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By

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Abstract

The Nassau grouper, *Epinephelus striatus*, was once an important commercial fish species in the Caribbean, but is now considered commercially extinct throughout its range. Protection measures have included protection of adults via seasonal closures and spawning aggregation site reserves (SASRs). Marine protected areas (MPAs) are a promising fisheries management tool being used increasingly worldwide but are not specifically directed at the conservation of Nassau grouper. This thesis uses Belize as a case study location to determine how the established MPA network may contribute towards its protection. It was found that the Belize MPA network as a system may not contribute greatly, however, on an individual basis some MPAs contribute more to protection than others. Those MPAs which have characteristics most suitable for this species are Gladden Spit and Silk Cayes, Sapodilla Cayes, Bacalar Chico, Glovers Reef, Hol Chan, and South Water Caye Marine Reserves.

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1.0 Introduction

A number of key papers have highlighted the decline in global fishery resources (Pauly et al. 1998; Hutchings 2000; Jackson et al. 2001; Myers and Worm 2003; Pauly 2009) and the need to improve fishery management practices is evident with the collapses in commercial fish stocks that have occurred due to overfishing: e.g., the Atlantic cod, *Gadus morhua* (Hutchings and Myers 1994), the Atlantic blue fin tuna, *Thunnus thynnus* (Safina and Klinger 2008), the Pacific sardine, *Sardinops sagax* (Shank 1999), and the haddock, *Melanogrammus aeglefinus* (IUCN 2010). In every ocean in the world, one or more important commercial stocks have been classified as collapsed, overfished, or fished to their maximum levels, and at least one quarter are considered overexploited or significantly depleted (Millennium Ecosystem Assessment 2005).

There are a host of management tools that have been used by governments around the world in an attempt to manage fisheries: e.g., gear restrictions, quotas, capacity reductions, and fishery closures (Worm et al. 2009). These tools for management, which in practice are concerned with optimum exploitation of desirable species, have largely failed because they often ignore the habitat and prey of the target species and other ecosystem components and interactions (Pikitch et al. 2004). Among the more obvious recent changes in management that have come about in response to these failures are a shift in concern from individual fisheries to ecosystem scales (Appeldoorn 2008). One promising development has been the advocation of a more holistic ecosystem oriented approach using marine protected areas (MPAs) as a management tool because they embrace preservation of biodiversity and maintenance of ecosystem structure and function (Koenig et al. 2000). The first MPA was established in the Dry Tortugas, Florida, in the

1930s (PDT 1990) and today there are as many as 5878 MPAs around the world (Toropava et al. 2010). This sounds impressive, but in reality <1% of the world's oceans are currently under some form of legal protection (WDPA 2009).

According to the International Union for the Conservation of Nature (IUCN), an MPA may be defined as 'any area of intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment' (Kelleher 1999). Although the majority of MPAs have been established on an individual basis (Wood 2007) scientists have been encouraging an even broader ecosystem based approach via the establishment of networks of MPAs (Airamé et al. 2003; Friedlander et al. 2003; Roberts et al. 2003; Palumbi 2004; Gaines et al. 2010). According to IUCN World Commission on Protected Areas (IUCN-WCPA 2008), an MPA network is 'a collection of individual MPAs or reserves operating co-operatively and synergistically, at various spatial scales and with a range of protection levels that are designed to meet objectives that a single reserve cannot achieve'. Marine protected area is an umbrella term as there are about 350 different designations worldwide which reflect variation in regulations and degree of protection (Wood 2007). That is, MPAs can range from allowing various levels of human activity (e.g., fishing, diving, sight seeing) to absolute protection. The latter typically takes the form of marine reserves or no-take areas where all forms of fishing or exploitation are prohibited (Unsworth et al. 2007). Despite the push for absolute protection (Gell 2003; Halpern and Warner 2002; Roberts et al. 2005; Russ et al. 2008), and growing evidence that reserves and no-take areas contribute to increasing fishery yields outside protected borders (Mosquera 2000;

Roberts et al. 2005; Russ et al. 2003, 2008; Lester and Halpern 2008) the majority of MPAs around the world allow some level of human activity (UNEP-WCMC 2008).

Poor and ineffective management is often to blame for the demise of once abundant commercial fishery species (Chakalall et al. 2007). A good example is the Nassau grouper, *Epinephelus striatus*, (Bloch 1972), a species which occurs in the waters of 34 countries in the wider Caribbean (García-Moliner and Sadovy 2008) and was once the most commonly caught species in the region. The fishery is now almost extinct due to over exploitation (Beets and Friedlander 1992; Heemstra and Randall 1993; Sadovy 1994; Sadovy and Eklund 1999; García-Moliner and Sadovy 2008). In the past, the Nassau grouper was known to form large spawning aggregations of 30,000-100,000 individuals (Smith 1972; Sadovy 1993; Carter et al. 1994; Sadovy and Domeier 2005) and up to 80 traditional historical aggregation sites have been identified in the Caribbean basin (Sadovy De Mitcheson et al. 2008). Sadly, heavy fishing pressure has had such a severe impact that already in 1999, Sadovy and Eklund reported that ~1/3 of the 80 known sites no longer formed. Complete losses have been recorded in Belize, the Bahamas, Cuba and the Greater Antilles (Sadovy and Eklund 1999), the Dominican Republic (Colin 1992), Mexico (Aguilar-Perera and Aguilar-Davilá 1996), Puerto Rico (Sadovy 1993), and elsewhere. Figure 1 depicts all the known Nassau grouper spawning aggregations reported since 1884 in the upper map, and the lower map displays those believed to be active today. It clearly demonstrates the severity of the situation which is alarming as Starr et al. (2007) reports that when a spawning site is abandoned, it will no longer be used again. Sadovy and Eklund (1999) indicate that aggregations of <1000 individuals are not known to be sustainable over the longterm.

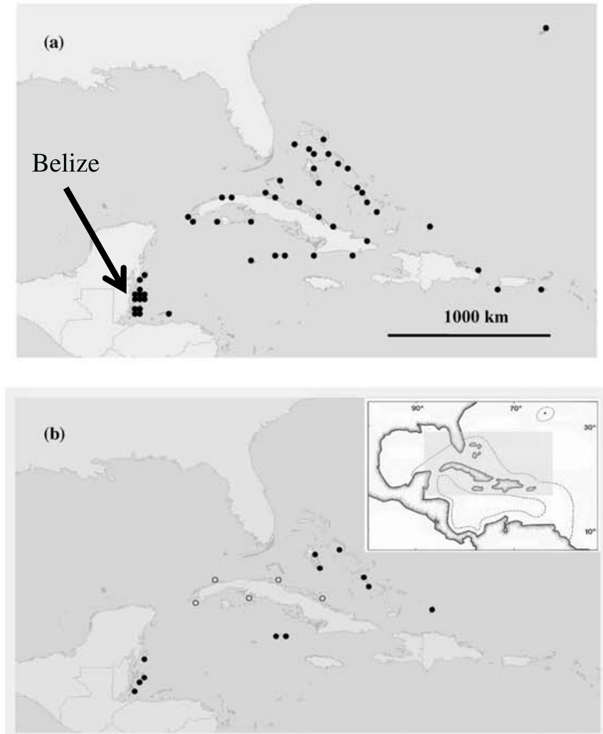

Figure 1. Known spawning aggregations of the Nassau grouper in the Caribbean; (a) All known aggregations reported since 1884; reported numbers range from 10,000-100,000 fish (b) Closed circles represent sites known to be active today with fish numbers between 100-3000, while open circles represent sites believe to be active but not assessed directly (Sadovy De Micheson et al. 2008, p. 1240). The location of Belize is indicated in (a).

Adult Nassau grouper are typically taken with handlines, spear guns, and fish pots (Carter et al. 1994). Spawning aggregation sites have proven irresistable to fishermen because they are able to catch large numbers of fish in a short amount of time with very little effort. In the case of Belize before the collapse of the Nassau grouper, the cultural and economic importance of this species was considerable. Groupers are often the most expensive fishes in local markets (Heemstra and Randall 1993). In 1969, Craig reported that the share of a good catch of Nassau grouper at Cay Glory, Belize, could amount to more than what was normally earned in six months of routine work. Also, until stocks plunged, for nearly 100 years Christmas was traditionally associated with the annual harvest of Nassau grouper (Heyman and Wade 2007).

The cessation of spawning at once plentiful sites in Belize and elsewhere is the most tangible evidence that management approaches have not been and are still ineffective (Sadovy De Mitcheson et al. 2008). Indeed, effectively managing a fishery species in an attempt to maintain or restore severely depleted stocks so that they recover and serve as a longterm renewable resource, may be one of the greatest challenges for ocean conservation today. Experts say that standard fishery management approaches such as quotas and size limits do not work for larger reef species like the Nassau grouper and the greatest protection is likely afforded by restrictions or elimination of gear and effort, or properly placed marine reserves which protect all the critical habitats on which immature and adult Nassau grouper depend (Sadovy and Eklund 1999; Starr et al. 2007). Today, the use of MPAs is one of the most widely advocated tools for grouper fisheries management (Young et al. 2006; García-Moliner and Sadovy 2008).

A number of authors state that in order for MPAs to contribute to the conservation of any fishery species, selection of sites must be supported by at least some of the basic understanding of the life cycles and habitat requirements associated with various developmental stages of the managed stock (Gleason et al. 2006; Koenig et al. 2000; Young et al. 2006). Sadovy who has published more extensively on Nassau grouper (Sadovy 1993; Sadovy 1994; Sadovy and Colin 1995; Sadovy and Eklund 1999; Sadovy and Domeier 2005; García-Moliner and Sadovy 2008; Sadovy De Micheson et al. 2008) than any other author reports that stock monitoring and effective management are impossible without knowledge of the biology, status, and exploitation levels. Yet surprisingly little is known about the Nassau grouper, its conspecifics, and most other marine species, so lack of robust data appears to be the norm rather than the exception. Johannes (1998) claims that the resources to collect and process management data for the great majority of marine species do not exist now, nor will exist in the foreseeable future. Johannes (1998) also states that managing fisheries sub-optimally, however, is preferable to not managing them at all. That is, take the pieces of information that are available and make as informed decisions as is possible, incorporating new information as it comes along. In other words, take a precautionary and adaptive approach to management.

1.1 Research Objective

Throughout the Caribbean, the majority of the effort for the protection and recovery of the endangered Nassau grouper (*Epinephelus striatus*) has focused on the protection of adults via a seasonal fishery closure and spawning aggregation site reserves (SASRs). The use of MPAs is also believed to contribute to conservation, but these have not been established specifically for the protection of this species. The extent to which the Nassau grouper might benefit from MPAs is currently unknown (García-Moliner and Sadovy 2008). Using Belize as a case study location, the objective of this study is to determine how the MPA network in Belize contributes towards the protection of the endangered Nassau grouper.

1.2 Research Questions

In order to achieve the research objective, the following questions need to be answered:

- What is the current state of management of the Nassau grouper in Belize?
- What is currently known about the Nassau grouper in relation to habitat needs and movement during key life stages (larval, post-settlement, juvenile, and adult)?
- What is the relative proportion of marine ecosystem types within the current Belize MPA/SASR network?

- Do the existing MPAs in Belize function as a network with respect to peer-reviewed recommendations for MPA inter-spacing, i.e., ecological connectivity?

1.3 Content of study

In order to achieve the research objective, it was necessary to first conduct a thorough literature review to lay the foundation on which this thesis is built. Chapter 2 begins with an in depth look at the general biology and status of the case study species, the Nassau grouper. The chapter ends with a detailed overview of the case study region, Belize, including current legislation and management framework. Chapter 3 describes the software and data source that were used to perform the analysis. In order to achieve the research objective a GIS framework using two different approaches is used. Chapter 4 takes the first approach and examines the distribution of different marine ecosystems in relation to the current MPA/SASR set-up in Belize and what is known about the resource needs of Nassau grouper. The second approach, in Chapter 5, considers whether the MPAs/SASRs function as a network based on ecological connectivity in relation to known movement patterns of Nassau grouper. The results and significance of what was found are discussed in Chapter 6. The main conclusions are highlighted in Chapter 7.

1.4 Scope of Research

There are many other aspects that can be considered in relation to declining grouper numbers including management effectiveness, enforcement, illegal fishing, and socioeconomic issues. The scope of this thesis is strictly to consider the Nassau grouper in relation to MPAs as this may be the most promising management tool for any chance of recovery for this species.

2.0 Literature Review – Case Study Species and Region

In order to achieve the research objective it was necessary to first understand the Nassau grouper as well as the case study location, Belize. The first section provides a detailed overview of the case study species beginning with an introduction to the grouper family (Serranidae), and next a description of the Nassau grouper itself including general information on the species, reproduction, population status in Belize, importance, threats, and reasons for selecting it as the study species. The section which follows provides some background knowledge on Belize and why it is a suitable study location for this thesis. Next, the existing legislative framework, management authority, and management tools in relation to fisheries, the Nassau grouper, and MPAs/SASRs in Belize are described.

2.1 Case Study Species – Nassau Grouper, *Epinephelus striatus*

2.1.1 <u>General background</u>

Groupers are generally characterized as bottom dwelling fish that occur in the marine waters of all subtropical and tropical oceans (Heemstra and Randall 1993). According to Heemstra and Randall (1993) the grouper Family, Serranidae, is divided into 5 subfamilies: Serranidae, Anthilinae, Niphoninae, Epinephelinae, and Grammistinae. The genus *Epinephelus,* which falls under the Serranidae, is made up of some 98 species that can be found in the Pacific, Atlantic, and Indian Oceans (Heemstra and Randall 1993). The following is the taxonomic classification for this genus.

Kingdom: Animalia
    Phylum: Chordata
        Class: Actinopterygii

Order: Perciformes
Suborder: Percoidei
Family: Serranidae
Subfamily: Epinephelinae
Genus: Epinephelus

Very little is known about the life history of most grouper species (Liu and Sadovy 2005; Unsworth et al. 2007; Pina-Amargós and González-Sansón 2009). From what is known, although each species exhibits unique traits they also share some common characteristics (Heemstra and Randall 1993). Adults are considered unspecialized top-level carnivores on the reef feeding on a variety of food items including fish, crustaceans, and cephalopods (Carter et al. 1994). Most species are ambush predators, hiding amongst the coral and rocks, and the typical large head and mouth allows them to catch prey instantly with a quick snap of the jaws or by sucking into the mouth (Heemstra and Randall 1993). Certain life history characteristics make grouper susceptible to human exploitation: a relatively long lifespan, large size at sexual maturation, slow growth, and the ease with which they are caught by fishermen (Sadovy 1994). Those species that form spawning aggregations are especially vulnerable to exploitation. For example, Johannes (1998) reported that in the mid 1980s an aggregation that had fed Palauans for centuries was wiped out in only three years of intensive fishing.

Twenty species of grouper are considered to be of commercial and/or recreational value in the Western Atlantic, e.g., Nassau grouper (*Epinephelus striatus*), jewfish (*E. itajara*), black grouper (*Mycteroperca bonaci*), red hind (*E. guttatus*), and red grouper (*E. Morio*) (Sadovy 1994). Despite their economic importance and declining numbers very little is known about the population status of most grouper species (IUCN 2010). In many tropical regions fisheries are not monitored at the species level, long-term data sets are few, there is little documented history of declines from which to draw lessons, and there are virtually no long-term data sets (Sadovy De Mitcheson et al. 2008). As a result, information on the historical condition of grouper stocks[1] in general is largely patchy and incomplete (Sadovy 1994). A primary reason is that most are caught in artisanal fisheries, which do not report catch statistics (Heemstra and Randall 1993). Nevertheless, grouper stocks around the world have been so overfished that in 1996, 21 species were proposed for inclusion on the IUCN Red List as vulnerable or endangered, three being considered critically endangered (Johannes 1998).

2.1.2 The Nassau grouper

As depicted in Figure 2, the Nassau grouper is distributed throughout the waters of the western north Atlantic: Bermuda, Florida, Bahamas, Yucatan Peninsula, and throughout the Caribbean to southern Brazil (Heemstra and Randall 1993). It can reach ~1 m total length, weigh up to 25 kg

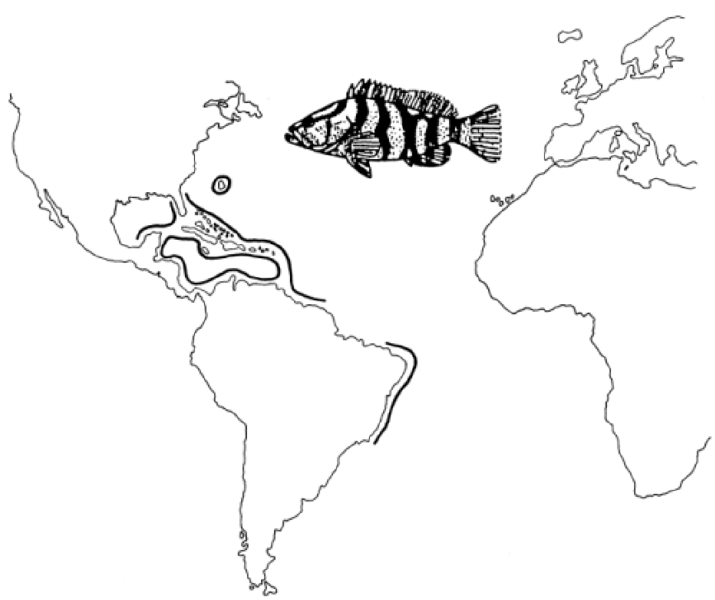

Figure 2. Geographic distribution (indicated by the solid line) of the Nassau grouper (Sadovy and Eklund 1999, p. 7, redrafted from Heemstra and Randall 1993).

[1] A stock is the part of a fish population which is under consideration for actual or potential use (Sadovy 1994).

(Heemstra and Randall 1993) and live as long as four decades (Sadovy and Eklund 1999). It has an estimated growth rate of 12 cm/year (Beets and Hixon 1994). The Latin word, *striatus*, is in reference to the Nassau grouper colour pattern and the name 'grouper' comes from the Portuguese 'garrupa', probably derived from a similar sounding name that South American natives used for large groupers (Sadovy and Eklund 1999). The Nassau grouper has the ability to change its colour, i.e., its skin can change colour in a few minutes from almost white to uniformly dark brown depending on its mood (Heemstra and Randall 1993). The top image in Figure 3 illustrates its typical 'barred' colouration which includes five irregular dark brown bars that circle the body, a broad black patch near the base of the tail fin, and a prominent dark streak running from the snout through the eye (Carter et al. 1994). During spawning the Nassau grouper is usually seen with the bicoloured colouration as depicted in the lower image in Figure 3 (Colin 1992).

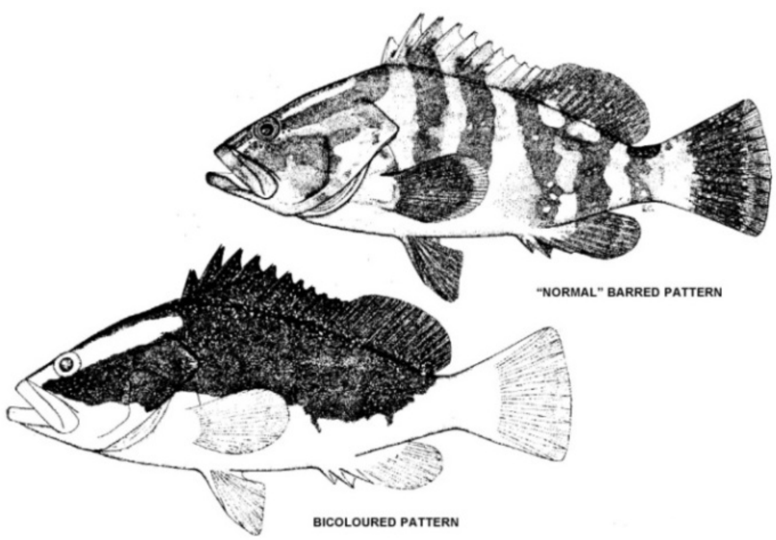

Figure 3. The two dominant colour patterns of the Nassau grouper: the upper 'normal' barred pattern is the most common while the lower bicoloured pattern is normally seen during spawning (Heemstra and Randall 1993, p. 236).

2.1.3 Reproduction

Nassau grouper reach sexual maturity when they are about 4+ years of age (Sadovy and Eklund 1999). They are considered to have a predominantly gonochoristic (separate sexes – no sex change) sexual pattern, unlike most other grouper species which are protogynous and undergo female to male sex change at a certain point in their life cycle (Sadovy and Eklund 1999). It is unknown why the latter occurs, but for a number of grouper species, e.g., gag (*Mycteroperca microlepis*), black grouper (*M. bonaci*), brown marbled grouper (*Epinephelus fuscoguttatus*), after several years of reproductive activity mature females change sex and thereafter function as males (Heemstra and Randall 1993).

Nassau grouper is one of 164 known species of coral reef fish that aggregate to spawn at specific times of the year and at specific sites (Claydon 2004). Fish spawning aggregations (FSAs) can be defined as a group of conspecific fish gathered for the purposes of reproduction with fish densities or numbers significantly higher than those found in the area of aggregation during non-reproductive periods (Domeier and Colin 1997). In Belize, Nassau grouper are known to form FSAs for approximately one week around the full moon in December and January (Smith 1972; Colin 1992; Carter et al. 1994) with spawning activity peaking near sunset (Heemstra and Randall 1993). There is no direct evidence that they breed outside this period so reproduction at these sites is believed to represent their total annual reproductive output (Sadovy and Eklund 1999). There is no clear understanding why aggregations are so site specific (Gleason et al. 2006) or the environmental and biological cues that lead groupers to form them (Young et al. 2006). It has been suggested that immature fish learn this behaviour, so when sexually mature individuals are extirpated from a spawning site juveniles are unable to locate the historical aggregations thus leading to the disappearance of that particular spawning site (Sadovy and Eklund 1999).

2.1.4 Nassau grouper population status in Belize

In Belize, Carter and Marrow (1991) report that from 1972 to 1984, groupers, primarily Nassau grouper, constituted the second most commonly caught and most valuable family of marine fishes. Jacobs (1998) reported that in the mid- to late-1980s, Nassau grouper represented over 60% of the total finfish catch. Outside these accounts, little else is known. The Belize Fisheries Department has the responsibility for maintaining records of the commercial landings and exports of marine products; however, in the past species were lumped into single categories so there are few official records that accurately illustrate historical landings of Nassau grouper within the country (Heyman and Wade 2007). This is unfortunate as already in 1969 Craig reported that the grouper fishery was at serious risk due to uncontrolled exploitation. Mostly historical accounts from local fishermen provide the only evidence that it was once a highly abundant species in Belize and throughout the Caribbean (Heyman and Wade 2007).

In early 2000, in response to the severely declining numbers of Nassau grouper, a standardized annual monitoring programme at aggregation sites was initiated by the Belize Spawning Aggregation Working Group (BSAWG). Although there are 11 known and protected spawning sites, only 7 are actively monitored. Figure 4 shows the numbers that were recorded annually at each of these sites for the last 9 years from 2003 until 2011 (BSAWG 2011). These results are published in the BSAWG annual newsletter and the most recent monitoring results indicate that in 2011, only 2 sites had >1000 individuals during the spawning period: Northeast Point SASR in Glovers Reef Marine Reserve and Sandbore Caye SASR. SASRs with a count of zero for the last five years in a row are Dog Flea Caye and Rocky Point SASRs.

