shelf	11:21:13	Low	1	32	No	-
	27/08/2012	Fore reef shelf	12:31:40	Low	1	11	No	-
	25/09/2012	Channel	09:37:47	Low	1	10	No	-
	25/10/2012	Channel	10:35:15	Low	1	17	No	-
	13/11/2012	Seagrass meadow[b]	07:39:29	High	1	10	No	-
	22/01/2013	Channel	10:56:20	Low	1	16	Yes (1)	Reef flat
	03/06/2013	Fore reef shelf	10:37:57	Low	1	33	No	-
	27/06/2013	Fore reef shelf	16:30:15	Low	2	10 & 11	Yes (1)	Seagrass meadow
	24/07/2013	Fore reef shelf	14:49:15	Low	1	40	No	-
	22/08/2013	Channel	15:09:43	Low	1	11	Yes (1)	Seagrass meadow

Source of data	Date (dd/mm/yyyy)	Habitat type	Time of observation (hh:mm:ss)	Tide	No. dugong herds sighted	Herd size	Presence of shark (Group size)	Location of shark sighting
Transiting flights	1/07/2003	Fore reef shelf	09:48:00	High	1	45	No	-
	23/04/2004		10:44:32	High	1	16	No	-
	27/05/2008		10:35:20	Flood	2	66 & 10	No	-
	02/07/2008		10:47:42	Ebb	1	50	No	-
	03/09/2008		11:20:59	Ebb	2	10 & 30	No	-
	20/04/2009[a]		10:24:51	Low	1	20	No	-
	20/04/2009[a]		13:45:39	Flood	1	11	No	-
	29/05/2009[a]		07:36:45	Flood	1	12	No	-
	29/05/2009[a]		11:05:22	High	1	≥ 70	No	-
	07/07/2009[a]		07:36:37	High	2	12 & 11	No	-
	07/07/2009[a]		11:00:06	Ebb	3	15 & 11 & 19	No	-
	22/06/2011		09:58:11	Flood	1	69	No	-
	30/07/2013		09:08:05	Flood	1	30	No	-

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Source of data	Date (dd/mm/yyyy)	Habitat type	Time of observation (hh:mm:ss)	Tide	No. dugong herds sighted	Herd size	Presence of shark (Group size)	Location of shark sighting
Province Sud helicopter patrol video footage	07/07/2011	Fore reef shelf	Unknown	-	2	17 & 51	No	-
	12/07/2012		Unknown	-	1	≥ 28	No	-
Province Sud underwater video footage	18/04/2011		10:00:00	Low	1	Un-known	No	-

[a] Another dugong herd was sighted on the same day but at a different stage of the tide.

[b] The only dugong herd observed on the seagrass meadow was characterised as a feeding herd creating sediment plumes.

Table D.6: Results of Analysis of Deviance for log-linear model with Poisson distribution and log link function. Response was the total number of dugongs counted per survey.

|	Df	Deviance Res	Df Resid.	sid. Dev	Pr(> Chi)
NULL			19	1306.59	
tide	1	69.05	18	1237.54	< 0.0001
season	1	273.43	17	964.11	< 0.0001
habitat	4	380.01	13	584.1	< 0.0001
tide:season	1	35.17	12	548.93	< 0.0001
tide:habitat	4	372.68	8	176.25	< 0.0001
season:habitat	4	107.7	4	68.54	< 0.0001
tide:season:habitat	4	68.54	0	0	< 0.0001

Appendix E

*Aerial and underwater footage of dugong aggregations on the fore reef shelf in Cap Goulvain, New Caledonia*

Included as DVD in hard copy of the thesis and provided as a separate file for e-thesis users.