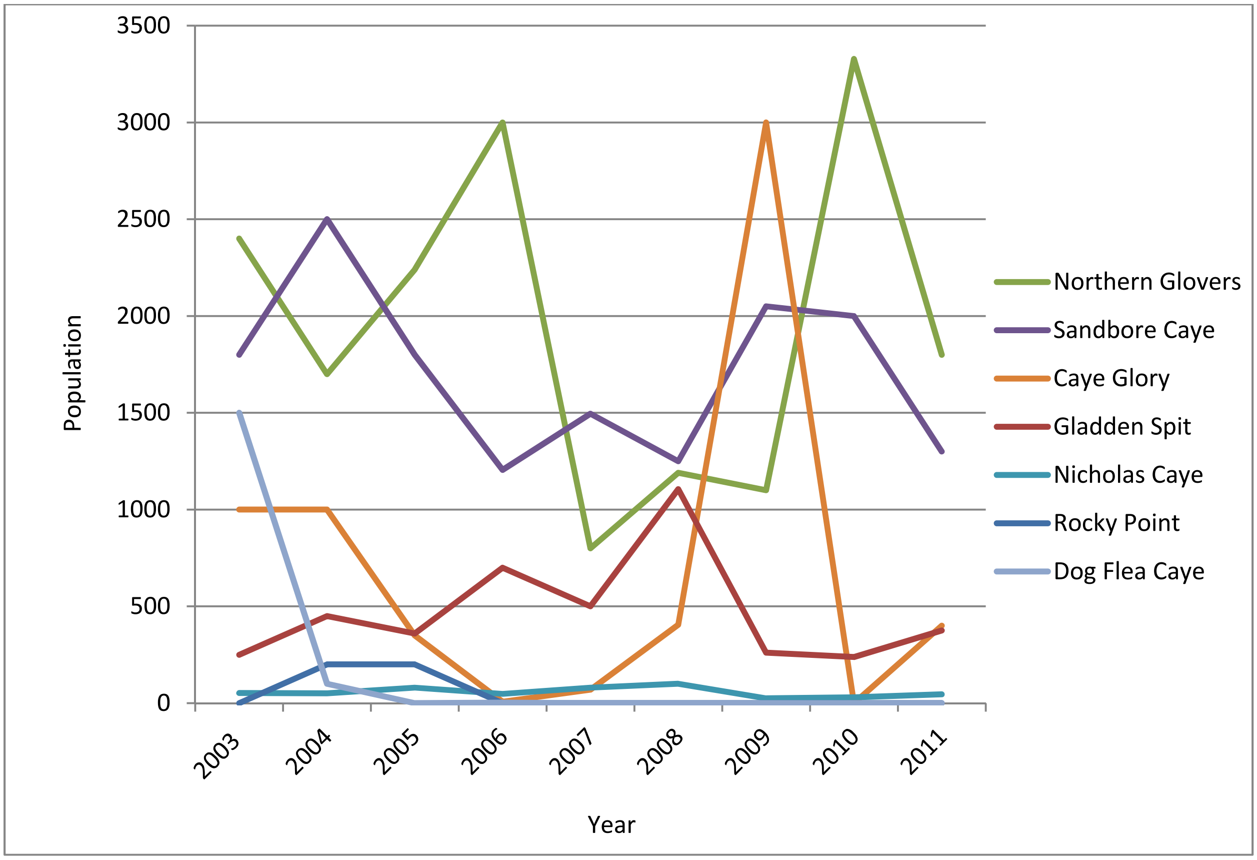

Figure 4. Nassau grouper numbers at 7 of 11 monitored spawning aggregation site reserves (SASRs) as reported by the Belize Spawning Aggregation Working Group (Data source: BSAWG 2011).

2.1.5 Threats

Overfishing at the spawning aggregation sites is considered the primary cause of the decline of Nassau grouper in Belize and throughout the Caribbean (Gibson et al. 2007). Adult Nassau grouper have been particularly vulnerable to such exploitation due to a number of natural characteristics including:

- Predictability of timing and location of spawning aggregations (Sadovy and Domeier 2005) has made it relatively easy for fishermen to locate and target this species for exploitation.
- Late age of sexual maturity, long life span, and slow rate of growth (PDT 1990) means that once adults are removed from a population they are not quickly replaced by immature individuals.
- Nassau grouper have an unwary nature and are not fearful, leading to easy capture by a wide range of fishing gear (Sadovy 1994; Gleason et al. 2006).
- Desirability as a seafood ensures a constant market demand (Beets and Hixon 1994). It is reported to be the most expensive fish in local markets of many countries (Heemstra and Randall 1993).

Other probable threats to coastal ecosystems in Belize that have been identified, and thereby likely affecting the Nassau grouper, include coastal development, tourism, pollution, climate change (APAMO 2009).

2.1.6 Importance of protection

There are many reasons to push for the protection and improved management of grouper species around the world. It is not only to prevent the loss of species that are of considerable economic value, but also to prevent the loss of biologically significant creatures. The once common spawning aggregations of 10,000-100,000 individuals should have been considered one of nature’s mysterious wonders, and their disappearance an outcome that could have been avoided had proper fisheries management been in place.

The importance of protecting large mature females in maintaining healthy fish populations is also very clear because they contribute the most reproductively to a population. For example, although no information specific to Nassau grouper fecundity was found in the literature, it is known that for a similar species, the red snapper (*Lutjanus campechanus*), a single 61 cm (12.5 kg) female produces the same number of eggs (9,300,000) as 212 females at 42 cm (1.1 kg each) (PDT 1990). Clearly, removal of large mature females can have severe consequences for a fishery population.

Furthermore, the role of top predators like Nassau grouper in coral reef ecosystems are not well understood and the impact of their removal is largely unknown (Mumby et al. 2012). Socioeconomically, one predictable outcome has been termed 'fishing down marine food webs' by Pauly et al. (1998). This occurs when top predators are removed from an ecosystem and fishermen begin targeting species at lower trophic levels which were ignored in the past (Liu and Sadovy 2005). The ecological effects of this are complex and are not well studied, but there is evidence that removal of top predators leads to shifts in density of remaining species. In a review conducted by Ritchie and Johnson (2009) on the effect of removal of vertebrate apex predators in both terrestrial and marine ecosystems, it is reported that removal leads to increases in mesopredators leading to increases in predation on smaller prey. Mumby et al. (2012) found this in Belize where the decline in large bodied groupers was accompanied by an 8 fold increase in medium sized reef predators (e.g., hinds, coney, and graysby) but decreases in herbivourous parrotfish and damselfish. Mumby et al. (2012) suggests that the effects are complex, but the observed decline in parrotfish was partly due to fishermen changing their target species in response to declining Nassau grouper numbers.

2.1.7 <u>Nassau grouper as the study species</u>

The Nassau grouper is a good species to examine whether and how MPA set-up may influence fisheries management for a number of reasons.

- It is the most well studied reef fish species of commercial value that aggregates to spawn (Sadovy De Mitcheson et al. 2008) and therefore makes it a good study species to examine the research question.
- In 1996, the Nassau grouper was included on the 'Red List' of endangered species by the International Union for the Conservation of Nature (IUCN 2010) and despite management interventions the species is still not showing signs of recovery (Garcia-Moliner and Sadovy 2008). Any new insight into improving management could be beneficial to the longterm sustainability of the species.
- To date, the majority of research and published accounts of the Nassau grouper have focused primarily on adult life stages therefore it would be beneficial to examine earlier life stages with respect to MPA set-up.
- Targeted protection has focused on adults via SASRs and a seasonal closure, but the unusual and complex biology and ecology of groupers mandates that their entire life-history traits be incorporated into any management strategy (Posada and Appeldoorn 1995; Sadovy and Eklund 1999).
- There is no published habitat assessment that considers current MPA set-up in Belize with respect to resource needs of Nassau grouper at its various stages of development (larval, post-settlement, juvenile, and adult).
- An online source of spatial metadata, including the marine ecosystems and protected area boundaries of Belize, is freely available (Meerman and Sabido 2001).

2.2 Case Study Region – Belize

2.2.1 Belize as the case study region

Belize, previously called the British Honduras before gaining independence in 1981, is a developing country in Central America with a population of approximately 312,700 (CSO 2010). The official language is English; Mestizo, Creole, Maya, Garifuna, and Mennonite are the five largest ethnic groups (CSO 2010). This country is bordered by Mexico in the north, Guatemala to the west and south, and the Caribbean Sea in the east. It has a land area of 22,966 km^2 and its coastline is roughly 386 km long (CIA 2011). Belize was chosen as the case study location for a number of reasons. This country is renowned for its biodiversity: it has more than 150 species of mammals, 540 species of birds, 151 species of amphibians and reptiles, nearly 600 species of freshwater and marine fishes and 3,408 species of vascular plants (BTFS 2012). Belize also possesses a rich and diverse array of marine ecosystems and habitats such as important reef types (barrier reef, lagoon patch reef, fringing reefs, and offshore atolls) and associated habitats (mangroves, seagrass beds, estuaries, and islands or cayes). The Belize Barrier Reef (BBR) which forms part of the Mesoamerican Reef (MAR) system occurs here, is the largest in the Atlantic, and the second largest in the world: it is 280 km long and 1400 km^2 in area (BAS 2008).

Coastal resources are very important to the national economy of Belize, i.e., the BBR contributes approximately 30% to the Gross Domestic Product (GDP) via fisheries (mostly artisanal), tourism, coastal development and aquaculture (Cho 2005). Despite its small size, this country has demonstrated dedication towards protection of its marine resources. Figure 5 depicts the currently established MPAs and SASRs of Belize. There are 13 established MPAs, seven of which form the Belize Barrier Reef Reserve System World Heritage Site (Bacalar Chico Marine Reserve, Laughing Bird Caye National Park, Half Moon Cay Natural Monument, Blue Hole Natural Monument, Glovers Reef Marine Reserve, South Water Cay Marine Reserve, and the Sapodilla Cayes Marine Reserve) designated in 1996 under the UNESCO World Heritage Convention (Cho 2005). In 2003, 11 spawning aggregation site reserves were established to protect known spawning aggregations of the Nassau grouper. As listed in Table 1, a number of laws designed to protect wildlife, habitats, and national heritage are in place. Also, Belize is a signatory to 24 international conventions and treaties concerning marine life and coastal protection (Gillet 2003) which demonstrates commitment by the national government towards preserving the country's natural resources. Table 1 lists some of the most important international and regional commitments to which Belize is signatory.

Despite these measures and significant economic value of the marine environment to Belize (Cho 2005), it is reported that coastal resources are threatened by over-exploitation and degradation via fishing and tourism industries (BAS 2008). In the case of the Nassau grouper, it was once an abundant commercial species in Belize but is now in severe decline and the fishery is considered commercially extinct (Sadovy and Eklund 1999): only 4 of 11 historical spawning sites are considered active and in 2011 only 2 sites recorded more than 1000 spawning individuals (BSAWG 2011). The reasons stated make Belize a good case study location to answer the proposed research question.

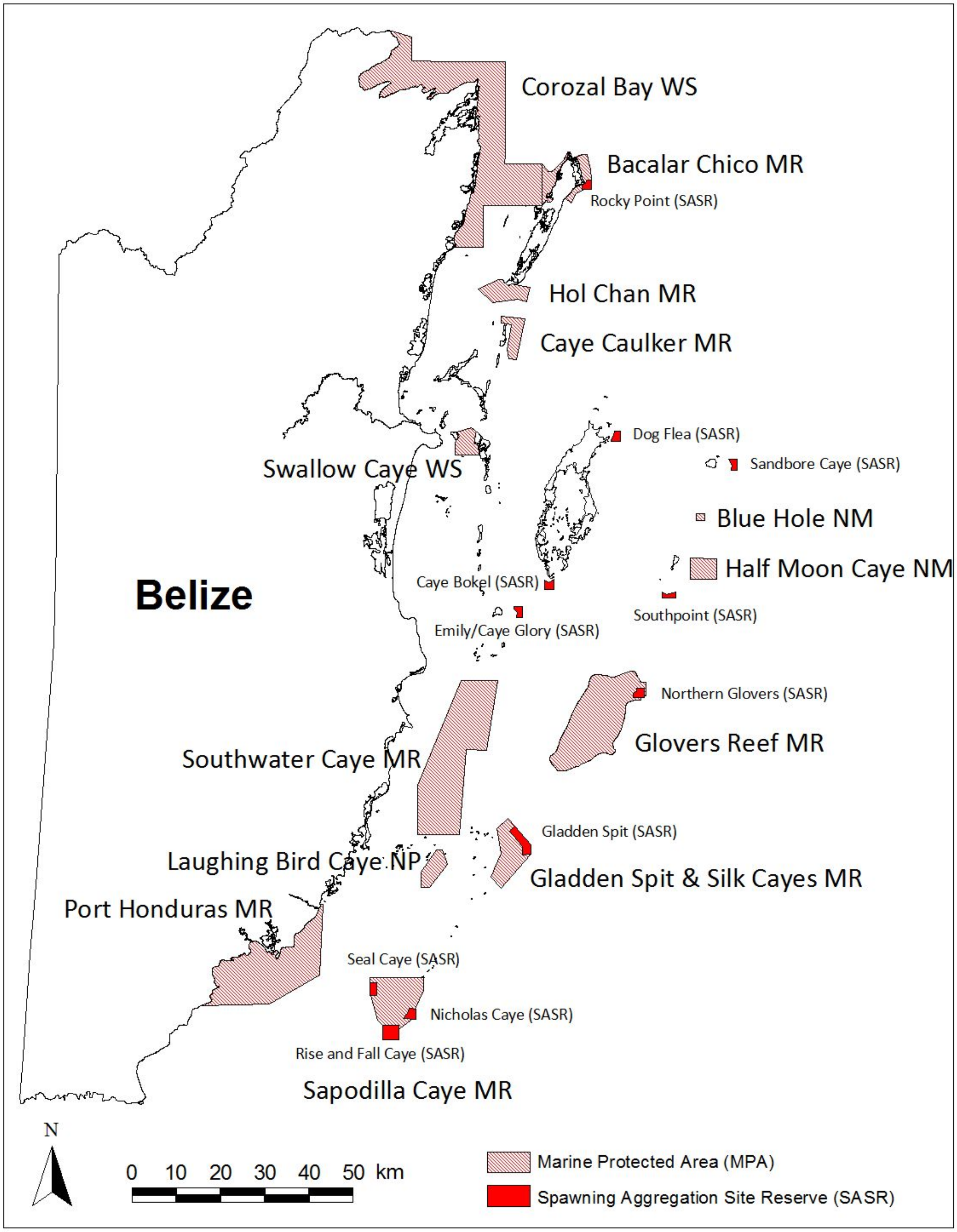

Figure 5. Marine protected areas (MPAs) and spawning aggregation site reserves (SASRs) of Belize.

Table 1. International and regional commitments relevant to MPAs/SASRs to which Belize is a signatory (Wood 2007; APAMO 2009; Wildtracks 2010b).

Convention or Commitment	Description
Convention on Biological Diversity (CBD), 1993	International agreement to conserve biological diversity to promote the sustainable use of its components, and encourage equitable sharing of benefits arising from the utilization of natural resources
UNESCO – World Heritage Site Convention (UNESCO-WHS), 1975	International agreement that aims to protect places of exceptional universal value. The convention links nature conservation and cultural preservation; recognizing the fundamental need to preserve the balance between humans and nature.
UN Convention on the Law of the Sea (UNCLOS), 1982	International agreement which defines the rights and responsibilities of nations in their use of the world's oceans, establishing guidelines for businesses, the environment, and the management of marine natural resources.
Convention for the Protection and Development of the Marine Environment of the Wider Caribbean Region (1983)	Regional convention with the objective of protecting the marine environment of the Wider Caribbean through promotion of sustainable development and prevention of pollution.
Alliance for Sustainable Development of Central America (ALIDES) (1994)	Regional alliance supporting sustainable development initiatives.
Tulum Declaration, 1997	Belize, Guatemala, Honduras and Mexico signed this declaration for the conservation and management of the Mesoamerican Reef (shared) as a single ecosystem.

2.2.2 Legislative framework

Belize's national objectives for conservation revolve around the protection, conservation and rational use of its natural resources within the context of sustainable human development (Wildtracks 2007). Table 2 lists and describes the main pieces of legislation directly related to the sustainable management of Belize's marine resources; the Fisheries Act, the National Parks System Act and the Coastal Zone Management Act (GOB 2010). The Environmental Protection Act is considered a supporting element for the use of natural resources in Belize (GOB 2010). The Fisheries Act allows the Minister of Agriculture and Fisheries to create Marine Reserves

(MR) while the National Parks System Act allows the Minister of Natural Resources and the Environment to create Wildlife Sanctuaries (WS), Natural Monuments (NM), Nature Reserves (NR), and National Parks (NP). The Gladden Spit and Silk Cayes Marine Reserve Management Plan (Wildtracks 2010b) reports that there is significant fragmentation in decision making since these different Acts fall under different Ministries. It is also reported that competing legislation and management authorities has led to an uncoordinated approach and incohesiveness (Cho 2005).

The Fisheries Act is the most significant piece of legislation that affects the Nassau grouper, and in 2003 two statutory instruments were enacted specifically under this Act for the protection of this species; SI 161 – declaration of 11 marine reserves closed to fishing year round and SI 162 – establishment of a 4 month closed season from December to March where the take, sale, and possession of Nassau grouper is prohibited. Additional measures enacted specifically to help manage and protect the Nassau grouper include minimum and maximum size limits of 80 cm and 120 cm, a ban on spear fishing within all marine reserves, a requirement that all Nassau grouper be landed whole, and that all other fish landed as fillets must have a 2.5 cm by 5 cm (1" by 2") skin patch so that species can be identified (Mumby et al. 2012). However, there is no single over-riding piece of legislation which protects endangered species like the Nassau grouper and each of the other existing pieces of legislation described are said to sometimes directly or indirectly affect marine natural resource use or conservation (Cho 2005), laying the foundation for confusion, conflict and turf disputes among government agencies (Jacobs 1998).

Table 2. Legislation relevant to Nassau grouper and MPAs/SASRs in Belize (Cho 2005; Paz and Truly 2007; GOB 2010; Wildtracks 2010b; Mumby et al. 2012).

Legislation	Description
Fisheries Act, 1948	Administered under the Fisheries Department, this is the principal governing legislation which regulates the fishing industry, and is directly concerned with maintaining sustainable fish stocks and protecting marine and freshwater environments. Amendments: 1983 The Minister of Agriculture and Fisheries was granted the authority to designate any area in Belize waters a Marine Reserve and to prohibit entry into the reserve 2003 Two statutory instruments enacted for the protection of Nassau grouper: SI 161 – declaration of 11 Marine Reserves closed to fishing year round SI 162 – establishment of a 4 month closed season from December to March where the take, sale, and possession of Nassau grouper is prohibited 2009 Additional measures enacted specifically to help manage and protect the Nassau grouper: – minimum and maximum size limits of 80 cm and 120 cm – ban on spear fishing within all marine reserves – all Nassau grouper be landed whole, and that all other fish landed as fillets must have a 2.5 cm by 5 cm (1” by 2”) skin patch.
Wildlife Protection Act, 1981	Provides for the conservation, restoration and development of wildlife, for the regulation of its use and for all other matters connected therewith”; does not apply directly to fish.
National Parks System Act , 1981	Administered under the Forest Department, empowers the Minister to create or maintain a “national system” of protected areas. It allows for the creation of Wildlife Sanctuaries, Natural Monuments, Nature Reserves, and National Parks.
Environmental Protection Act, 1992	Administered under the Department of the Environment, Ministry of Natural Resources, it promotes the preservation and improvement of the environment, the rational use of natural resources, the control of pollution, and matters connected therein – important in managing development impacts in seascapes adjacent to Marine Reserves.

Coastal Zone Management Act, 1998	Calls for a Coastal Zone Management Plan to include *inter alia* guidelines for development in Belize's coastal zone; general monitoring of the coastal zone; various policies and proposals on land use, planning for marine protected areas and conservation of threatened or potentially threatened or endangered species, recreation and tourism; public education programs and recommendation for public participation in management of coastal resources; recommendations for strengthening governmental policies; and the conduct of research for the purposes of coastal resources conservation and management.

2.2.3 Management authority

Figure 6 provides a schematic diagram of how the MPAs and SASRs in Belize are administered. Two government agencies, the Fisheries Department and the Forest Department, administer and have legal designation. Five MPAs fall under the jurisdiction of the Forest Department while 8 MPAs and all 11 spawning aggregation site reserves (SASRs) fall under the authority of the Fisheries Department. The Fishery Department, under the Department of the Ministry of Agriculture and Fisheries, is responsible for promoting and managing national fisheries, maintaining records of commercial landings and exports of marine products, and issuing commercial fishing licenses and vessel permits (Heyman and Wade 2007). The Ministry of Natural Resources and the Environment has the responsibility of overseeing the overall management of all natural resources. The Forest Department is one of five departments which is tasked with the responsibility of overseeing Belize's forest resources (MNRE 2012).

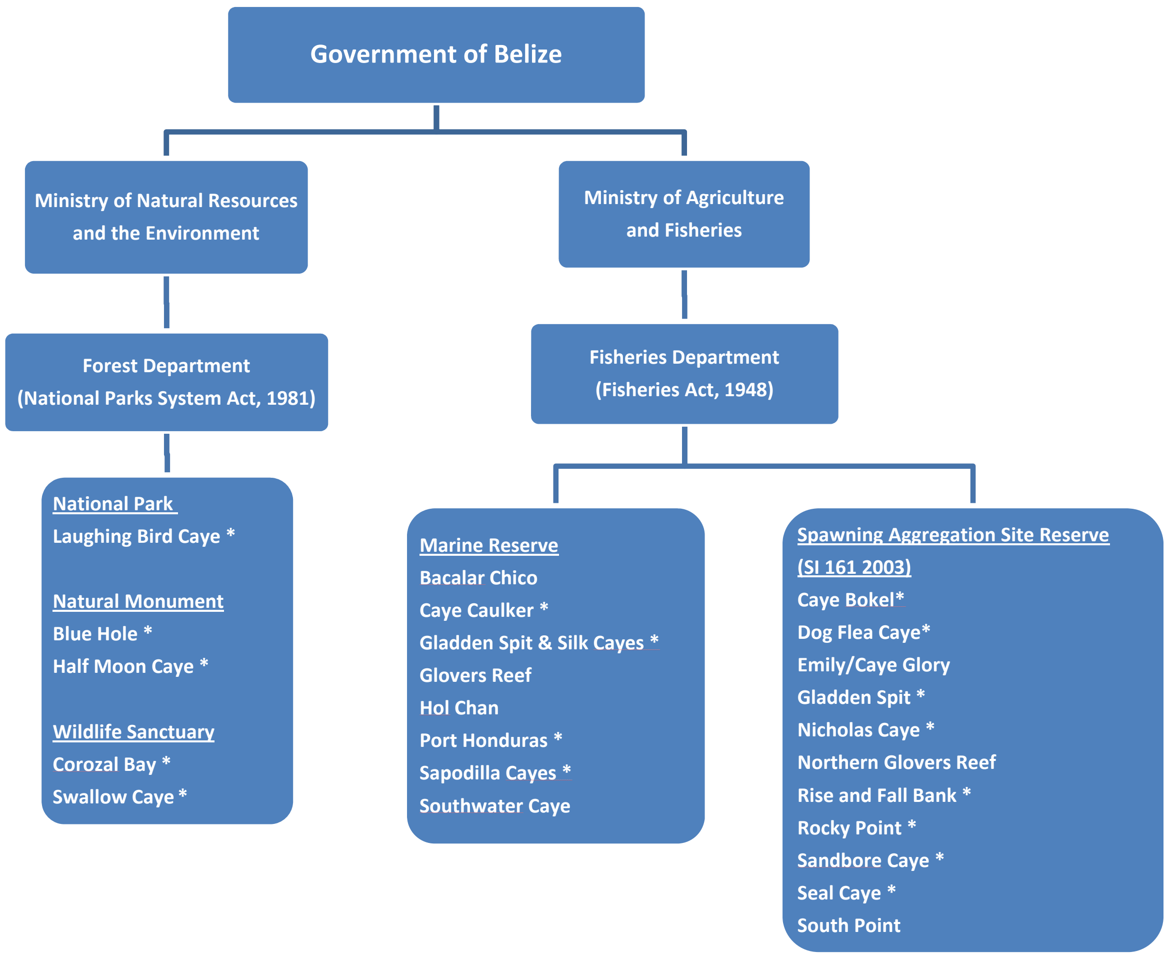

Figure 6. Government agencies with legal jurisdiction over MPAs and SASRs in Belize (* indicates those that are co-managed with an NGO).

The National Protected Areas Policy (NPAP), adopted by the national government in 2005, is the key statement of the role and management of protected areas within Belize (BAS 2008). It aims to guide the establishment, management, and administration of protected areas (terrestrial and marine), and to create the Belize National Protected Area System Plan (NPASP) in which all important sites are included in one coherent framework and meet all obligations under international agreements as listed in Table 1 to which Belize is a signatory (BAS 2008). This plan is currently guided by two bodies: the National Protected Areas Secretariat and the National Protected Areas Technical Committee (NPATC) (Wildtracks 2010b). However, it is not clear what level of interaction they have with either government department with respect to management of the MPAs.

The fact that responsibility for the various MPAs falls under the authority of two very different federal departments highlights weak central governance. This has been suggested as one of the greatest threats to Belize's National Protected Areas System (APAMO 2009). Furthermore, it appears counterintuitive that MPAs would fall under the jurisdiction of the Forest Department with respect to management of marine resources. Perhaps this explains one difference between the two agencies; i.e., that the Forestry Department has transferred administrative responsibilities of all of its MPAs to co-management partners while the Fisheries Department has only shared authority with about half of the MPAs/SASRs it manages. Cho (2005) goes as far to say that both departments lack the human and financial resources to properly manage the MPAs alone. Involving local NGOs demonstrates the importance of community participation in the management of natural resources has now been widely accepted (Brown and Pomeroy 1999).

The concerns about declining Nassau grouper numbers resulted in the formation of a group in July 2001, the Belize National Spawning Aggregation Working Group (BSAWG), whose mandate is to stem the decline of this species. It is made up of the Fisheries Department, University of Belize, fisheries cooperatives, and national and international NGOs (Heyman and Wade 2007). The Forestry Department is likely not part of this group as the SASRs do not fall under its jurisdiction. One of BSAWG's goals was to begin monitoring the spawning aggregation sites using standardized underwater visual surveys using a jointly developed monitoring protocol. Initial reports highlighted the severity of the decline and convinced the Government of Belize to take action and protect the 11 known spawning aggregation sites as Marine Reserves in 2003 and simultaneously enacting legislation that offered further protection via a closed Nassau grouper season from December through March (Heyman and Wade 2007). With respect to the spawning aggregation site reserves (SASRs) it is now illegal to fish Nassau grouper within the reserve boundaries year round and it is also illegal to fish Nassau grouper from December-March, with violations subject to $500 fine and/or up to six months imprisonment (BSAWG 2011).

2.2.4 Management tools

In Belize, there are two management tools that are specifically targeted at managing Nassau grouper stocks. First, are the 11 spawning aggregation site reserves (SASRs) where all forms of fishing activity are prohibited year round. These were established based on evidence and historical accounts from fishermen that these locations were used as spawning grounds by the Nassau grouper. Although primarily established in response to declining Nassau grouper numbers, these SASRs are also important to other aggregating species. For example, Gladden Spit SASR protects a unique geological promontory that falls sharply into the sea, providing conditions that attract >30 aggregating species (e.g., jacks, grouper, and snapper) throughout the year (Wildtracks 2010b). At Dog Flea Caye SASR researchers have identified 15 species (e.g., Tiger grouper, *Mycteroperca tigris*; Yellowfin grouper, *Mycertoperca venenosa*; Black grouper, *Mycteroperca bonaci*; and Yellowtail snapper, *Ocyurus chrysurus*) that gather to spawn while 18 species (e.g., Tiger grouper, *Mycteroperca tigris*; Bar jack, *Caranx rube*; Black snapper, *Lutjanus griseus*; and Ocean triggerfish, *Canthidermis sufflamen*) have been documented at Caye Bokel SASR (WWF and University of Belize 2008). The second management tool is a 4 month seasonal closure from December to March where the take, sale, and possession of Nassau grouper is prohibited within all marine waters of Belize.

Table 3 lists the main reasons each of the MPAs were established in Belize. It is evident that excluding those cases where the MPA encompasses one or more SASRs, that conservation of Nassau grouper was not a primary objective. Table 4 shows that each of the MPAs designated as a marine reserve are divided into a number of different management zones. Each of these zones has a set of rules that can be found in the corresponding management plan for each reserve; these are not provided in this table as ultimately fishing activity has been identified as the primary threat to the Nassau grouper population. Therefore, the table only provides a distinction between which zones allow or prohibit fishing outside the 4 month seasonal closure of Nassau grouper. The Natural Monuments, Wildlife Sanctuaries, and National Parks have no designated management zones and fishing is either permitted or prohibited. Overall, is evident that even when including the SASRs, very little area has been set aside as complete protection to the Nassau grouper. The total area under the Belize MPA/SASR system is roughly 2550 km^2, and only 341.7 km^2 (13.4%) is zoned as no-take where all fishing activity is prohibited year round.

Table 3. Primary reason(s) for establishment of the MPAs in Belize as stated in respective management plans.

MPA	Primary Reason for Establishment	Source[1]
Bacalar Chico Marine Reserve	Rocky Point is the only location in Belize where the Belize Barrier Reef touches the shoreline. During the 1990's, this area was recognized as an important sea turtle nesting area, supporting the largest number of loggerhead and green sea turtle nests in the country. It is also an important breeding area for the commercially valuable Queen conch, Nassau grouper, and other species. It encompasses Rocky Point SASR.	Green Reef Environmental Institute 2004
Blue Hole Natural Monument	The geological formations found within the sink hole of Blue Hole attracts divers from all over the world who visit to explore its unique features.	Wildtracks 2007
Caye Caulker Marine Reserve	It protects many unique features that support commercial species as well as attractions for tourists.	McRae 2004
Corozal Bay Wildlife Sanctuary	It provides protection for a large population of West Indian manatee (*Trichechus manatus*). It is a premier sport fishing destination for tarpon, bonefish, and other sportfish. Tourism is low, but growing. It includes numerous coastal lagoons with inlets, mangrove forests, and salt marshes which are connected to the bay and a number of freshwater rivers.	Wildtracks 2010a
Gladden Spit and Silk Cayes Marine Reserve	It protects one of the most prominent barrier reef structures in the region. It has a unique geological promontory dropping to a depth of 250m to the east, resulting in conditions favorable for spawning aggregations. It is home to one of the largest predictable whale shark congregations in the country. It encompasses Gladden Spit SASR.	Wildtracks 2010b
Glovers Reef Marine Reserve	It is not only the best developed coral reef biologically, but also possesses the greatest diversity of reef types. Its deep lagoon is studded with about 850 patch reefs and pinnacles rising to the surface. Six sand cayes lie on the reef crest along its southeastern edge. A large grouper spawning site is located at the northeastern end of the atoll.It is considered a high priority area in the Mesoamerican Caribbean Reef system, providing important habitat for lobster, conch and fish species.	Wildtracks and WCS 2007
Half Moon Caye Natural Monument	It was established due to its biological significance as an important fishery area with a pre-existing terrestrial component on account of the red footed booby.	Wildtracks 2007
Hol Chan Marine Reserve	It was established in recognition that this area is under threat from human populations and tourist development. The reefs near San Pedro have been exposed to heavy use and show signs of stress caused by over collecting, over fishing, and damage by anchors. It has a natural attraction called Shark Ray Alley where tourists are guaranteed a snorkel with sharks and stingrays. It is the most visited PA in all of Belize, with over 37,000 visitations/year. It is the only self-financing MPA in Belize.	Yong and Bilgre 2002
Laughing Bird Caye National Park	It is considered one of the best examples of faro formation in the Caribbean. It supports high biological diversity, a wide range of habitats, and 22 species of international concern (critically endangered, endangered or vulnerable). It is an important source for Queens conch and has critical nesting grounds for hawksbill turtles.	Wildtracks 2010c
Port Honduras Marine Reserve	This area is unique along the coast of Central America in lagoon system size and the number of and proximity of mangrove islands to the coast. This ecological system includes three related components: coastal and tidal	TIDE 1998

MPA	Primary Reason for Establishment	Source[1]
	wetlands, marine lagoon, and the mangrove islands.	
Sapodilla Cayes Marine Reserve	It protects a unique hook-shaped reef formation and has the highest coral biodiversity in Belize. Its littoral forest provides an important connectivity point for migrating birds. At least twenty two species of international concern (critically endangered, endangered or vulnerable) occur here. It serves as an important nesting site for hawksbill and green sea turtles. It encompasses Nicholas Caye, Rise and Fall Bank, and Seal Caye SASRs.	Wildtracks 2010d
South Water Caye Marine Reserve	It was established to protect an important mangrove system and extensive seagrass meadows, which provide valuable habitat for commercial and non-commercial species including queen conch (*Strombus gigas*) and lobster (*Panulirus argus*). The sheltered waters and mangrove systems of the Pelican cayes in the southern area of the Marine Reserve have been identified as one of the most biodiverse marine systems within the western hemisphere. It includes Emily/Caye Glory SASR which occurs northeast of the MR.	Wildtracks 2009
Swallow Caye Wildlife Sanctuary	Reason for establishment unknown.	Management plan does not exist

[1] Source for most current management plans (Healthy Reefs for Healthy People 2012)

Table 4. MPAs and SASRs of Belize.

MPA	Designation	Year Established	Zoning	Use	Total Marine Area (km^2) [1]	Total Marine Area (km^2)[1]	Management Authority	
							Gov't Depart.	Co-manager
Bacalar Chico	Marine Reserve	1996	Conservation Zone 1	No-take	6.4	65.8	Fisheries	NONE
			Conservation Zone 2	Fishing permitted	4.1			
			General Use Zone 1	Fishing permitted	8.7			
			General Use Zone 2	Fishing permitted	5.0			
			Preservation Zone	No-take	2.8			
			Not zoned	Fishing permitted	33.1			
	Rocky Point (SASR)	2003	Reserve	No-take	5.7			Green Reef
Blue Hole	Natural Monument	1996	Not zoned	No-take	4.1	4.1	Forest	Belize Audubon Society (BAS)
Caye Caulker	Marine Reserve	1998	Conservation	No-take	8.2	39.1	Fisheries	Forest & Marine Reserves Association of Caye Caulker (FAMRACC)
			General Use South	Fishing permitted	6.8			
			General Use North	Fishing permitted	8.1			
			Limited Extraction	Fishing permitted	10.3			
			Preservation	No-take	5.8			
Corozal Bay	Wildlife Sanctuary	1998	Not zoned	Fishing permitted	730.5	730.5	Forest	Sarteneja Alliance for Conservation & Development
Gladden Spit & Silk Cayes	Marine Reserve	2000	Conservation	No-take	1.5	105.2	Fisheries	Southern Environmental Association (SEA)
			General Use	Fishing permitted	86.8			
	Gladden Spit (SASR)	2003	Reserve	No-take	16.9			
Glovers Reef	Marine Reserve	1993	Conservation Zone	Fishing permitted	70.7	351.1	Fisheries	NONE
			General Use Zone	Fishing permitted	225.0			
			General Use Zone	Fishing permitted	35.7			
			Seasonal Closure	No-take/Fishing	10.9			
			Wilderness Zone	No-take	2.7			
	Northern Glovers Reef (SASR)	2003	Reserve	No-take	6.2			
Half Moon Caye	Natural Monument	1982	Not zoned	No-take	39.2	39.2	Forest	Belize Audubon Society (BAS)
Hol Chan	Marine Reserve	1987	Conservation	No-take	2.7	55.3	Fisheries	NONE
			Conservation Zone B	Fishing permitted	21.7			
			General Use	No-take	3.8			
			General Use Zone C	Fishing permitted	25.7			
			Recreational	No-take	1.5			
Laughing Bird Caye	National Park	1991	Not zoned	No-take	41.0	41.0	Forest	Southern Environmental Association (SEA)

MPA	Designation	Year Establis hed	Zoning	Use	Total Marine Area (km²) [1]	Total Marine Area (km²)[1]	Management Authority	
							Gov't Depart.	Co-manager
Lighthouse Reef Atoll (not an MPA)	Sandbore Caye (SASR)	2003	Reserve	No-take	5.2	5.2	Fisheries	Belize Audubon Society (BAS)
	South Point (SASR)	2003	Reserve	No-take	5.3	5.3		
Port Honduras	Marine Reserve	2000	Conservation	No-take	13.2	404.7	Fisheries	Toledo Institute for Development & Environment (TIDE)
			General Use	Fishing permitted	391.5			
Sapodilla Cayes	Marine Reserve	1996	Conservation Zone 1	No-take	2.6	172.0	Fisheries	Southern Environmental Association (SEA)
			Conservation Zone 2	No-take	17.2			
			General Use Zone	Fishing permitted	119.6			
			Preservation Zone	No-take	2.2			
	Nicholas Caye (SASR)	2003	Reserve	No-take	6.7			
	Rise and Fall Bank (SASR)	2003	Reserve	No-take	17.2			
	Seal Caye (SASR)	2003	Reserve	No-take	6.5			
South Water Caye	Marine Reserve	1996	Conservation	No-take	78.0	482.5	Fisheries	NONE
			Conservation	No-take	10.6			
			General Use	Fishing permitted	387.7			
			Preservation	No-take	0.8			
	Emily/Caye Glory (SASR)	2003	Reserve	No-take	5.5			
Swallow Caye	Wildlife Sanctuary	2002	Not zoned	Fishing permitted	36.4	36.4	Forest	Friends of Swallow Caye (FOSC)
Turneffe Islands Atoll (not an MPA)	Caye Bokel (SASR)	2003	Reserve	No-take	5.6	5.6	Fisheries	University of Belize
	Dog Flea Caye (SASR)	2003	Reserve	No-take	5.8	5.8		

[1] Area based on ArcGIS 10.1 calculations.

2.2.5 Summary

Overall, the literature review provided in this chapter provides an overview of the Nassau grouper as the case study species and Belize as the case study region. This chapter demonstrates that there is much local and national activity that is directed towards the conservation of marine resources and the Nassau grouper in Belize. It appears that the Belizean government along with fishery cooperatives and NGOs are quite concerned about the potential loss of the species. There are also a number of significant pieces of legislation in place and a number of management tools that either directly or indirectly contribute to the conservation of this species. However, the literature review also highlights that there is a lack of coordination between agencies and that competing pieces of legislation may be compromising efforts.

3.0 Software and Data Source

This chapter provides a description of the software and data source that were used for the analysis.

3.1 Software

ArcGIS software was used to conduct the analysis. ArcGIS is a geographic information system (GIS) which integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information (ESRI 2011). This software is a powerful tool for environmental managers because it has spatial analysis and mapping capabilities that allows for the visualization and analysis of data (e.g., habitat coverage and species distribution) so that existing relationships, patterns, and trends can be revealed. In this study, ArcGIS was used to calculate total area (km^2) of the different habitat types as well as measure distances between MPAs.

3.2 Data source

Secondary spatial metadata from the Biodiversity and Environmental Resource Data System (BERDS) of Belize were used in the analysis. BERDS is a comprehensive biodiversity and environmental data warehouse and research system which provides shared access to biodiversity and environment-related data for Belize (BTFS 2012). Spatial metadata for Belize are based on the UTM Zone 16 Projection, the NAD 27 Central Datum, and the Clark 1866 Spheroid. BERDS was chosen as the data source as it is freely available and includes spatial metadata for all of Belize. No other similar data set was found. A comprehensive nation wide dataset such as that provided by BERDS is necessary to achieve the research objective, i.e., for comparability of data between MPAs/SASRs. Although no published studies similar to this thesis were found which use the BERDS spatial metadata as a data source, it is considered acceptable for the analysis as the BERDS data are used in the most current management plans for almost all of the MPAs in Belize (e.g., Bacalar Chico MR, Blue Hole NM, Corozal Bay WS, Gladden Spit and Silk Cayes MR, Laughing Bird Caye NP, Half Moon Caye NM, Sapodilla Cayes MR, and South Water Caye MR). GIS shapefiles including MPA/SASR boundaries, Belize basemap, and marine habitat classifications were downloaded via the BERDS website.

The marine habitat data found in BERDS were first compiled by Meerman and Sabido in 2001 who gathered available information on the terrestrial and marine (including deep sea habitats) ecosystems of Belize. Meerman and Sabido (2001) used a number of sources to create the habitat map: Landsat TM images, published vegetation, climatological and geological data, as well as field data. The final product was an all encompassing Belize Ecosystems Map on a scale of 1:100,000. It includes 65 Terrestrial classes, 14 Marine classes, 7 Agriculture classes, 6 Mangrove classes, 3 Inland water classes, and 1 Urban class. Figure 7 shows the 14 Marine and 6 Mangrove classes that were defined. These spatial metadata were updated in 2004, and revised again by Meerman in 2012 (BTFS 2012).

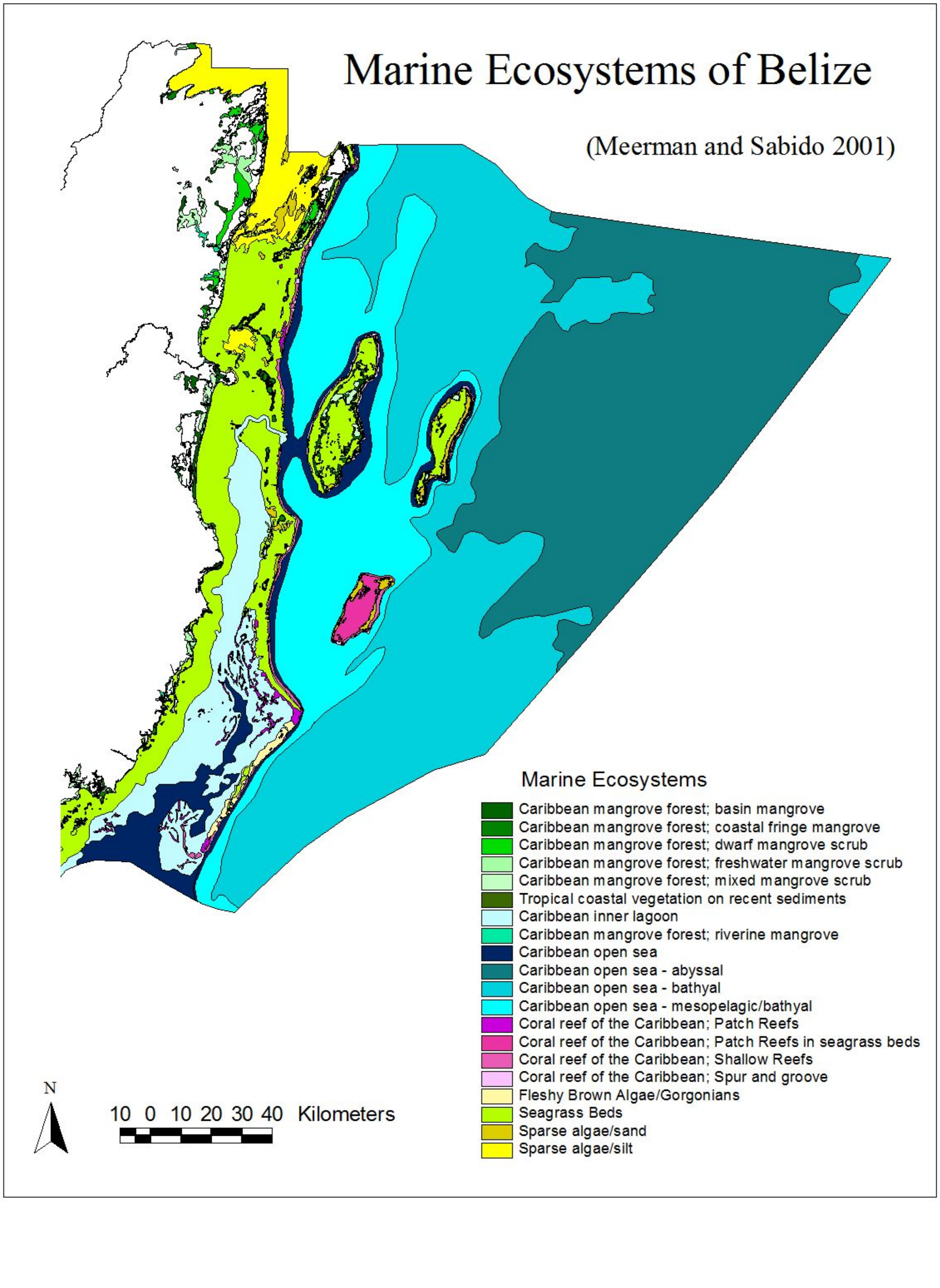

Figure 7. Marine ecosystems of Belize (Source of data: Meerman and Sabido 2001).

4.0 Habitat Assessment of the MPA/SASR System

This chapter examines the distribution of the various marine ecosystems within the MPA/SASRs in Belize. First, an introduction to the importance of habitat protection with respect to management of commercial fishery species is provided along with a description of the different marine ecosystems of Belize. The methods section includes an overview of what is currently known about the life cycle of the Nassau grouper in relation to habitat requirements during each of its primary life stages (larval, post-settlement, juvenile, and adult). The last section presents the results of the analysis.

4.1 Introduction

Habitat protection is often cited as an important goal for MPAs because it is believed that habitat loss is the single greatest cause for the worldwide decline in biodiversity and has serious implications for ecosystem functioning (Gray 1997; Pimm and Raven 2000). Besides the consequences of overfishing, habitat destruction is also known to profoundly affect the productivity of a fish stock (Boersma and Parrish 1999). Experts recommend that for any fishery species being targeted for protection an understanding of its life history in combination with identification and protection of essential fisheries habitat (EFH) are important management considerations (Posada and Apppeldoorn 1995; Friedlander 2001). For example, in the USA, the Sustainable Fisheries Act of 1996 (the principal piece of national fisheries legislation) mandates that commercial fish species require protection of those waters and substrates necessary for fish spawning, breeding, feeding, or growth to maturity (Fogarty 1999).

Belize's nearshore marine environment is a mosaic of different habitat types, e.g., algal, seagrass, coral reef, and mangroves, as listed and briefly described in Table 5. Currently 13% of Belize's marine area falls under some level of protection within the MPA/SASR network (BAS 2008). As indicated earlier in this paper, the SASRs in Belize are closed to fishing year round and were specifically targeted at the protection of adult Nassau grouper during spawning. There is no question that such reserves protect essential fisheries habitat and are absolutely critical for any chance of longterm viability for this species. The MPAs, although not specifically established for this purpose, are generally believed to also contribute to conservation of the species. However, a number of researchers report that in order for MPAs to be effective in grouper conservation they must incorporate appropriate habitat types to protect all of this species life history stages (Sluka et al. 1997; Bolden 2000; Gleason et al. 2006), and not solely mature individuals. The extent to which MPAs do so in Belize and other regions is not clear as no published studies on this topic were found.

Table 5. Description of the primary marine ecosystems of Belize.

Ecosystem	Description
Algae beds	Algae are marine plants that are simple in structure and are different from typical land plants because they lack roots, stems and true leaves. Algae have a large variety of growth forms ranging form single celled plankton algae to large seaweeds that can reach lengths of several meters (CRC Reef Research Centre Ltd. 2012). Algae are reported to provide shelter and food for fish larvae as well as food for organisms on which larvae feed (Reitan et al. 1997).

Coral reefs	Coral reefs are extraordinary living geological structures. They are highly diverse and productive, but grow best in oceanic waters with very low levels of nutrients. They only occur in relatively clear, warm waters, where water temperature rarely falls below 18° C. The basic building block of any coral reef system are corals, a group of animals (Cnidarians) whose basic structure is the coral polyp. They contribute a significant amount of calcium carbonate (limestone) building material on which a coral reef is built. Coral reefs are largely confined to shallow waters because the corals on which reefs rely contain small algae, called zooxanthellae, that are dependent on natural light for survival (CRC Reef Research Centre Ltd. 2012). The two distinct reef types classified by Meerman and Sabido (2001) include: 1. Patch reefs – Coral formations that are isolated from other coral reef formations by sand, seagrass, or other habitats and that have no organized structural axis relative to the contours of the shore or shelf edge. A surrounding halo of sand is often a distinguishing feature of this habitat type when it occurs adjacent to submerged vegetation (National Ocean Service 2011). 2. Spur and groove – alternating sand and coral formations that are oriented perpendicular to the shore or bank/shelf escarpment. The coral formations (spurs) of this feature typically have a high vertical relief compared to pavement with sand channels and are separated from each other by 1-5meters of sand or bare hardbottom (grooves), although the height and width of these elements may vary considerably. This habitat type typically occurs in the outer fore reef or bank/shelf escarpment zone (National Ocean Service 2011).
Mangroves	Mangroves are a diverse group of predominantly tropical trees and shrubs that grow in marine intertidal zones and share several highly specialized and collectively well-known adaptations, e.g., exposed breathing roots, support roots and buttresses, salt-excreting leaves, and viviparous water-dispersed propagules (Duke 1992). Their rich invertebrate faunas render them productive feeding areas, while their shallow waters and structural complexity provide sanctuary habitats for a variety of organisms (Sheaves 2005).
Seagrass beds	Seagrasses are not true grasses but are flowering plants which grow fully submerged and rooted in estuarine and marine environments (Green and Short 2003). They are a critical ecosystem for many fish and invertebrate species – an acre of seagrass can support up to 40,000 fish and 50 million small invertebrates (Seagrass Ecosystems Research Laboratory 2005).

4.2 Methods

Prior to conducting the habitat analysis, it was first necessary to determine and describe the habitat preferences of the Nassau grouper during each stage of its life cycle (early, juvenile, and adult life stages). GIS was then used to calculate the total area (km^2) of each marine habitat (ecosystem) type within the Belize MPA/SASR network.