Appendix F
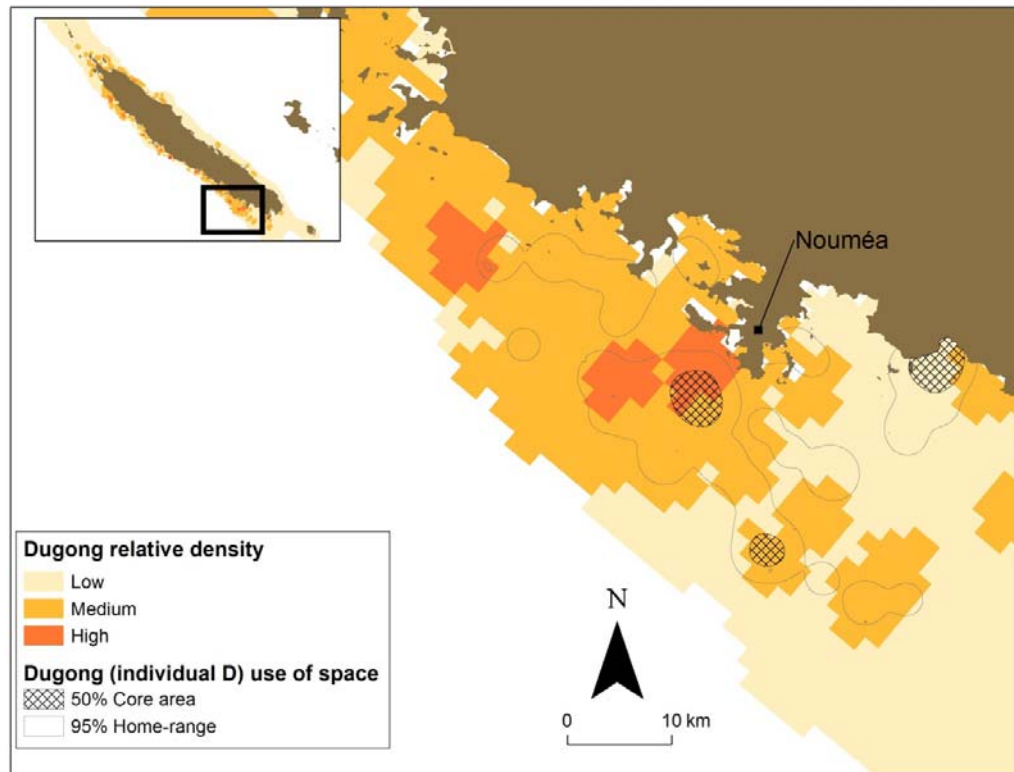
Figure F.1: Close-up of the Nouméa region in New Caledonia showing the spatially-explicit model of dugong distribution and relative density based on aerial survey data of nearly 10 years, overlaid with the 95% home range and 50% core area of a dugong (individual D) satellite tracked over 13 days in this region. The space used by the tracked dugong globally matched with the important dugong habitats identified using the spatially-explicit model of dugong distribution and relative density.
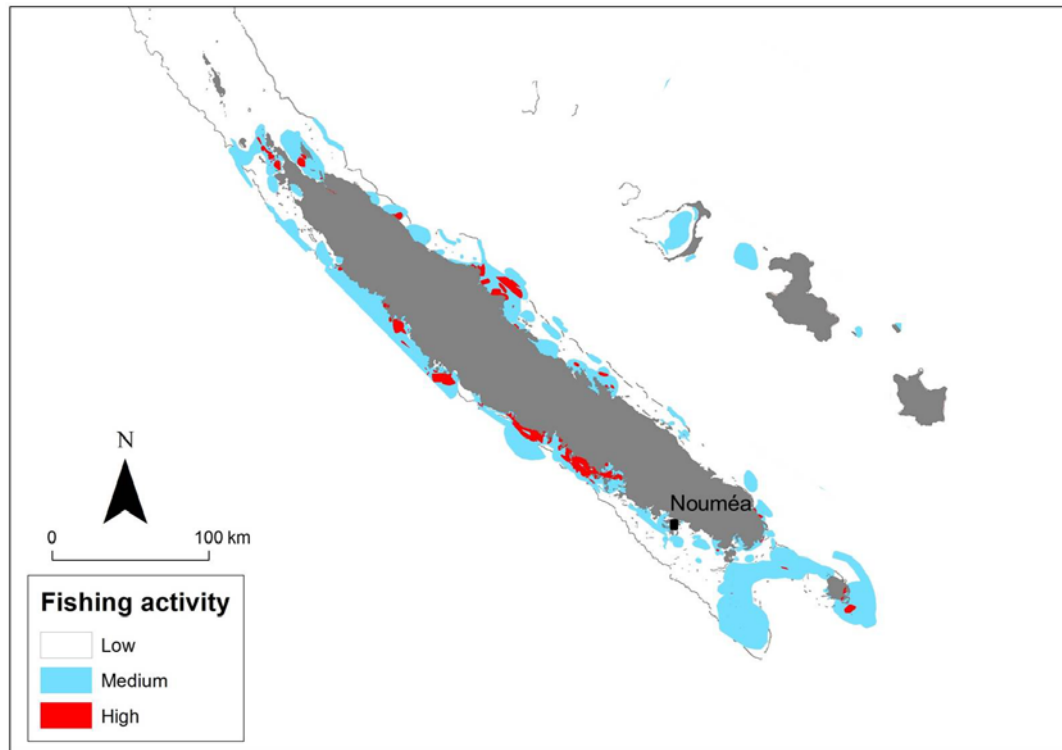
Figure F.2: Fishing activity collected from interviews conducted throughout the main island of New Caledonia by a local audit company and compiled by Pilcher *et al.* (2014). Fishing activity was binned into three categories based on their frequency distribution: low fishing (no fishing zones drawn), medium fishing (1-3 overlaps in fishing zones), high fishing (4-10 overlaps in fishing zones).