4.2.1 <u>Current state of knowledge – Nassau grouper essential habitat</u>

The Nassau grouper, like most other reef fish species, experiences ontogenic[2] habitat shifts, e.g., movement from one habitat type to another, as an individual transitions from early to late life stages. This is believed to occur because as requirements for survival shift during growth, a specific habitat type will offer an organism lower mortality rates from predation and more optimal conditions for feeding than other habitat types (Dennis 1992). Figure 8 illustrates how a reef fish predator similar to the Nassau grouper, the red emperor snapper (*Lutjanus sebae*), requires many habitats throughout its life in order to survive; open ocean, shallow seagrass and sponges, inter-reef gardens and seaweed mounds, and deep-water reefs and seagrass (PISCO 2007). If one or more of its required habitats are unavailable, then that species might not persist or have reduced chances of survival.

Generally, the Nassau grouper is considered a shallow bottom dwelling species that can be found from inshore to about 100 m in reef, mangrove, seagrass, and estuarine habitats depending on age and stage of development (Sadovy and Eklund 1999). That is, like most other reef fish species, the Nassau grouper goes through various stages of development from birth to sexual

[2] Developmental history of an organism within its own lifetime (Dennis 1992).

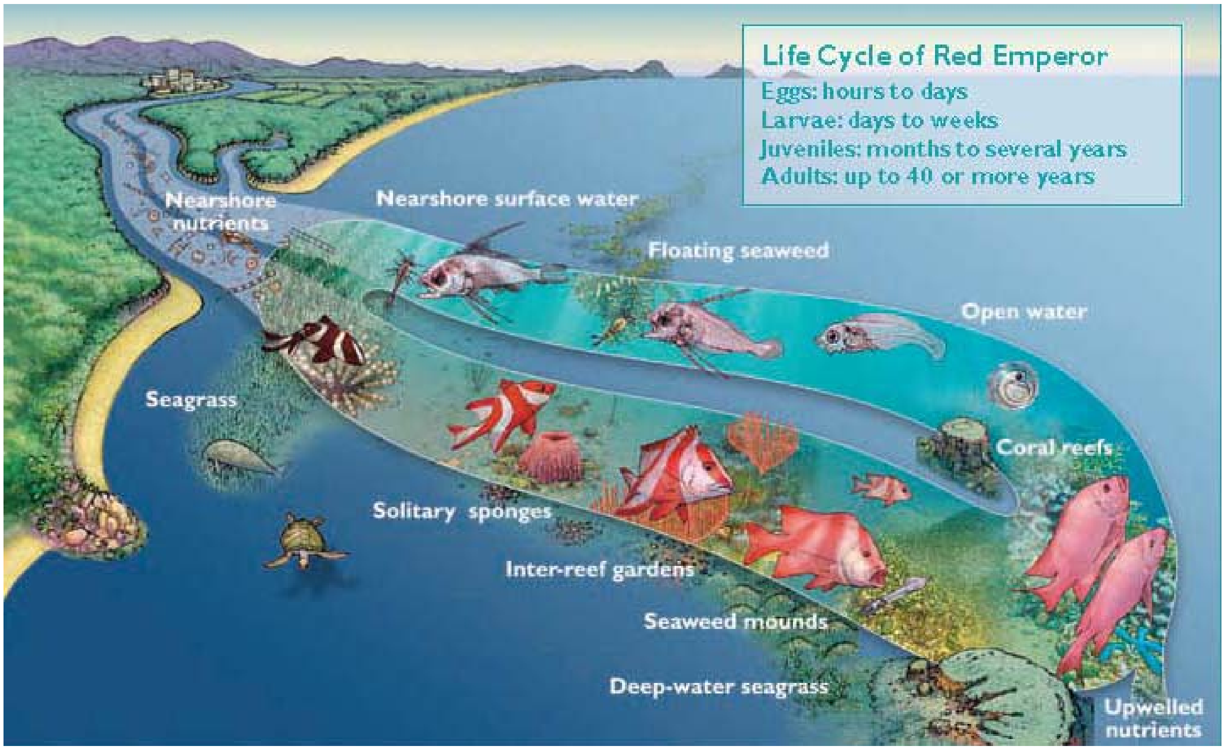

Figure 8. Life cycle of the red emperor snapper, *Lutjanus sebae* (PISCO 2007, p. 13).

maturity. These can be grouped into four broad categories: larval, post-settlement, juvenile, and adult life stages. Although there is evidence that habitat structure determines local distribution and abundance (Sluka et al. 1998), few studies concerning the habitat preferences of Nassau grouper during early life stages have been conducted (Beets and Hixon 1994; Eggleston 1995; Colin et al. 1997). This is also true for other commercially important conspecifics due to difficulties in sampling caused by the small size, typical low densities, and cryptic nature of early stage individuals (Aburto-Oropeza 2007). Most studies thus far have been performed on adult Nassau grouper (e.g., Smith 1972; Carter et al. 1994; Eggleston 1995; Colin et al. 1997; Sluka et al. 1997; Sluka et al. 1998; Sadovy and Eklund 1999; Gleason et al. 2006) not only because they are easier to sample, but also due to greater interest in their study as they are the prime targets for exploitation. Despite the data gaps, research is pointing in the direction that habitat selection is not a random process during all stages of growth and Nassau grouper actively select specific habitat types to optimize chances for survival (Montgomery et al. 2001; Cocheret et al. 2002). The following section is a summary of what is currently known about the Nassau grouper in relation to its habitat preferences (also summarized in Table 6).

i . <u>Larval Stage</u>

Like nearly all other reef fish, Nassau grouper produce eggs which hatch into larvae that have a pelagic stage in the ocean before settling into post-larval habitat (Eggleston 1995; Colin et al. 1997). In laboratory conditions, eggs hatch within 27-29 hours after fertilization at 25°C and 23-25 hours after fertilization at 28°C (Powell and Tucker 1992). New born larvae are quite small as depicted in Figure 9 where a 1 day old individual was measured at 2.5 mm total length (TL).

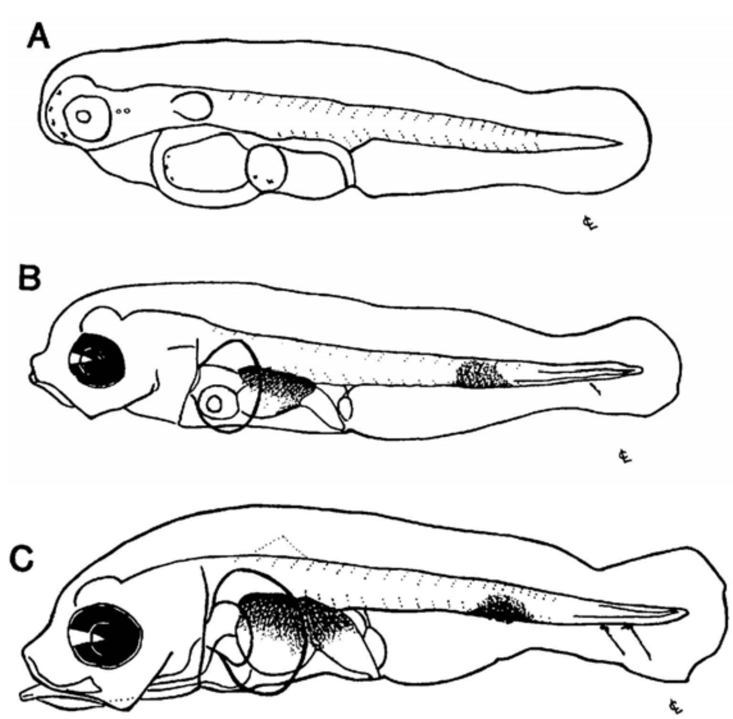

Figure 9. Early larval stages of laboratory-reared Nassau grouper A) 2.5 mm, 1 day old; B) 2.6 mm, 3 days old C) 2.9 mm, 5 days old (Powell and Tucker 1992, p. 174).

ii. Post-settlement Stage

The stage that follows the larval stage is called post-settlement. Settlement has been described as the consequence of biological and physical processes operating on larvae during the transition from a pelagic to benthic existence (Eggleston 1995). In simpler terms, it is the period when larvae leave the plankton and colonize the substrate (Sadovy and Eklund 1999). It is reported that for reef fishes in general, suitable settlement habitat is an important factor in enabling young, vulnerable fishes to avoid predation (Sadovy 1994). Colin et al. (1997) sampled settlement-ready and newly-settled Nassau grouper and reported that captured individuals at this stage of development were strong swimmers despite their small size and able to direct their movements. Thus, it is reasonable to expect that settlement is not random as each species has specific resource needs at each life stage and so some direct selection of habitat on the part of the individual must occur to increase its chances of survival. There is little published research on the specific habitat requirements of post-settlement Nassau grouper and only Eggleston (1995) reports that recently settled individuals (2.5 to 3.5 cm TL) were found to reside exclusively within coral clumps (*Porites* spp.) covered by masses of macroalgae (primarily *Laurencia* spp.). Eggleston (1995) further suggests that the algal-covered coral clumps formed an open lattice that facilitated movement of the post-settlement larvae. The importance of algal habitat has also been reported for leopard grouper (*Cephalopholis leopardus*) where abundance of post-settlement larvae was dependent on availability of shallow rocky bottoms with brown algal (*Sargassum* spp.) beds (Aburto-Oropeza 2007).

iii. Juvenile Stage

The juvenile stage is that which follows post-settlement. Juvenile habitat, sometimes called nursery habitat, has been described as areas used for some period of time by juvenile fish prior to movement into adult habitat (Gillanders et al. 2003). Sadovy and Eklund (1999) report that specific habitat needs limit suitable nursery habitat for immature Nassau grouper. Young juveniles are reported in seagrass beds (Heemstra and Randall 1993), macroalgal clumps and beds (Sadovy and Eklund 1999), and shallow macroalgal meadows (Gillanders et al. 2003). Eggleston (1995) made a distinction between habitats used by early and late juveniles, reporting that early juveniles (6.0 to 15.0 cm TL), 3-5 months, reside mainly outside of and adjacent to algal-covered coral clumps while larger juveniles (>l5.0 cm TL), >5 months, were generally associated with patch reefs. There does not appear to be any publication that indicates mangroves as important habitat to juvenile Nassau grouper, though mangroves are cited as important to juveniles of goliath grouper, *Epinephelus itajara,* (Cavalieri Gerhardinger et al. 2006), and other reef fish species (Dennis 1992; Cocheret et al. 2002; Sheaves 2005; Faunce and Serafy 2006). Also, a number of scientists agree that both seagrass and mangrove habitats are critical to many species of juvenile reef fish (Weinstein and Heck 1979; Stoner 1983; Parrish 1989; Cocheret et al. 2002) so until further research is conducted, the importance of mangroves to Nassau grouper should not be discounted. Seagrass and mangrove habitat are believed to offer food resources and protection from predation and allow immature fish to reach sizes that increase their chances of survival on coral reefs (Dennis 1992). Intuitively, smaller fish avoid predation more easily by hiding among seagrass beds or between mangrove roots, whereas over a hard exposed substrate like a coral reef they would be more exposed to predation.

iv. Adult Stage

There is more literature on the preferred habitat of adult Nassau grouper than at any other life stage. Adult Nassau grouper are found in high-relief coral habitats and over rocky surfaces (Sadovy and Eklund 1999), offshore coral reefs (Eggleston 1995), channel reef, fringing reef, patch reef, and hard bottom substrates (Sluka et al. 1997), and hard substrates with complex substrates such as caves, crevices, and ledges (Gleason et al. 2006). It is generally assumed that adult reef fish in general, including the Nassau grouper, migrate to coral reefs when they reach or are near maturity because this habitat is more suitable in terms of reproduction, food, and shelter (Dorenbosch et al. 2007).

The habitats that Nassau grouper use during spawning are very specific and only frequented during the reproductive period. Although the reasons for the specificity of these sites will likely always remain a mystery, they share some common characteristics. Reported sites are described as offshore edges of banks in water 29-38 m deep (Smith 1972), the end of broad low relief rocky coral shelves (Carter et al. 1994), edges of insular shelves (Colin et al. 1997), and edges of insular platforms close to drop-offs into deep water (Sadovy and Eklund 1999). Although the reasons are unclear, tagged adults are also known to inhabit deeper ocean environments ~70 m for several months, between February and April, following the spawning season (Starr et al. 2007).

Table 6. Published information on the specific habitat requirements of Nassau grouper during key life cycle stages.

Life Stage	Habitat Description	Sources
Larval	Suspended within the water column	Eggleston 1995; Colin et al. 1997
Post-settlement larvae	Coral clumps (*Porites* spp.) covered by masses of macroalgae (primarily *Laurencia* spp.)	Eggleston 1995
Juvenile	Seagrass beds	Heemstra and Randall 1993
	(1) Early juveniles (6.0 to 15.0 cm TL), 3-5 months, reside outside and adjacent to algal-covered coral (2) Larger juveniles (> 15.0 cm TL), > 5 months, associated with natural and artificial patch reefs	Eggleston 1995
	Artificial reefs / bank environments and offshore reefs	Colin et al. 1997
	Macroalgal clumps and beds	Sadovy and Eklund 1999
	Shallow macroalgal meadows	Gillanders et al. 2003
Adult (non – reproductive)	Offshore coral reefs (>30.0 cm TL), 3 to 4 yr following post-settlement	Eggleston 1995
	Reef and hard bottom substrates	Sluka et al. 1997
	Most abundant in clear water with high relief corals or rocky substrate	Sadovy and Eklund 1999
	Hard substrate with high local heterogeneity; complex substrates (caves, crevices, ledges)	Gleason et al. 2006
	Deep reef ocean environments ~70 m for several months following the spawning season	Starr et al. 2007
Adult (spawning)	Edge of a bank in water from 29-38 m deep. The bottom was a thin sand veneer over limestone base rock with abundant soft corals, sponges, and occasional colonies of stony coral	Smith 1972
	Near the seaward end of a broad, relatively low relief coral shelf sloping gently to about 27-30 m, extending approximately 100-200 m eastward of the exposed reef crest. Beyond this the narrow rocky shelf ledge drops away vertically to abyssal depths	Carter et al. 1994
	Edges of insular shelves	Colin et al. 1997
	Edge of insular platforms, as little as 350 m from the shore, and close to a drop-off into deep water over a wide (6-50 m) depth range and diversity of substrate types	Sadovy and Eklund 1999

4.2.2 GIS analysis – distribution of marine ecosystems within current MPA/SASR set-up under three perspectives

ArcGIS 10.1 software was used to group the 14 marine classes and 6 mangrove classes defined by Meerman and Sabido (2001) into 11 marine ecosystem types as illustrated in Figure 10. The various main habitat types, coral reef, patch reefs, spur and groove, seagrass, algae, and mangroves, are described in Table 5. This was performed based on what was derived from the literature review, which indicated that for the purposes of this thesis, it is not necessary to differentiate all the marine ecosystems types at the low level defined by Meerman and Sabido (2001). For example, the 6 Mangrove classes (e.g., basin mangrove, coastal fringe mangrove, and dwarf mangrove scrub) depicted in Figure 7 in Chapter 3 were grouped into a single category called Mangroves (0-5 m), and the 3 Algae classes (i.e., Fleshy Brown Algae/Gorgonians, Sparse Algae/Sand and Sparse Algae/Silt) were grouped into a single class called Algae. Information on depth for each of the marine ecosystems was included in the final map.

The most current management plans for each of the MPAs/SASRs were downloaded freely via the Healthy Reefs for Healthy People (2012) website, with the exception of Lighthouse Reef Atoll (Sandbore Caye and South Point SASRs) and Swallow Caye WS for which no management plan currently exists. The metadata for the boundaries and management zones for each of the MPAs/SASRs in Belize were downloaded via the BERDS website. The information found within this spatial dataset were compared and verified against that found in respective management plans.

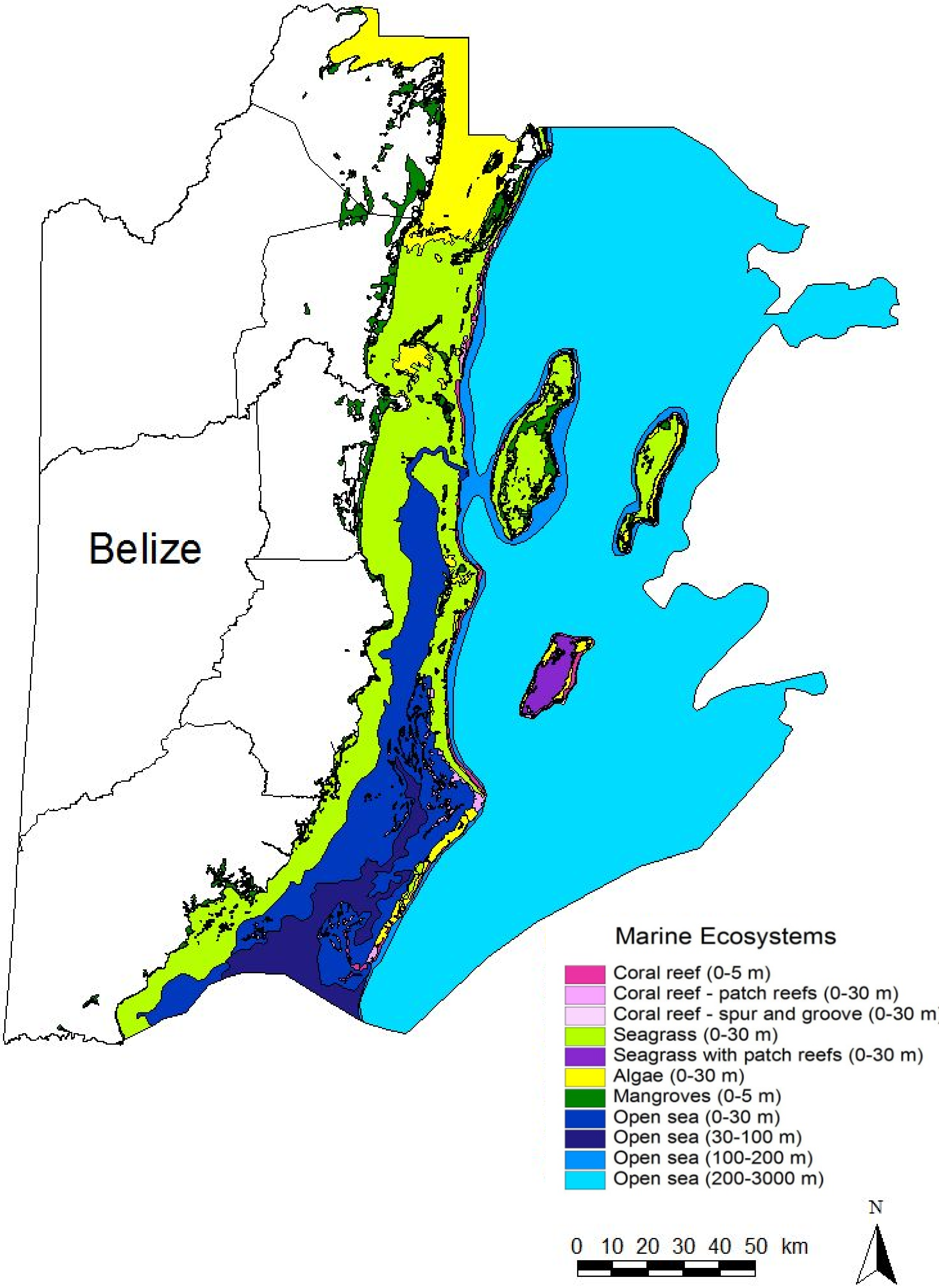

Figure 10. Marine ecosystems of Belize (Source of data: Meerman and Sabido 2001) regrouped into 11 classes.

The last step was taking the newly generated marine ecosystem and MPA/SASR boundary maps and using GIS to calculate the total area (km^2) of each marine ecosystem type under three perspectives:

i. Marine ecosystem distribution within the entire Belize MPA network;

ii. Marine ecosystem distribution within the SASRs (excluding MPAs); and,

iii. Marine ecosystem distribution per MPA/SASR.

4.3 Results

This section describes the results that were generated following the GIS analysis under the three perspectives listed above.

4.3.1 Marine ecosystem distribution within the Belize MPA network

The total area calculated for all the MPAs/SASRs is 2546.1 km^2 and Figure 11 displays the total area (km^2) calculated for each marine ecosystem category. The most abundant marine ecosystem is Algae (842.0 km^2), roughly one third of the total area under protection within the Belize MPA network. The Open Sea – 0-30 m category followed in size at 527.7 km^2, with Seagrass (500.3 km^2), Open Sea – 200-3000m (168.0 km^2) and Seagrass with Patch Reefs (152.3 km^2) following with respect to total area. The areas calculated for other marine ecosystem types were <100 km^2. The coral reef types are among the lower areas; 0-5 m coral reef (87.7 km^2), 0-30 m patch reefs (78.3 km^2), and spur and groove (25.2 km^2).

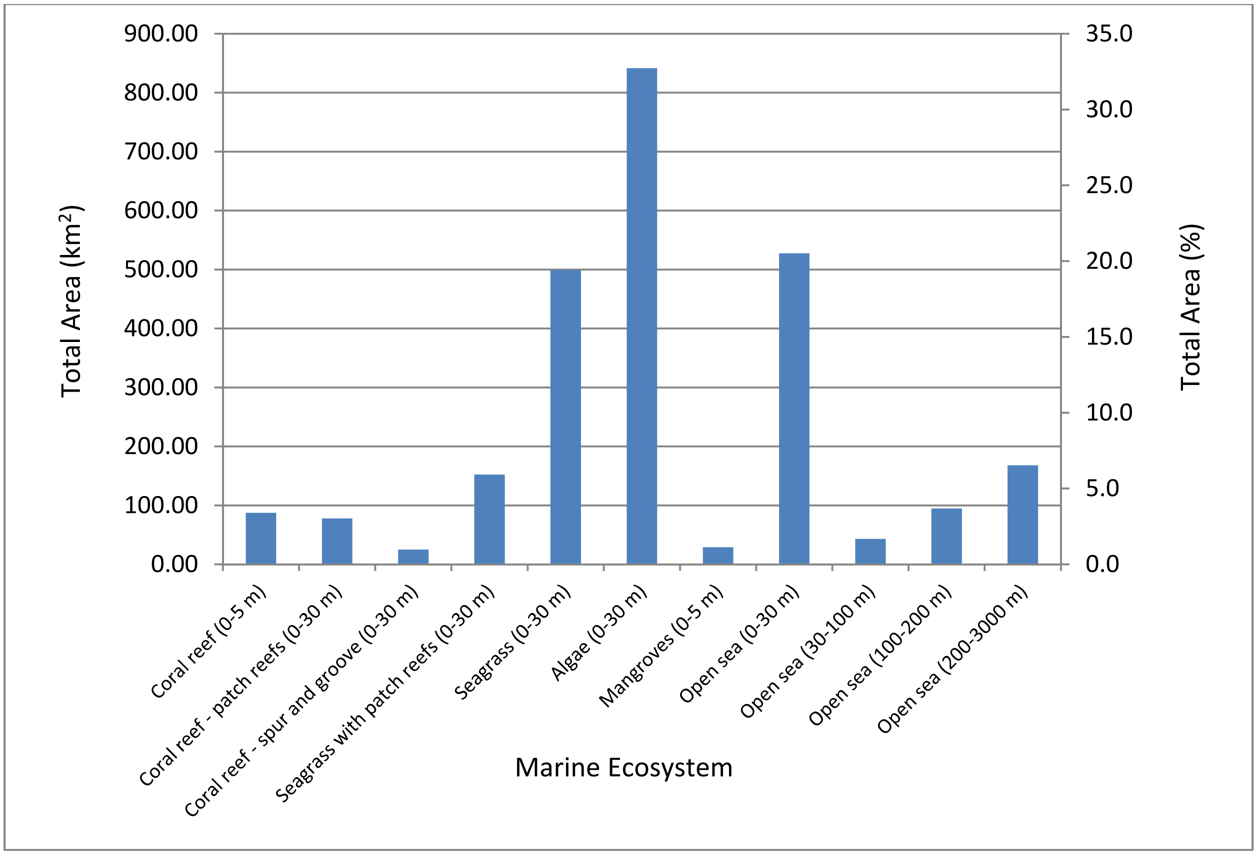

Figure 11. Total combined area of each marine ecosystem protected within the Belize MPA/SASR network.

4.3.2 Overall marine ecosystem distribution within SASRs

The total area calculated for the SASRs combined (excluding MPAs) is 86.5 km^2. Figure 12 displays the total area (km^2) that was found for each of the marine ecosystems for all the SASRs. The largest proportions protected fall under the open sea categories; 200-3000 m open sea (27.3 km^2), 100-200 m open sea (22.4 km^2), and 0-30 m open sea (18.9 km^2). These are followed by 0-5 m coral reef (11.3 km^2) and 0-30 m spur and groove coral reef (1.1 km^2). The algae, seagrass, and mangrove ecosystem types are negligible (respectively <1.0 km^2).

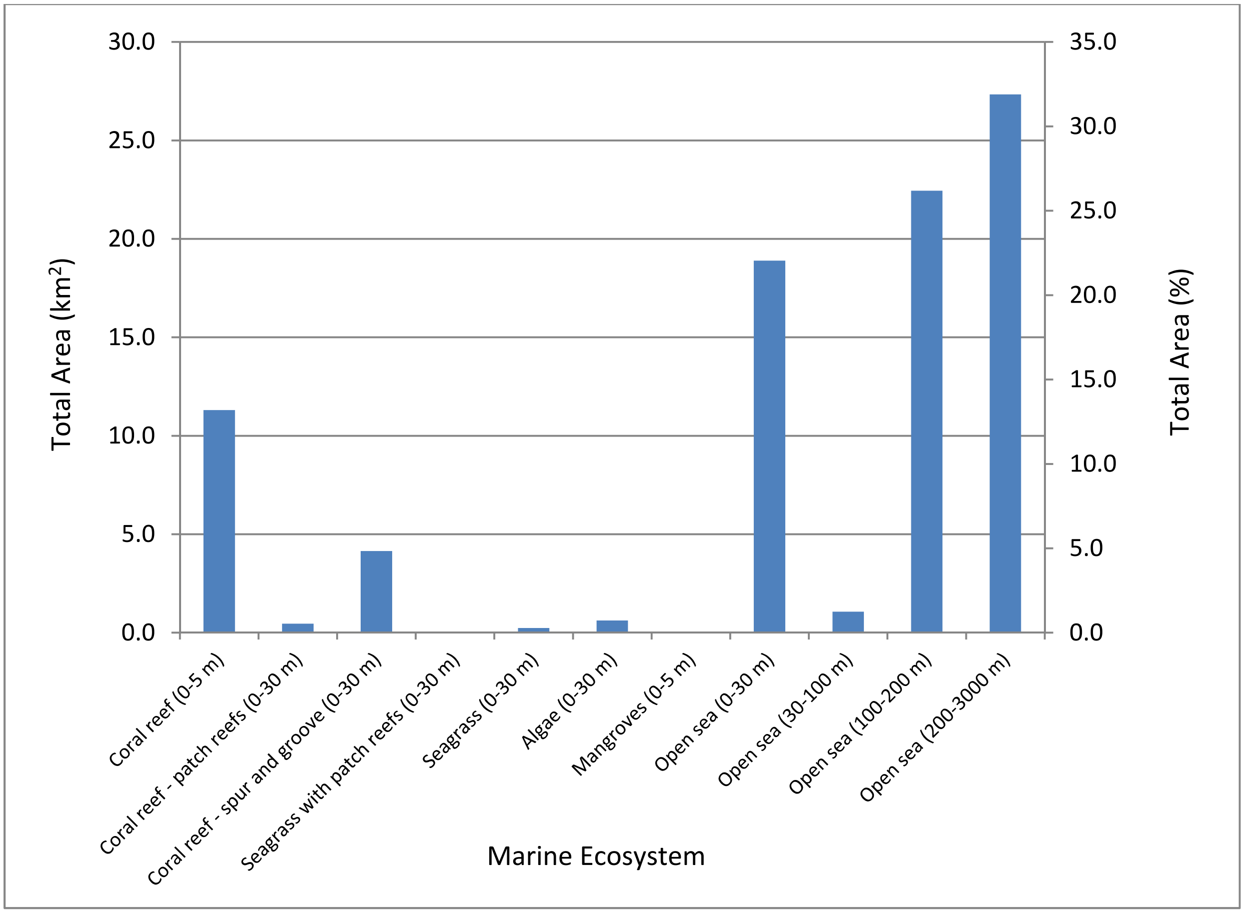

Figure 12. Total area of each marine ecosystem protected within the Belize SASRs.

4.3.3 Marine ecosystem distribution within individual MPAs/SASRs

In the final analysis, a separate map was generated for each MPA/SASR in order to determine the percent coverage of each marine habitat type within the boundaries of each of the MPAs/SASRs. For example, Figure 13 is the map that was generated for Bacalar Chico Marine Reserve. Although the boundaries for the separate management zones were not used in the analysis, these are also illustrated for those MPAs having such zones. Refer to Appendix for all generated maps. Table 7 displays the total area (km^2) that was calculated for each marine ecosystem per MPA in Belize. It is evident from that the distribution of marine ecosystems is quite different among MPAs.

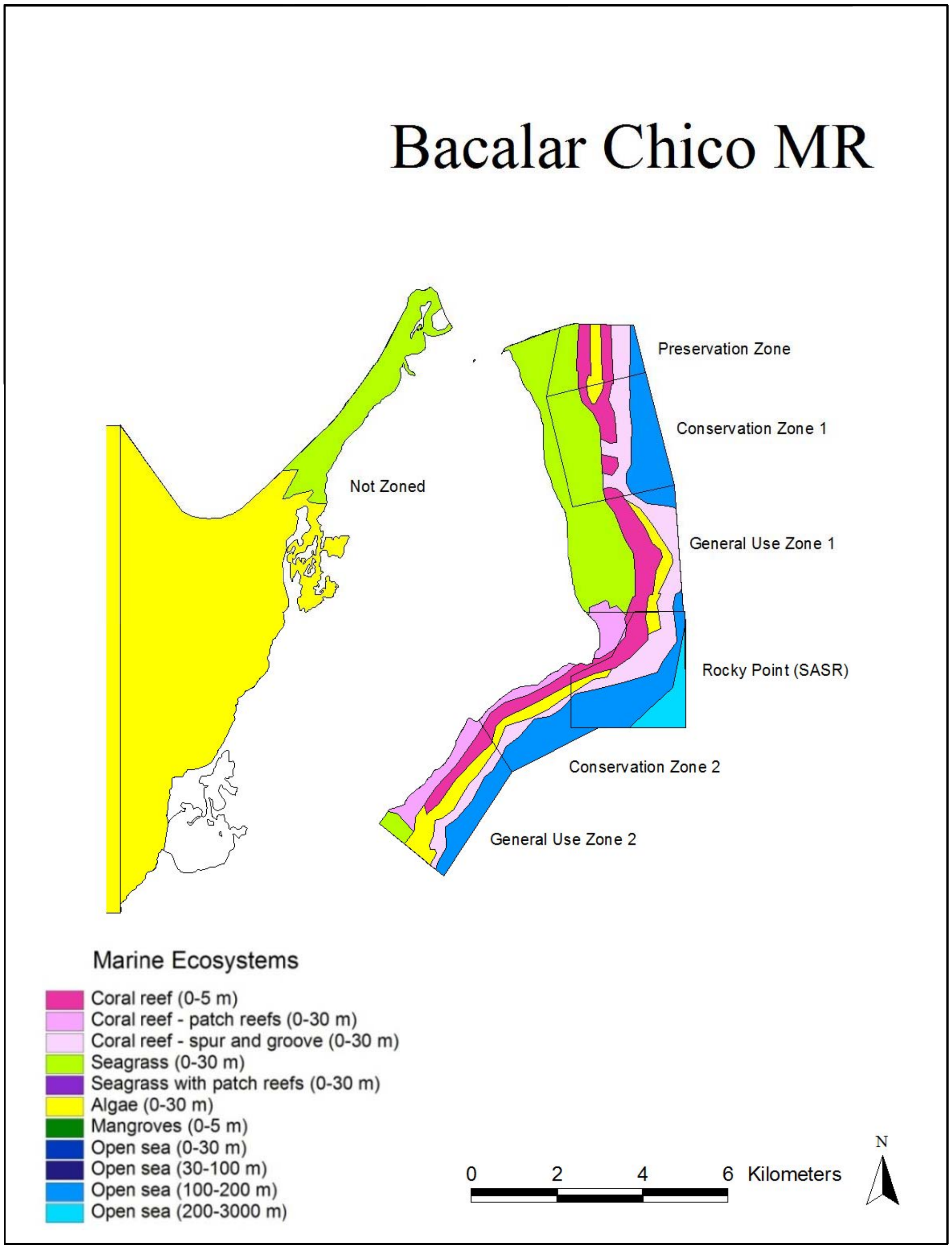

Figure 13. Marine ecosystems and management zones for Bacalar Chico Marine Reserve. Refer to Appendix 1 to see maps generated for other Belize MPAs/SASRs.

Table 7. Total area (km^2) of each marine ecosystem within the Belize MPA network (*Dog Flea, Caye Bokel, Sandbore, and Southpoint SASRs do not fall under an MPA).

MPA/SASR	Total Area (km^2)	Total Area per Marine Ecosystem (km^2)										
		Algae (0-30 m)	Seagrass (0-30 m)	Mangroves (0-5 m)	Seagrass with Patch Reefs (0-30 m)	Coral Reef (0-5 m)	Coral Reef Patch Reefs (0-30 m)	Coral Reef Spur & Groove (0-30 m)	Open sea (0-30 m)	Open sea (30-100 m)	Open sea (100-200 m)	Open sea (200-3000 m)
Bacalar Chico MR	65.8	30.1	13.5	0.0	0.0	5.5	2.5	5.5	0.0	0.0	7.7	1.0
Blue Hole NM	4.1	1.3	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Caye Caulker MR	39.1	0.0	12.7	0.0	0.0	6.9	0.0	6.7	0.0	0.0	10.7	2.1
Corozal Bay WS	730.5	715.5	7.7	7.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dog Flea & Caye Bokel SASRs*	11.5	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	7.3	2.8
Gladden Spit & Silk Cayes MR	105.2	18.8	8.9	0.0	0.0	8.1	15.6	0.0	21.7	0.0	12.8	19.3
Glovers Reef MR	351.1	49.3	0.0	0.5	152.3	32.7	5.6	7.1	0.0	0.0	0.0	103.6
Half Moon Caye NM	39.2	1.3	1.6	0.3	0.0	0.2	0.5	1.5	0.0	0.0	2.8	31.0
Hol Chan MR	55.3	6.4	39.8	2.0	0.0	3.1	0.1	1.5	0.0	0.0	1.9	0.5
Laughing Bird Caye NP	41.0	0.0	0.0	0.1	0.0	0.0	5.9	0.0	33.6	1.2	0.0	0.0
Sandbore & South Point SASRs*	10.5	0.0	0.2	0.0	0.0	0.5	0.0	1.5	0.0	0.0	3.8	4.6
Port Honduras MR	404.7	0.0	282.0	6.8	0.0	0.0	7.8	0.0	101.7	6.3	0.0	0.0
Sapodilla Caye MR	172.0	11.9	0.0	1.0	0.0	19.7	9.4	0.0	93.6	23.1	12.2	1.1
Southwater Caye MR	482.5	7.4	98.6	7.0	0.0	11.1	30.9	0.0	277.0	12.7	35.8	2.0
Swallow Caye WS	36.4	0.0	32.3	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL AREA	**2548.9**	**842.0**	**500.3**	**29.1**	**152.3**	**87.7**	**78.3**	**25.2**	**527.7**	**43.3**	**95.0**	**168.0**

5.0 Ecological Connectivity

This chapter includes an overview of ecological connectivity and how it relates to the movement of marine organisms and the spacing of individual MPAs within a network. Following this, a review of the current state of knowledge of the movement (also referred to as dispersal) patterns of the Nassau grouper during four primary life stages (larval, post-settlement, juvenile, adult) is provided. The analysis then examines whether the Belize MPAs function as a network with respect to peer-reviewed recommendations for inter-MPA distances for spacing in relation to ecological connectivity. The last section presents the results of the analysis.

5.1 Introduction

A network of MPAs is said to be functioning when marine organisms move between individual MPAs via larval dispersal and juvenile or adult movement (Gaines et al. 2003; Lubchenco et al. 2003; Palumbi 2003). This exchange is called 'ecological connectivity' and there is a general consensus amongst scientists that it is important for a group of individual MPAs to function together as a network (Roberts 1997; Sale et al. 2005; Steneck 2006; Jones et al. 2007; Green et al. 2009; McLeod et al. 2009; Planes et al. 2009; Gaines et al. 2010). There is some discrepancy in how ecological connectivity is defined within the literature (Cowen et al. 2000; Palumbi 2003; Sale et al. 2005; Fogarty and Botsford 2007; Jones et al. 2007); however, for the purposes of this study the following definition by Palumbi (2003) will be used: 'Ecological connectivity is the extent to which populations of a species in different parts of its range are linked by the exchange of larvae, juveniles, or adults.' That is, only those MPAs having some level of exchange would be considered connected. Steneck (2006) provides a simplified illustration in

Figure 14 to depict well connected versus poorly connected MPAs within a network. The left image shows that having many MPAs within a given area provides more opportunities for exchange (arrows), and hence a network of well connected MPAs. The image on the right illustrates that fewer MPAs in a given area leads to lower connectivity.

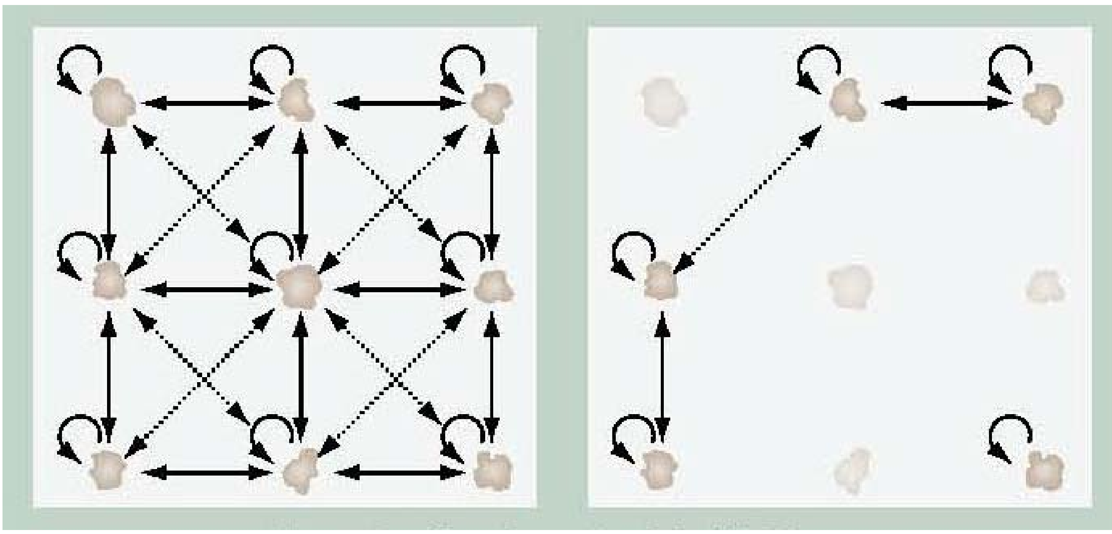

Figure 14. A well connected (R) versus poorly connected (L) MPA network. The arrows show exchange within and between MPAs (Steneck 2006, p. 481).

As described earlier, many species of fish, like the Nassau grouper, undertake ontogenetic migrations between seagrass beds, mangroves, and coral reefs as they transition from one life stage to another (Mumby 2006). A simple way to think of ecological connectivity is this movement of organisms between habitats. It is important to remember that ontogenic shifts are not random (Mumby 2006) but that mobile marine organisms actively select preferred habitats to increase their chances of survival.

In order to determine if the current MPAs/SASRs in Belize provide adequate protection to the Nassau grouper with respect to ecological connectivity would require several pieces of information: first, knowledge of which habitat types are important to the Nassau grouper; second, which habitats are protected within and between the MPAs; third, some knowledge of the home range and average distance that Nassau grouper migrate between habitat types; and fourth, knowledge of the spacing of those habitat types within and between MPAs. This information is important for management because in order to maximize protection of a target species, an understanding of its movement patterns and required habitats is essential. This knowledge would provide managers with some insight concerning how well the current MPAs in Belize are functioning as a network with respect to ecological connectivity and protection of that species. Unfortunately, very little is known about the movements and migration dynamics of Nassau grouper and other reef fishes in general (Starr et al. 2007), but especially at early life stages. Taking Johannes (1998) approach, scientists and managers must piece together what information is available. Intuitively, the less distance an organism must travel at earlier life stages to reach more mature habitats, the more likely its chances for survival.

5.2 Methods

5.2.1 Selection of approach

The method that is used to assess the connectedness of MPAs in Belize was employed by Wood (2007). No other method for assessing ecological connectivity within a network of MPAs was found in the literature. Wood (2007) examined the network characteristics of the world's MPAs and assessed the 'connectedness' of individual MPAs in terms of peer-reviewed recommendations for inter-MPA spacing. Using GIS, recommended distances were created into buffer 'bands' around the exact center, or centroid, of individual MPAs. Wood (2007) counted any MPAs occurring within these zones as being 'connected' to at least one other MPA. It is crude and simple, but no other similar study was found.

According to Palumbi (2003), to evaluate the extent of connectivity between MPAs within a network requires information on the inter-spacing of individual MPAs within that network. For this information to be meaningful for the conservation of a species like the Nassau grouper requires quantitative information about the movement patterns of that species throughout its life cycle. However, so little is known about the movement of the Nassau grouper and most marine organisms, and there is such variation between species, that the optimum distance between MPAs is still very much under debate within the scientific community. This is clear because the recommendations for ecological connectivity that can be found in the literature range quite widely (e.g., 10-20 km for Shanks et al. 2003; ≤ 50 km for Almany et al. 2009; ≤ 100 km for Sala et al. 2002, and ≤ 10-200 km for Palumbi 2004). The lower and upper limits signify that there is some variance in movement patterns between species, but that the proposed range should encompass them all.

The means by which these recommendations were made is confusing and does not appear to be based on robust data. For example, Shanks et al. (2003) compiled available estimates of dispersal distance for 32 taxa (e.g., algae, coral, crustacean, and fish species) and created a model which predicts that MPAs spaced 10 to 20 km apart should be close enough to allow for exchange of individuals of these taxa, i.e., ecological connectivity, between protected areas. Almany et al. (2009) conducted a review of published literature on MPA spacing and stated that 'conservatively, between reserve distances of ≤ 50 km should ensure sufficient connectivity for most species'. Sala et al. (2002) assumed that the largest gap between MPAs should not exceed 100 km based on estimates not yet published by Kinlan and Gaines (2003) concerning the movement of marine fish, as well as macroalgae and invertebrate species. Palumbi (2004) provides the most conservative recommendation of 10-200 km based on published estimates of larval dispersal distances and tagging studies of adult reef fish. This wide range and lack of consensus suggests that there are still many data gaps. Also, that optimal spacing is most likely species specific. Again, in order to be useful in the management of Nassau grouper, optimal inter-MPA spacing would require information about its movement patterns at all life stages.

5.2.2 Current state of knowledge – movement patterns of Nassau grouper at various stages of growth

To determine whether an existing MPA network incorporates ecological connectivity for a species like the Nassau grouper requires an understanding of that species' movement patterns at all life-history stages (Fogarty and Botsford 2007; Starr et al. 2007). The next step in the analysis is to determine what is known about the movement patterns of Nassau grouper at its various stages of development (larval, post-settlement, juvenile, and adult). Such knowledge should help determine whether the spacing of individual MPAs within the Belize network are allowing for adequate movement of Nassau grouper between individual protected areas.

i. Larval/post-settlement life stages

After Nassau grouper spawn, eggs float and reach the water surface within 3 to 5 h (Colin 1992). Besides a reported 37 to 45 day period suspended within the water column (Colin et al. 1997), where and how far larvae disperse from aggregation sites remains unknown (Almany et al. 2009) and little is known about movement patterns (Starr et al. 2007). Nevertheless, some information concerning what happens during the larval stages of marine fish in general can be found in the literature. For example, given their small size, marine fish larvae were once thought to be passive particles at the mercy of ocean currents, tides, and weather events (Carter et al. 1994; Roberts 1997; Montgomery et al. 2001).

On a regional scale, the Caribbean Current forms the main surface circulation in the Caribbean Sea flowing westwards from the Lesser Antilles towards southern Belize, then northwards offshore, beyond the atolls, eventually through the Yucatan Channel (Wildtracks 2010b). Sadovy and Eklund (1999) suggest that in Belize, currents in the vicinity of aggregation sites do not favour offshore transport of eggs and that eggs released at a particular site replenish populations within the vicinity of where they were released. Also, it is now accepted that although affected by their physical environment, the action of currents does not explain where larvae of marine organisms settle (Barber et al. 2000). Although the mechanisms are not well understood, there is growing evidence that the larvae of most reef fish species swim and direct their movements to actively select suitable habitat for settlement (Montgomery et al. 2001; Paris et al. 2005; Leis et al. 2011). Furthermore, although there is little empirical data on distance travelled from spawning sites, it is now accepted that larvae do not disperse as far from source populations as previously thought (Delgado et al. 2008; Jones et al. 1999, 2005; Thorrold et al. 2001; Cowen et al. 2003). If this is true, when eggs are released from a spawning site, larvae do not move far from their point of origin and possibly settle in suitable habitat not far from spawning sites. This means that in order for MPAs in Belize to offer protection to Nassau grouper at early life stages, then it would be important for suitable settlement habitat to be nearby.

The movement of larvae into settlement habitat is also not well understood. Studies are difficult due to the small size and large numbers of individuals that need to be monitored in order to recover a sufficient sample size (Gillander 2002). Furthermore, tagging eggs and larvae of any species to track their movement is extremely challenging and the extremely high rates of mortality at early life history stages means that the probability of recovering tagged individuals is very low (Thorrold et al. 2002). Some authors suggest that tracking larvae to directly measure connectivity is expensive and challenging, and will likely remain difficult in the foreseeable future (Palumbi 2003; Thorrold et al. 2006).

Figure 15. Larvae of *Epinephelus sp.* (Permission to use photo from C. Guigand).

ii. Juvenile/adult life stages

Juvenile (Eggleston 1995) and adult Nassau grouper are reported to lead solitary lives outside the spawning season, rarely venturing far from cover (Smith 1972; Carter et al. 1994; Sluka et al 1998; Sadovy and Eklund 1999). Although a number of publications report that adult Nassau grouper are capable of moving great distances, e.g., 250 km (Colin 1992), 16 km (Roberts et al. 1995), and 30 km (Starr et al. 2007), several authors agree that Nassau grouper are mostly sedentary and remain in a small territory outside the spawning season (Heemstra and Randall 1993; Beets and Hixon 1994; Starr et al. 2007). Site fidelity was reported during a tagging study of Nassau grouper juveniles conducted by Beets and Hixon (1994). Beets and Hixon (1994) found high site fidelity and homing of tagged individuals; 15 of the 17 grouper tagged and released over their original reefs persisted for over 2 weeks; only a single individual of another group of 50 tagged fish was observed on a reef other than where it was tagged; of 31 grouper which were displaced to reefs 140 m away from where they were captured, 29 homed to their original reef within 10 days. In a tagging study performed by Starr et al. (2007) at Glover's Reef Marine Reserve in Belize, it was found that all tag returns from fishers showed that Nassau groupers inhabiting the reef did not leave the atoll from which they were tagged. Site fidelity and possession of a small home range is also reported for goliath grouper (Pina-Amargós and González-Sansón 2009) and many other coral reef fishes (Holland et al. 1996; Friedlander 2001; Amargós et al. 2008; Sale and Kritzer 2008). However, it should be noted that there is reported variance of home range size within the genus *Epinephelus* itself, e.g., *Epinephelus guttatus* 862 m^2 (Kramer and Chapman 1999) and *Epinephelus tauvina* 344,000 m^2 (Kaunda-Arara and Rose 2004) so comparisons with other species may not be meaningful.

Starr et al. (2007) suggest that Nassau grouper are unlikely to swim long distances over deep water and that they require contiguous reef tracts to migrate. With respect to migration to spawning sites, Carter et al. (1994) reports that it is unlikely that Nassau grouper are drawn from great distances given their bottom dwelling nature and the sheer depths and distance that fish must negotiate to reach spawning sites. In a study conducted by Patterson et al. (1999) it was found that otoliths taken from Nassau grouper in various locations in the Bahamas were the same, but different when compared to those taken in Belize. This suggests genetic variation between regions which supports the general perception that Nassau grouper remain in one location throughout their lives.

5.2.3 GIS analysis: assessment of 'connectedness' of Belize MPA network

In order to assess the extend of 'connectedness' of individual MPAs within Belize, the following peer-reviewed recommendations for MPA spacing are used: 10-20 km (Shanks et al. 2003), ≤ 50 km (Almany et al. 2009), ≤ 100 km (Sala et al. 2002), and ≤ 10-200 km (Palumbi 2004). As performed by Wood (2007), GIS recommended distances were created into buffer 'bands' around the exact center, or centroid, of each MPA. MPAs occurring within the perimeter of a buffer band were considered 'connected' to the MPA in question; an MPA was counted as being within the buffer if any part of it fell within the buffer zone. Figure 16 is the map that was generated for Glover's Reef Marine Reserve including the 4 buffer bands. This was repeated for each MPA.

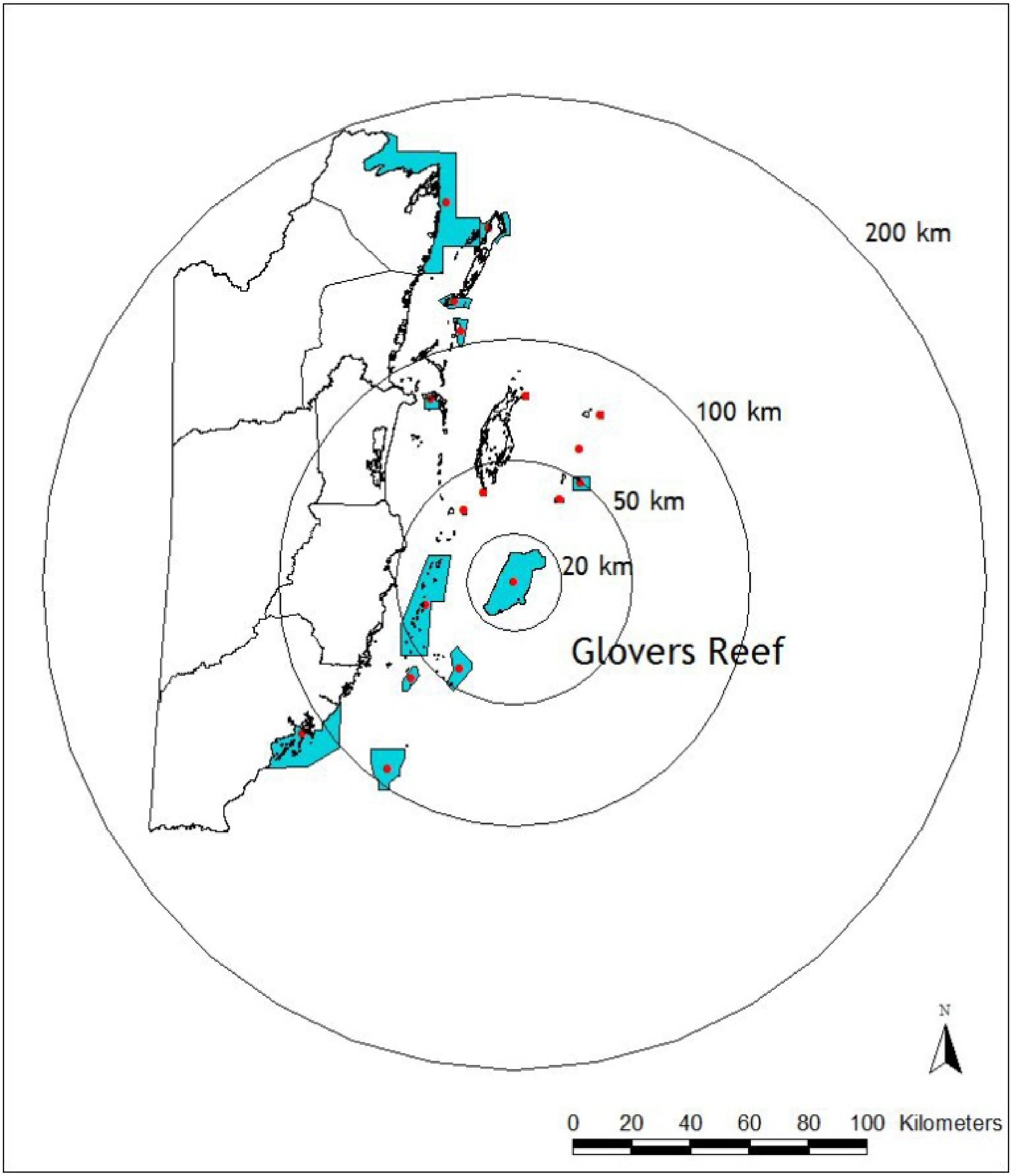

Figure 16. Glovers Reef Marine Reserve and nearest neighbour distances – based on four inter-MPA distance recommendations for ecological connectivity: 10-20 km (Shanks et al. 2003), ≤ 50 km (Almany et al. 2009), ≤ 100 km (Sala et al. 2002), and ≤ 10-200 km (Palumbi 2004).

5.3 Results

Table 8 shows some predictable results, that the larger the inter-MPA distance, the greater the number of MPAs that can be considered connected. That is, nearly all MPAs (97.7%) fell within the ≤ 10-200 km distance from each of the other MPAs as recommended by Palumbi (2004), 63.4% fell within the ≤ 100 km proposed by Sala et al. (2002), 30.1% fell within ≤ 50 km (Almany et al. 2009), and 5.6% 10-20 km (Shanks et al. 2003).

Table 8. Number of MPAs within specified distances of other MPAs within the Belize MPA network.

MPA	**10-20 km (Shanks et al. 2003)**	**≤ 50 km (Almany et al. 2009)**	**≤ 100 km (Sala et al. 2002)**	**≤ 10-200 km (Palumbi 2004)**
Bacalar Chico	1	3	7	15
Blue Hole	2	6	14	17
Caye Caulker	1	5	13	17
Corozal Bay	1	3	5	15
Gladden Spit & Silk Cayes	2	4	9	17
Glovers Reef	0	6	13	17
Half Moon Caye	2	7	12	17
Hol Chan	2	5	11	17
Laughing Bird Caye	2	5	8	17
Port Honduras	0	2	5	16
Sapodilla Cayes	0	4	5	15
South Water Caye	0	4	12	17
South Water Caye – Emily	1	6	15	17
Swallow Caye	0	5	13	17
Within Recommended Distances (%)	**5.6**	**30.1**	**63.4**	**97.7**

6.0 Discussion

The purpose of this study was to determine how the MPA network in Belize contributes towards the protection of the endangered Nassau grouper. This chapter begins with a discussion of the findings of the habitat analysis. The chapter then follows with a discussion on whether it could be determined if the Belize MPAs function as a network with respect peer-reviewed recommendations of ecological connectivity and what is currently known about the movement patterns of Nassau grouper. The significance of the findings in relation to the role that MPAs may play in the protection of Nassau grouper are discussed in the summary, followed by recommendations for future research.

6.1 Habitat assessment of the Belize MPA/SASR network

In order for the Belize MPA network to contribute to the preservation of the Nassau grouper requires it encompass all habitats this species needs to fulfill its entire life cycle (Sadovy and Eklund 1999; Starr et al. 2007). Overall, more is known about the habitat preferences of juvenile and adult Nassau grouper when compared to early life stages (refer to Table 6). Algal habitat is believed to be important for post-settlement larvae, algae, seagrass and patch reefs for early juveniles, hard bottom coral reefs for late juveniles and adults, and open ocean environments near reef edges for adult and late juveniles during and for several months following the spawning season. Mangrove habitat is considered important to the early life stages of other reef fish species, including conspecifics, but there is no direct evidence that this habitat is essential for the Nassau grouper to complete its life cycle.

The habitat analysis showed that when considering the MPAs/SASRs in Belize as a single entity, early stage habitats (i.e., algae and seagrass) compose the greatest amount of area under protection, while very little habitat for late juveniles and adults, i.e., coral reef habitat, is incorporated. The SASRs protect mostly what has been reported in the literature as spawning habitat, e.g., edges of banks and insular shelves, exposed reef crests, and narrow rocky shelf ledge. However, the SASRs only offer limited protection as they protect adults for only 1-2 weeks during the spawning period. The total area within the SASRs is <5% of the total area under the MPA network. This should flag some concern as it is late juveniles and adults which are most vulnerable to fishing pressure, i.e., if MPAs are to contribute to the protection of this species it is important they protect adequate late stage habitat required at other times of the year.

When a separate habitat analysis was performed for each MPA individually, it is evident that the habitat distribution is quite different between MPAs. That is, the degree to which the MPAs may contribute towards the protection of Nassau grouper varies considerably from one MPA to another. For example, Corozal Bay Wildlife Sanctuary, the largest estuary in Belize, is almost entirely composed of algal habitat (Appendix, Figure 3). This is not surprising as this MPA was established primarily to protect West Indian manatee (*Trichechus manatus*) essential habitat. This MPA may provide considerable post-settlement ground for Nassau grouper, but no late juvenile or adult habitat lies within its borders. Similarly, nearly three-quarters of Port Honduras Marine Reserve is classified as seagrass habitat and one fourth as open sea (Appendix, Figure 9). So neither MPA incorporates all habitat required by the Nassau grouper and therefore there is little likelihood that they provide good overall protection for this species. In contrast, Sapodilla Caye and Glovers Reef Marine Reserves incorporate nearly all habitat types required at all life stages, as well as spawning aggregation sites, implying that they have greater potential to contribute towards Nassau grouper protection. The significance of these findings is discussed in further detail in Section 6.3.

6.2 Ecological Connectivity

The second analysis was performed to evaluate whether the Belize MPAs function as a network with respect to peer-reviewed recommendations of ecological connectivity and what is currently known about the movement patterns of Nassau grouper. Although available data are insufficient to make strong conclusions, some general observations can be made. First, there is clearly no consensus amongst scientists on optimum inter-MPA distances. Indeed, proposed distances range from 10-20 km (Shanks et al. 2003) to 10-200 km (Palumbi 2004). According to the recommendation made by Palumbi (2004), there is an almost perfect level of connectivity within the Belize MPA network, whereas that proposed by Shanks et al. (2003) indicates a very low level of connectivity. Another layer of complexity is that these recommendations are not species specific, but are meant to encompass the movement patterns of many species. It is clear from the literature that very little is known about the spatial dynamics and movement patterns of Nassau grouper at any life stage, e.g., larval dispersal distances, home range size, or how far it moves between habitats when undergoing ontogenic habitat shifts. Therefore it is very difficult or perhaps not possible to determine which recommendation is most useful for management of Nassau grouper.

Until further studies are conducted, it is not realistic to incorporate connectivity into management planning. Nevertheless, taking Johannes (1998) approach, connectivity makes sense on a conceptual level and piecing together what is known may provide some insight. For one, it is currently thought that Nassau grouper larvae do not move far from the point of origin, i.e., from spawning sites. It is also known that Nassau grouper exhibit strong site fidelity outside the spawning period. Therefore, except for the 1-2 week reproductive period, it can be assumed that adult Nassau grouper remain within a specified home range for the remainder of the year. This suggests that no-take MPAs which incorporate adult habitat and prohibit fishing of mature Nassau grouper year round would be a good tool to protect this species. Furthermore, despite the lack of consensus on optimum inter-MPA distance to maximize connectivity, intuitively, there should be an inverse relationship between distance and connectivity, i.e., as distance decreases the level of connectivity should increase. If the Nassau grouper is truly a sedentary solitary creature which possesses a small home range, then it could be expected that MPAs would have to be close together for an MPA network to be effectively used for the protection of this species. Also, that each of its required habitats must be within a certain distance so that ontogenic shifts are possible. The importance of proximity between early and late stage habitat in relation to density of adults has been recognized for other species (Mumby 2006).

The main conclusion from the assessment of ecological connectivity is that there are many unknowns. Although there is much literature indicating its importance, there are so many gaps in knowledge and so little empirical data that it is difficult to incorporate it into MPA network design or management plans. Specific limitations include the fact that very few studies explicitly set out the movement (dispersal) patterns for any species in any region (Sale and Kritzer 2008), as confirmed by Airamé et al. (2003).

6.3 Summary

In summary, both assessments demonstrate that information on the life history and spatial dynamics of Nassau grouper, as well as ecological connectivity, is largely patchy and incomplete. However, using the results from Chapters 4 and 5, and information from the literature review, it may be possible to evaluate which MPAs in Belize offer the greatest or least protection to Nassau grouper. Table 9 shows the total area of each habitat type within each MPA in relation to the key life stages of Nassau grouper (i.e., post-settlement, early juvenile, and late juvenile and adult). Late juveniles and adults are considered as a single group as their habitat preferences are similar. The information in Table 9 was then used in Table 10 to score how well each MPA contributes towards the protection of Nassau grouper based on two main categories, habitat coverage and ecological connectivity. A description of this scoring system is found below.

Habitat coverage is considered the more important category because in order for an MPA to provide good protection to Nassau grouper would require that it incorporate all the required habitat types for each life cycle stage, and at least one SASR. The literature review performed in Chapter 4 indicates that algal habitat is important for post-settlement larvae; algal, seagrass, and patch reef habitat for early juveniles; and coral reef and open ocean for late juveniles and adults. Although no direct evidence was found in the literature, for the purposes of this study mangrove habitat is considered important to juveniles of Nassau grouper as this is true for juveniles of other reef fish species. A score of 2 indicates good habitat coverage (≥ 10%), 1 fair coverage (≤10%), and 0 poor coverage. Spawning aggregation sites are considered critical habitat for Nassau

Table 9. Total area of each habitat type within each MPA in relation to the key life stages of Nassau grouper.

MPA		Total Area per Marine Ecosystem (km^2)																	
		Post-Settlement Habitat			Early Juvenile Habitat							Late Juvenile - Adult Habitat							
Name	Total Area (km^2)	Algae (0-30 m)	Total Area (km^2)	TOTAL (%)	Algae (0-30 m)	Seagrass (0-30 m)	Mangroves (0-5 m)	Seagrass with Patch Reefs (0-30 m)	Coral Reef Patch Reefs (0-30 m)	Total Area (km^2)	TOTAL (%)	Coral Reef (0-5 m)	Coral Reef Spur and Groove (0-30 m)	Open sea (0-30 m)	Open sea (30-100 m)	Open sea (100-200 m)	Open sea (200-3000 m)	Total Area (km^2)	TOTAL (%)
Bacalar Chico MR	65.8	30.1	30.1	45.8	30.1	13.5	0.0	0.0	2.5	46.1	70.1	5.5	5.5	0.0	0.0	7.7	1.0	19.7	29.9
Blue Hole NM	4.1	1.3	1.3	31.3	1.3	2.8	0.0	0.0	0.0	4.1	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Caye Caulker MR	39.1	0.0	0.0	0.0	0.0	12.7	0.0	0.0	0.0	12.7	32.5	6.9	6.7	0.0	0.0	10.7	2.1	26.4	67.5
Corozal Bay WS	730.5	715.5	715.5	97.9	715.5	7.7	7.3	0.0	0.0	730.5	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gladden Spit & Silk Cayes MR	105.2	18.8	18.8	17.9	18.8	8.9	0.0	0.0	15.6	43.3	41.2	8.1	0.0	21.7	0.0	12.8	19.3	61.8	58.8
Glovers Reef MR	351.1	49.3	49.3	14.0	49.3	0.0	0.5	152.3	5.6	207.8	59.2	32.7	7.1	0.0	0.0	0.0	103.6	143.4	40.8
Half Moon Caye NM	39.2	1.3	1.3	3.3	1.3	1.6	0.3	0.0	0.5	3.7	9.5	0.2	1.5	0.0	0.0	2.8	31.0	35.5	90.5
Hol Chan MR	55.3	6.4	6.4	11.5	6.4	39.8	2.0	0.0	0.1	48.3	87.3	3.1	1.5	0.0	0.0	1.9	0.5	7.0	12.7
Laughing Bird Caye NP	41.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	5.9	6.1	14.8	0.0	0.0	33.6	1.2	0.0	0.0	34.9	85.2
Port Honduras MR	404.7	0.0	0.0	0.0	0.0	282.0	6.8	0.0	7.8	296.6	73.3	0.0	0.0	101.7	6.3	0.0	0.0	108.0	26.7
Sapodilla Caye MR	172.0	11.9	11.9	6.9	11.9	0.0	1.0	0.0	9.4	22.3	13.0	19.7	0.0	93.6	23.1	12.2	1.1	149.7	87.0
Southwater Caye MR	482.5	7.4	7.4	1.5	7.4	98.6	7.0	0.0	30.9	143.8	29.8	11.1	0.0	277.0	12.7	35.8	2.0	338.7	70.2
Swallow Caye WS	36.4	0.0	0.0	0.0	0.0	32.3	4.0	0.0	0.0	36.4	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 10. Application of a scoring system to evaluate the potential contribution of individual MPAs to the protection of the Nassau grouper. Higher total score indicates higher contribution.

MPA	Habitat Coverage				Ecological Connectivity (within 10 km) [4]				Total Score
	Available habitat for various life stages[1]			SASR within borders[3]	≥ 1 unassociated SASRs	Neighbouring MPA having required habitat for various life stages			
	Post-settlement larvae[2]	Early juvenile[2]	Late juvenile & adult[2]			Post-settlement Larvae	Early Juvenile	Late Juvenile & Adult	
Bacalar Chico MR	2	2	2	2	0	0	0	0	8
Blue Hole NM	2	1	0	0	0	0	0	0	3
Caye Caulker MR	0	2	2	0	0	1	1	1	7
Corozal Bay WS	2	2	0	0	0	0	0	0	4
Gladden Spit & Silk Cayes MR	2	2	2	2	0	1	1	1	11
Glovers Reef MR	2	2	2	2	0	0	0	0	8
Half Moon Caye NM	1	1	2	0	1	0	0	0	5
Hol Chan MR	2	2	2	0	0	0	1	1	8
Laughing Bird Caye NP	0	2	2	0	0	1	1	1	7
Port Honduras MR	0	2	2	0	0	0	0	0	4
Sapodilla Cayes MR	1	2	2	6	0	0	0	0	11
South Water Caye MR	1	2	2	0	0	1	1	1	8
Swallow Caye WS	0	2	0	0	0	0	0	0	2

1 Required habitat types per life stage: post-settlement larvae = algal habitat; early juvenile = algal habitat, seagrass, patch reefs; late juvenile & adult = coral reefs and open ocean environments near reef edges

2 Habitat scoring (based on Table 1, Appendix 2): good coverage (> 10%) = 2; fair coverage (< 10%) = 1; poor coverage = 0

3 SASR scoring: SASR within MPA borders = 2; Within 10 km of ≥ 1 unassociated SASRs = 1

4 Ecological connectivity scoring: yes = 1; no = 0

grouper therefore a score of 2 is also given to MPAs for each SASR incorporated within boundaries. The higher the total score, the higher the potential contribution of individual MPAs towards the protection of Nassau grouper. The lower the score, the less likely an MPA contributes to overall protection.

Ecological connectivity is considered a secondary category in Table 10 because although it is more desirable that a particular MPA incorporate all the required habitats for Nassau grouper, if a neighbouring MPA within a specified distance offers required habitat, then it may also be contributing towards protection. As discussed in Chapter 5, the Nassau grouper has a small home range outside the spawning season. Based on the <1 km^2 home range size reported for two other species within the *Epinephelus* genus (Kramer and Chapman 1999; Kaunda-Arara and Rose 2004), a conservative estimate of 10 km is given as a possible average dispersal distance for the Nassau grouper. The assumption is that Nassau grouper may move between neighbouring MPAs through ecological connectivity if within this specified distance. Therefore, in cases where required habitats are available in neighbouring MPA, or if an SASR is located within 10 km, a score of 1 is given in Table 9. If unavailable, a score of 0 is given.

Table 11 is a summary of the results from Table 10. It shows that when considering habitat coverage and ecological connectivity, the degree to which MPAs in Belize may contribute to the protection of Nassau grouper varies from one MPA to another. The MPAs that scored highest and provide the greatest potential for protection of Nassau grouper are Gladden Spit and Silk Cayes and Sapodilla Cayes Marine Reserves. Bacalar Chico, Glovers Reef, Hol Chan, and South Water Caye Marine Reserves fall next in order of importance. These MPAs provide all or most of the essential habitats required by Nassau grouper during its life cycle. With the exception of Hol Chan and South Water Caye Marine Reserves, these MPAs also include 1 or more SASRs within boundaries. The lowest scores were given to Blue Hole NM, Corozal Bay WS, Port Honduras MR, and Swallow Caye WS. These MPAs contribute the least towards the protection because they do no incorporate all the habitat types required by Nassau grouper to complete its life cycle. Futhermore, none incorporate a spawning aggregation site, and none are ecologically connected, i.e., within 10 km of an SASR or neighbouring MPA.

Table 11. Summary of the results from Table 10. Higher total score indicates higher contribution.

MPA	Total Score
Gladden Spit & Silk Cayes MR	11
Sapodilla Cayes MR	11
Bacalar Chico MR	8
Glovers Reef MR	8
Hol Chan MR	8
South Water Caye MR	8
Caye Caulker MR	7
Laughing Bird Caye NP	7
Half Moon Caye NM	5
Corozal Bay WS	4
Port Honduras MR	4
Blue Hole NM	3
Swallow Caye WS	2

Taking these results into consideration, additional measures to protect the Nassau grouper could perhaps focus on improving those MPAs that offer the greatest chance for recovery of this species. Bacalar Chico, Glovers Reef, Gladden Spit and Silk Cayes, and Sapodilla Caye Marine Reserves already have the essential habitat required by Nassau grouper at all life stages, including one or more SASRs within borders. However, as stated earlier, the total area under the Belize MPA system is roughly 2550 km^2, and only 341.7 km^2 (13.4%) is zoned as no-take where all fishing activity is prohibited year round. These MPAs could be improved by increasing the size of no-take zones which protect late juvenile and adult habitat as this is the most vulnerable life stage for Nassau grouper. Additional protection measures could include expansion of existing boundaries or the creation of new MPAs. For example, South Water Caye Marine Reserve has most of the essential habitat but lacks an SASR. As Figure 17 depicts, MPA boundaries could be extended to link South Water Caye Marine Reserve with Gladden Spit and Silk Cayes Marine Reserve, which has a SASR. Additionally, Figure 18 shows that 5 SASRs (Dog Flea, Sandbore, Caye Bokel, Southpoint, and Emily/Caye Glory) are not within the boundaries of any currently established MPAs. As suggested in Figure 18, further action could include expanding the borders of Half Moon Caye NM to include Southpoint SASR. But more imporant, considering that Sandbore Caye SASR is one of two Nassau grouper spawning sites known to be active today, and all the habitats required by the Nassau grouper surround this critical site, creating a new MPA which surrounds this SASR may be one of the most advantageous improvements that could be made.

6.4 Future Research

This study demonstrates that there are many gaps in knowledge concerning the basic life history traits and spatial dynamics of the Nassau grouper. Future work that could contribute to the conservation and management of this species include studies on the following:

- Habitat preferences and movement patterns at early life stages;
- Home range size of juveniles and adults;
- Densities in no-take zones versus multiple-use zones and outside MPA borders;

- Expanding the use of GIS to produce a model based on available habitat data to assess the potential for movement, i.e., ecological connectivity, between individual MPAs within the Belize MPA network; and,
- How to optimize MPA network design to balance fishery and conservation needs.

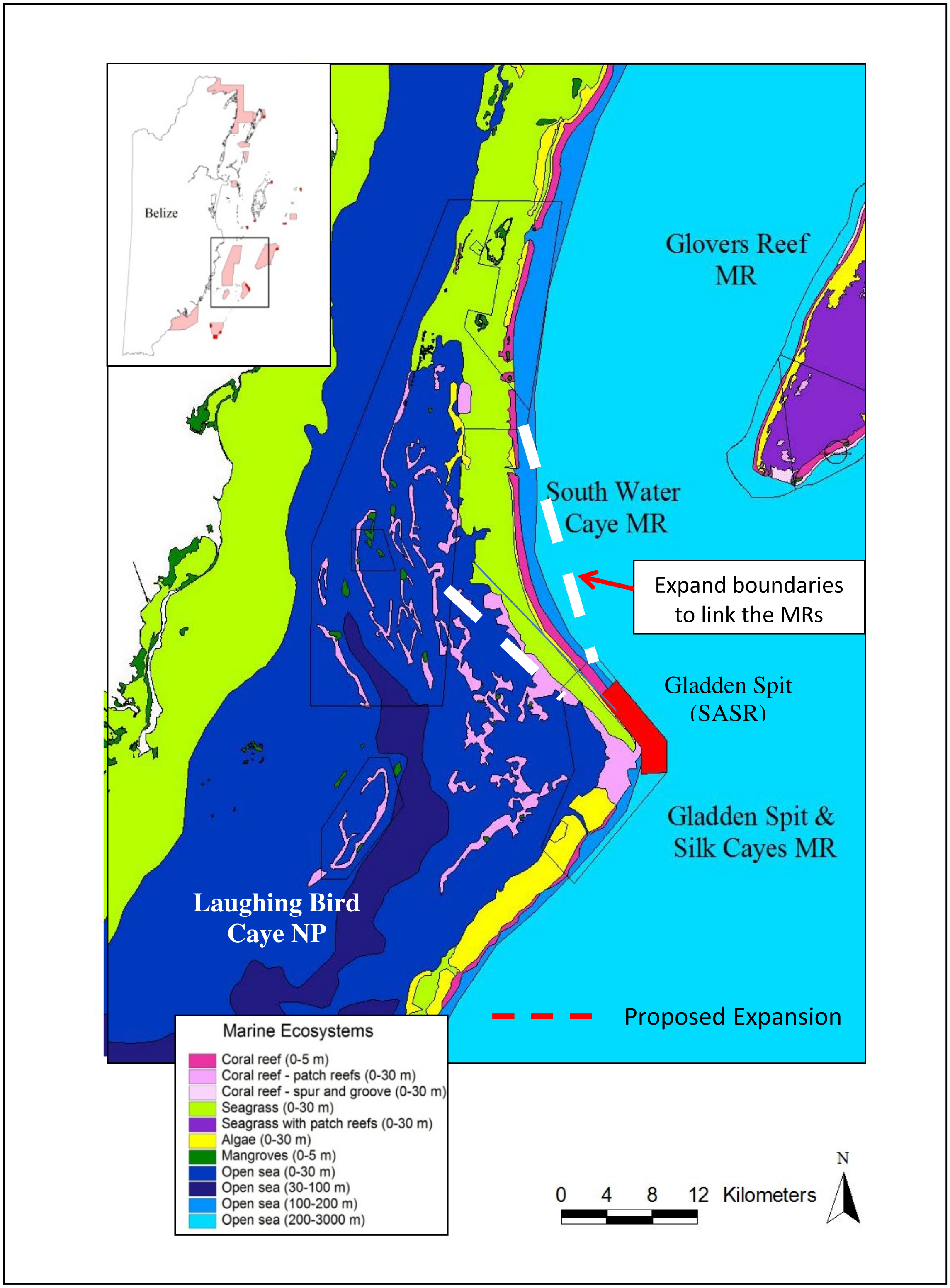

Figure 17. Proposed expansion of Southwater Caye and Gladden Spit MRs.

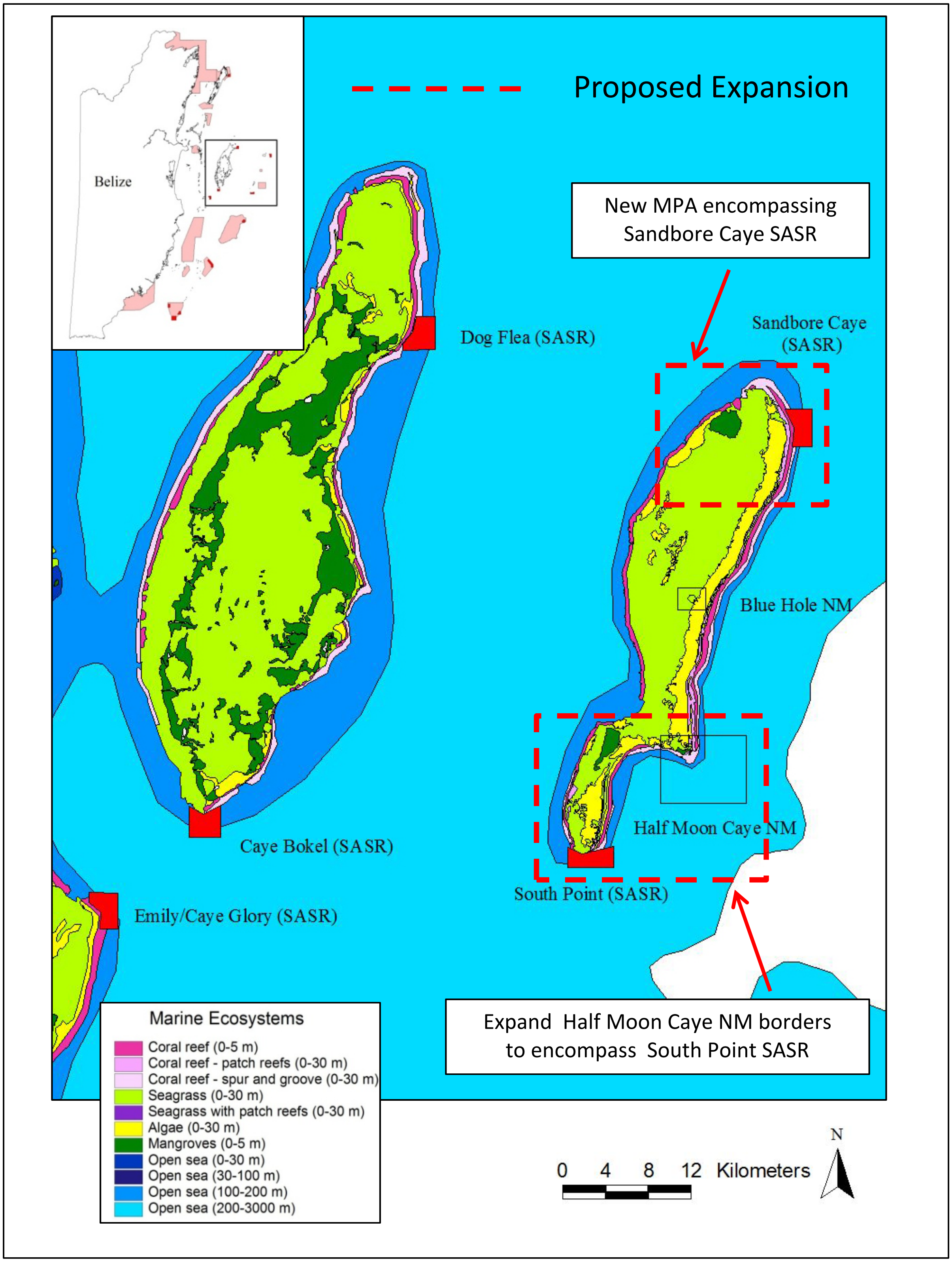

Figure 18. Proposed expansions for Belize MPA network: (1) Establishment of a new MPA which incorporates SandBore Caye SASR, and (2) Increasing the size of Half Moon Caye NM to include South Point SASR.

7.0 Conclusions

This is the first nationwide assessment of how the MPA network in Belize contributes towards the protection of the endangered Nassau grouper. This study highlights that there are many gaps in knowledge with respect to what is known about Nassau grouper habitat needs and movement patterns throughout its life cycle, as well as ecological connectivity. Nevertheless, as reported by Johannes (1998), for marine fish species in general, quantitative research will never provide sufficient knowledge of their dynamics to enable management that achieves optimum yield, whether it be biological, economic or social. Johannes recommends a precautionary approach by using whatever information is available to manage a fishery species. It is a fact that the Nassau grouper is disappearing throughout its range, and further action is needed to preserve what little population remains.

The main conclusion from this study is that the Belize MPA network as a system may not contribute greatly to the conservation of Nassau grouper. However, on an individual basis, some MPAs contribute more towards protection than others and therefore management efforts could focus on improving those MPAs which have the greatest potential to help this species recover. Taking a triage approach, some conclusions can be made concerning which MPAs offer the best possible protection, which can be improved, and which have the least potential. Five of the 13 Belize MPAs (Gladden Spit and Silk Cayes, Sapodilla Cayes, Bacalar Chico, Glovers Reef, Hol Chan, and South Water Caye Marine Reserves) were found to have good characteristics for this species. These MPAs provide all or most of the essential habitats required at each life stage, and with the exception of Hol Chan and South Water Caye Marine Reserves, these MPAs also include 1 or more SASRs within their boundaries. Recommendations to improve these particular

MPAs are limited but could focus on increasing the extent of no-take zones as there is growing evidence that such zones are beneficial. For example, after 5 years of establishment, Indo-Pacific grouper in the Wakatobi Marine National Park in Indonesia within the no-take area were more mature and nearly five times in number compared to those of a heavily fished site (Unsworth et al. 2007).

A second recommendation is the expansion or establishment of additional MPAs. Sandbore Caye being one of the only two historical spawning sites known to be active today in Belize is justification in itself that a new MPA be established to protect this site even further. Half Moon Caye National Monument could also be expanded to incorporate South Point SASR, thereby increasing the contribution that this MPA would have towards protection of Nassau grouper. Future conservation efforts for Nassau grouper should probably not focus on improving Blue Hole National Monument, Corozal Bay Wildlife Sanctuary, Port Honduras Marine Reserve, and Swallow Caye Wildlife Sanctuary, considering they are far from meeting the minimum habitat requirements for this species.

Overall, it is clear that any additional effort to conserve the Nassau grouper must be backed up by sound fishery management within and surrounding the existing MPAs and SASRs. Furthermore, there are many other threats which face the Nassau grouper including pollution and climate change. Pollution in various forms, e.g., agricultural and urban run off, is thought to pose a significant threat to MPAs (Boersma and Parrish 1999) and likely the Nassau grouper. The changes that are being brought about by climate change, including ocean acidification, are leading to severe loss and degradation of coral reefs (Hoegh-Guldberg et al. 2007) and the potential impact on Nassau grouper is unknown but can be expected to exacerbate existing challenges facing the recovery of this species. Experts recommend that managers build resilience into networks of MPAs by establishing MPAs in a variety of locations and protecting as many diverse habitats as possible (McLeod et al. 2009). Future research which improves the knowledge of Nassau grouper habitat needs and accurate measurements of its spatial dynamics, i.e., ecological connectivity, will also aid in effective management and conservation. However, in the words of McCook et al. (2009), given the urgency of the situation, it is better to act with incomplete knowledge than to wait for a detailed understanding that may come too late.

8.0 Appendices

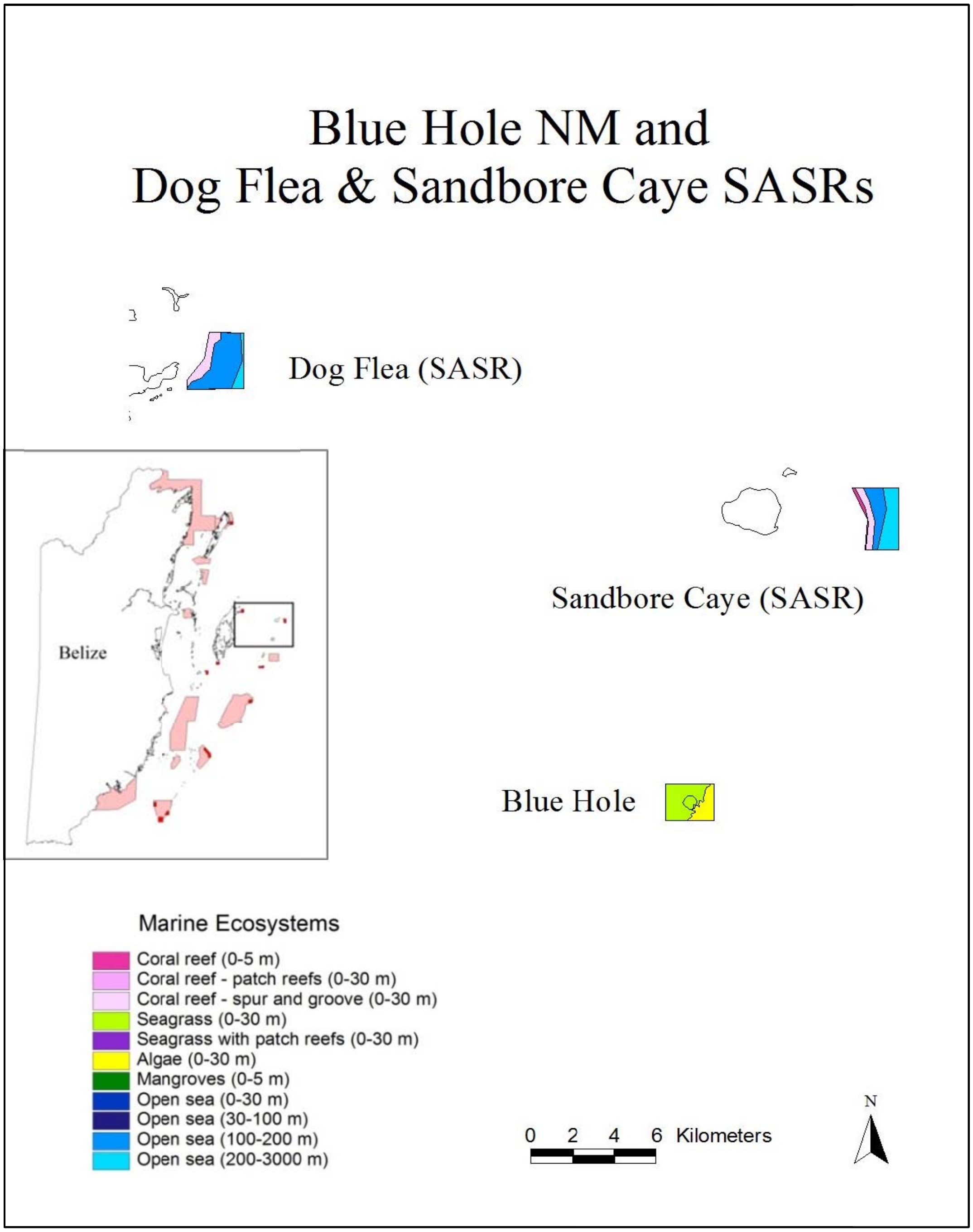

Figure 1. Marine ecosystems for Blue Hole Natural Monument, and Dog Flea and Sandbore Caye SASRs.

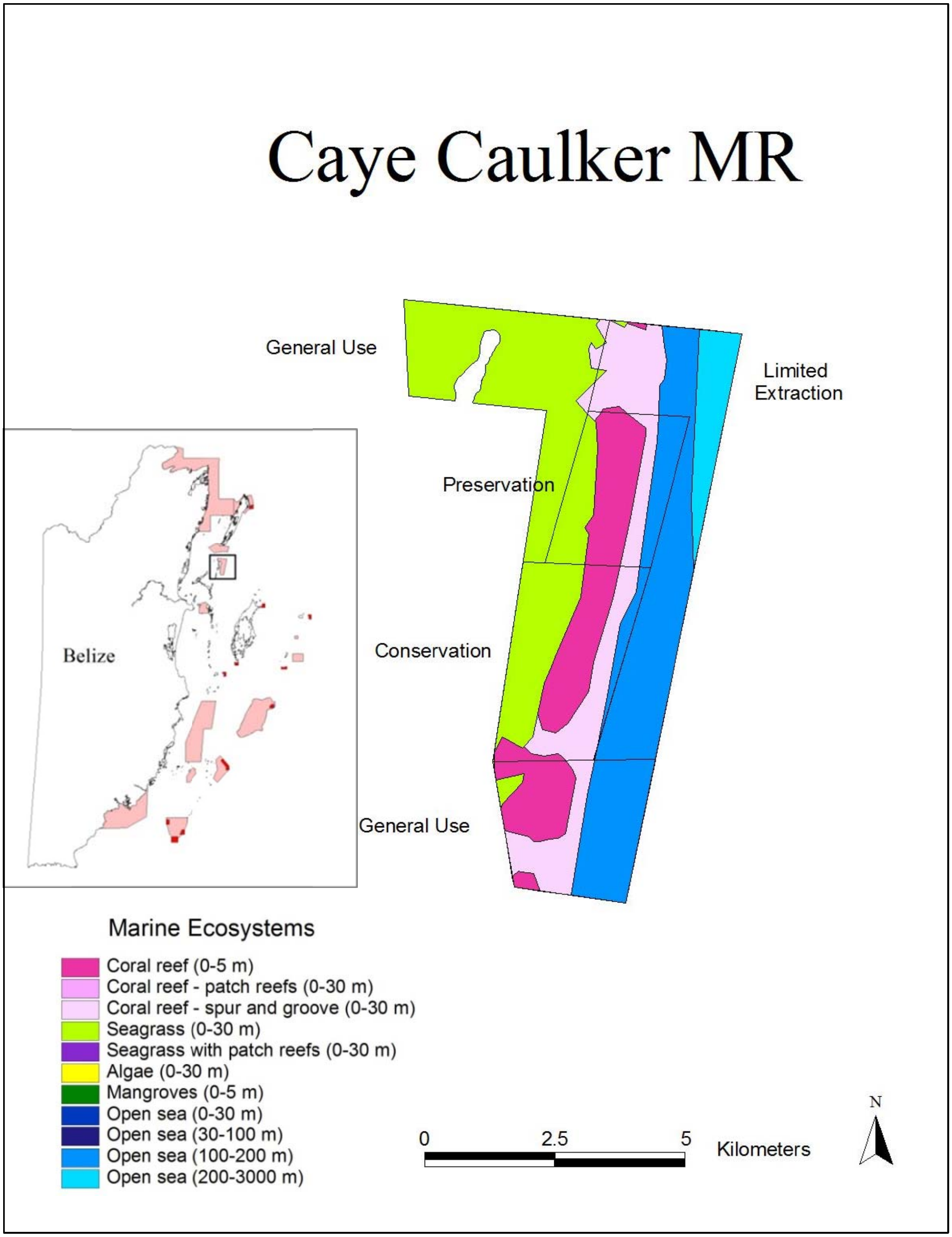

Figure 2. Marine ecosystemss and management zones for Caye Caulker Marine Reserve.

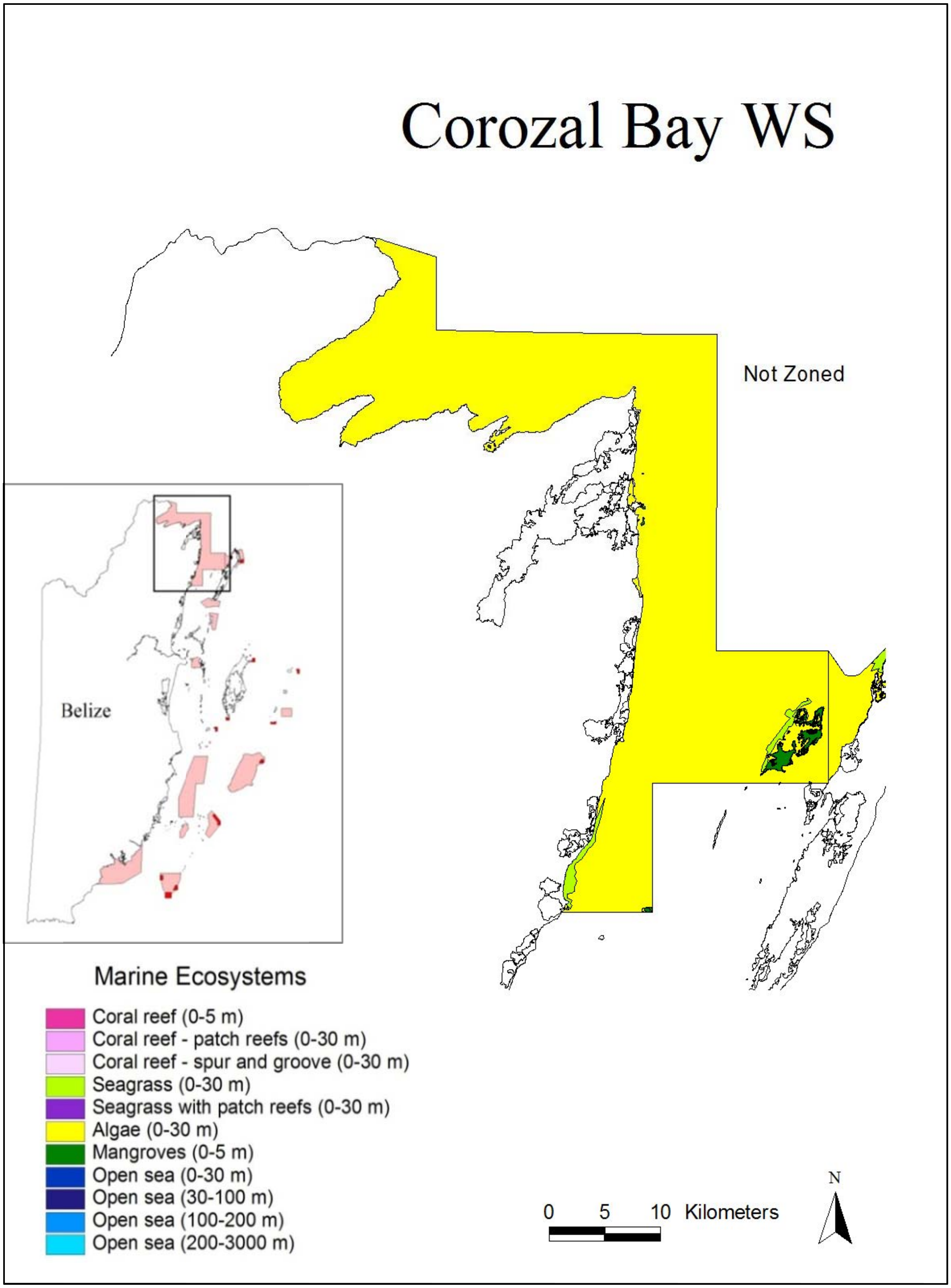

Figure 3. Marine ecosystems for Corozal Bay Wildlife Sanctuary.

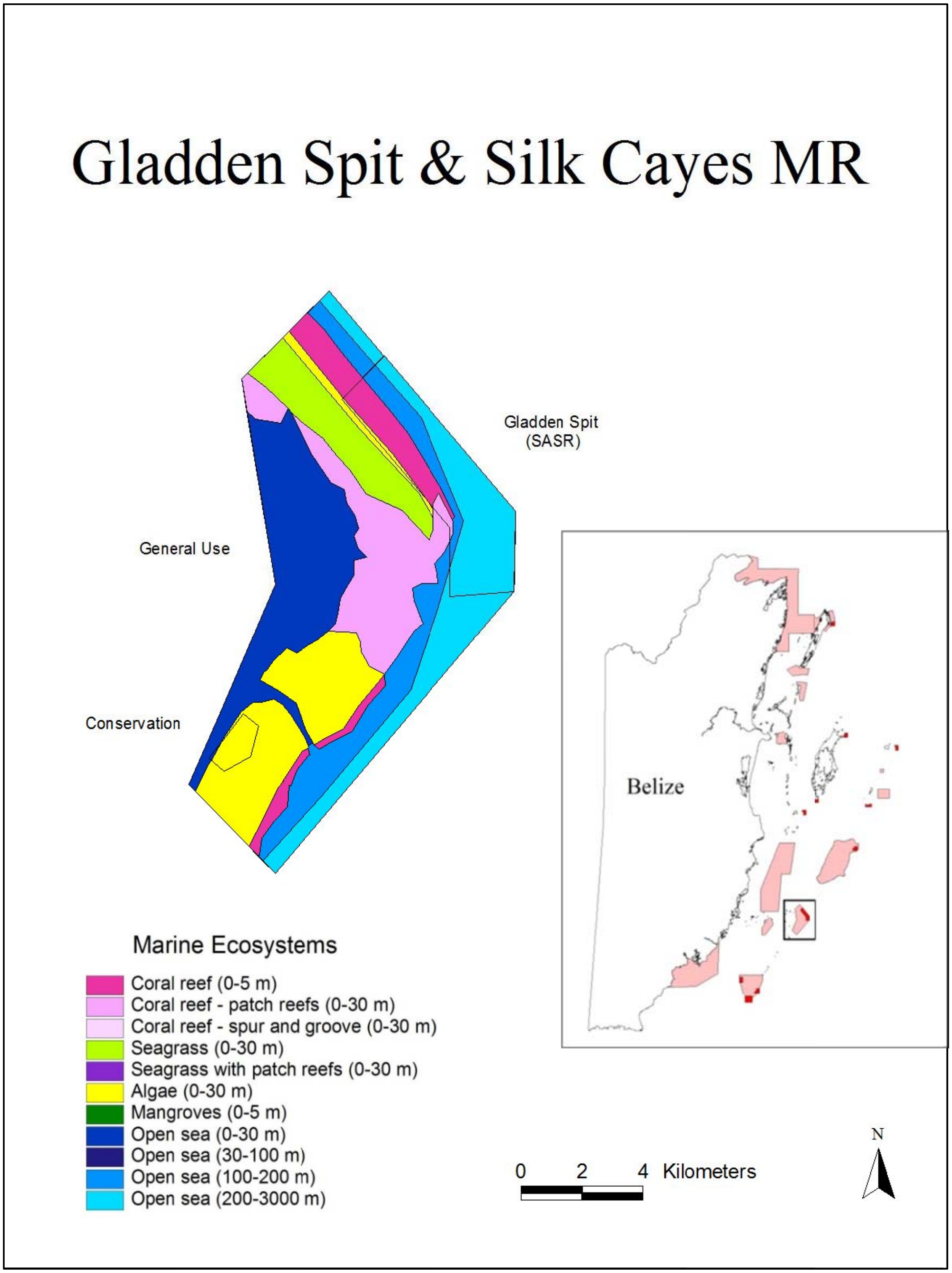

Figure 4. Marine ecosystems and management zones for Gladden Spit and Silk Cayes Marine Reserve.

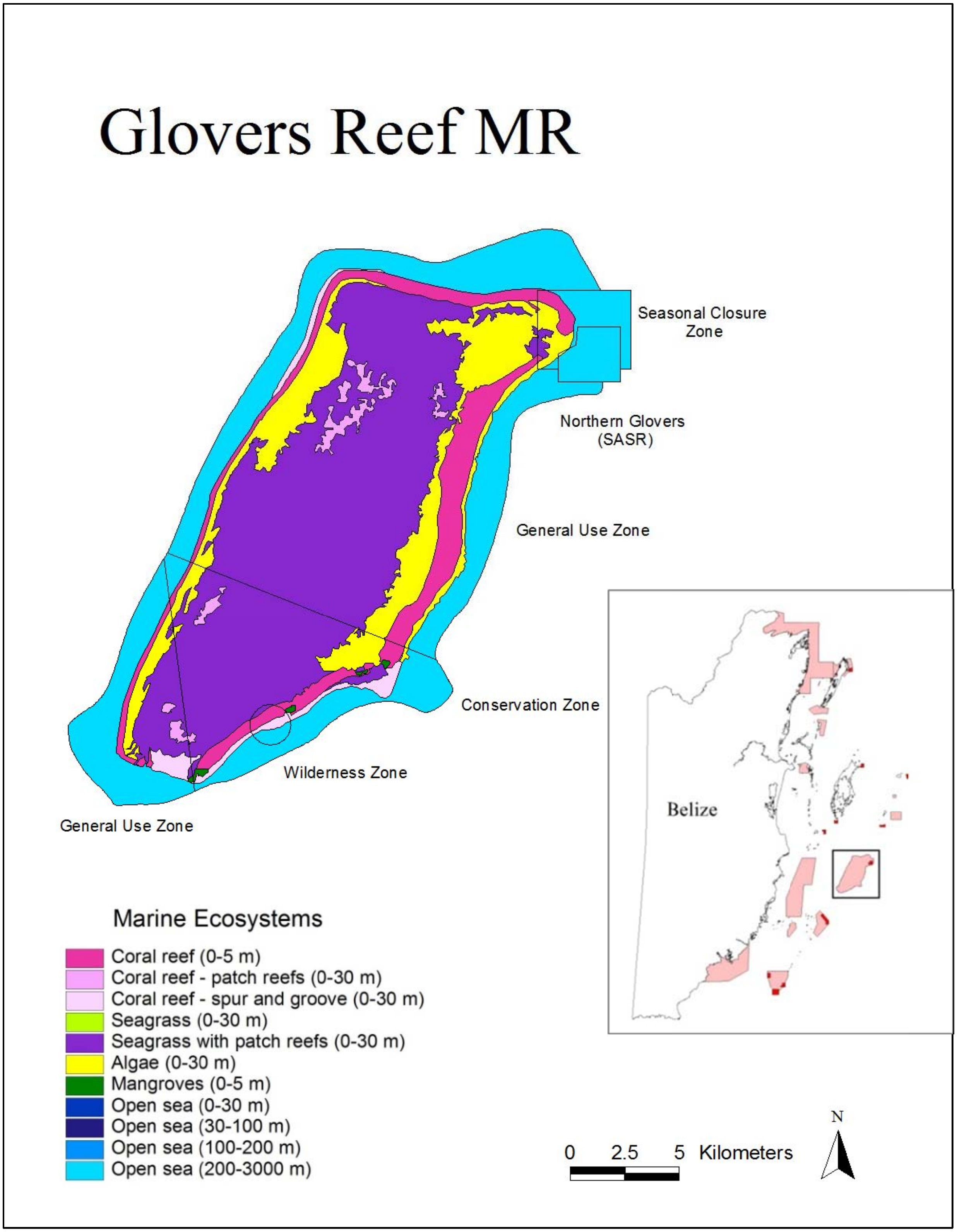

Figure 5. Marine ecosystems and management zones for Glovers Reef Marine Reserve.

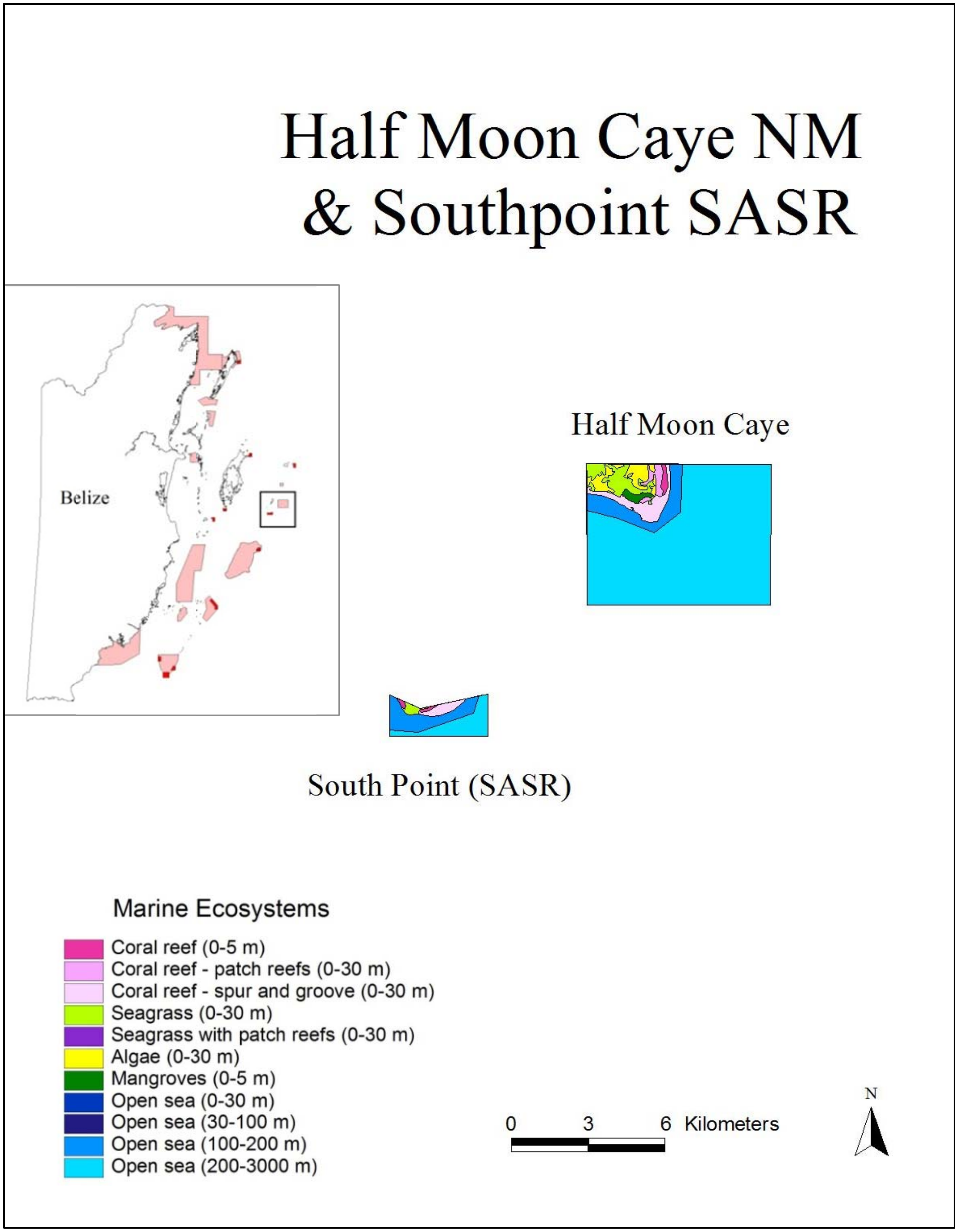

Figure 6. Marine ecosystems for Half Moon Caye Natural Monument and South Point SASR.

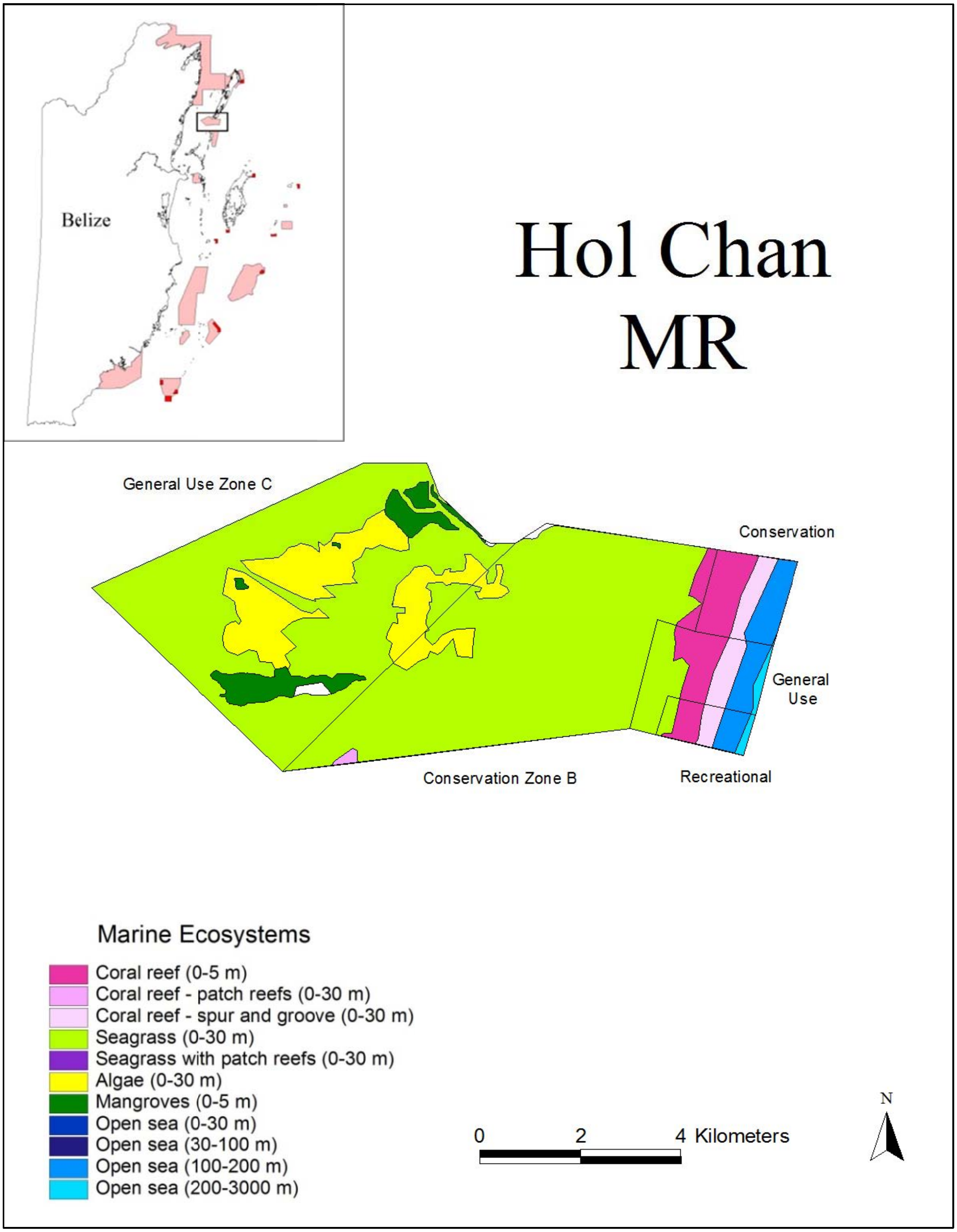

Figure 7. Marine ecosystems and management zones for Hol Chan Marine Reserve.

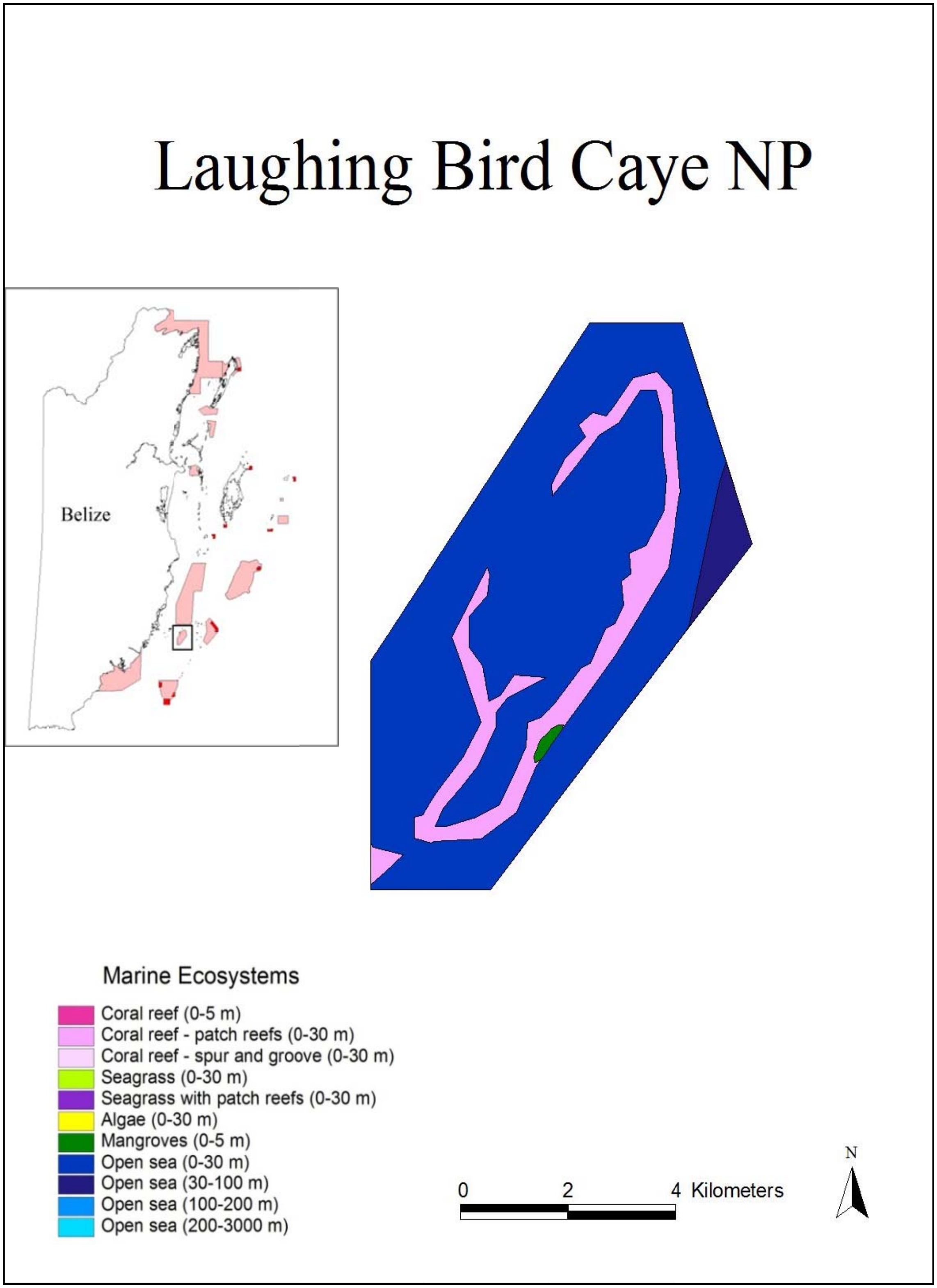

Figure 8. Marine ecosystems for Laughing Bird Caye National Park.

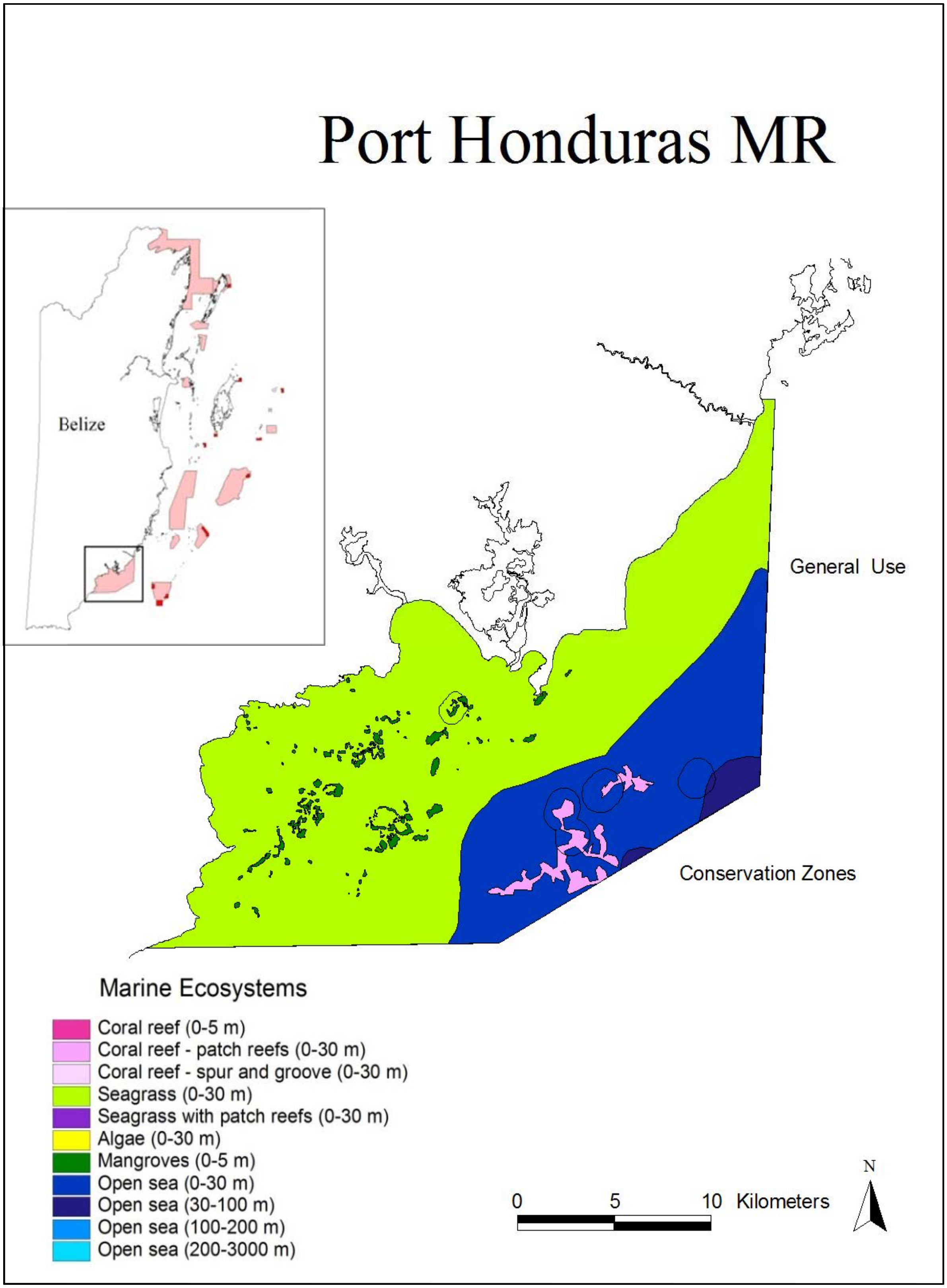

Figure 9. Marine ecosystems and management zones for Port Honduras Marine Reserve.

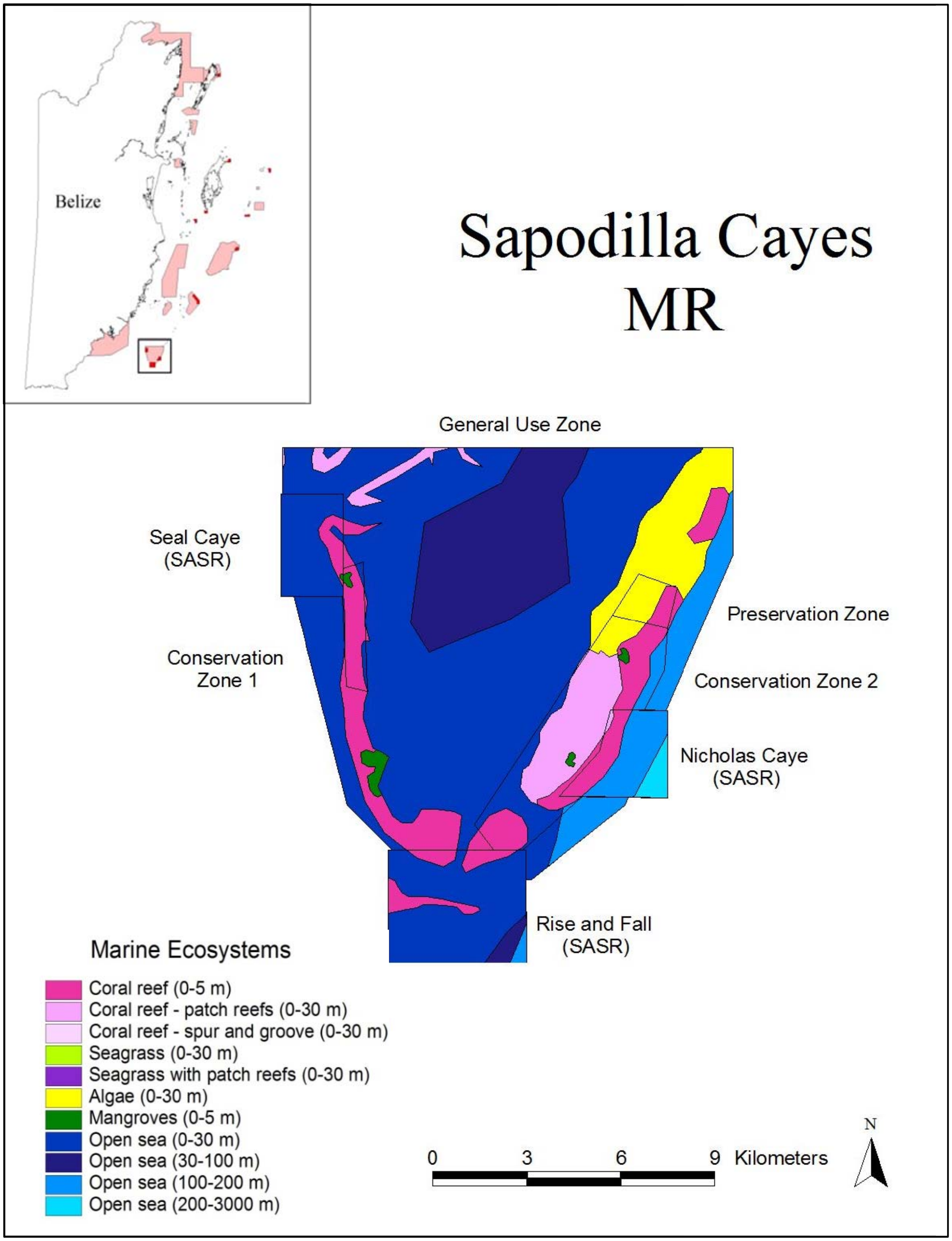

Figure 10. Marine ecosystems and management zones for Sapodilla Cayes Marine Reserve.

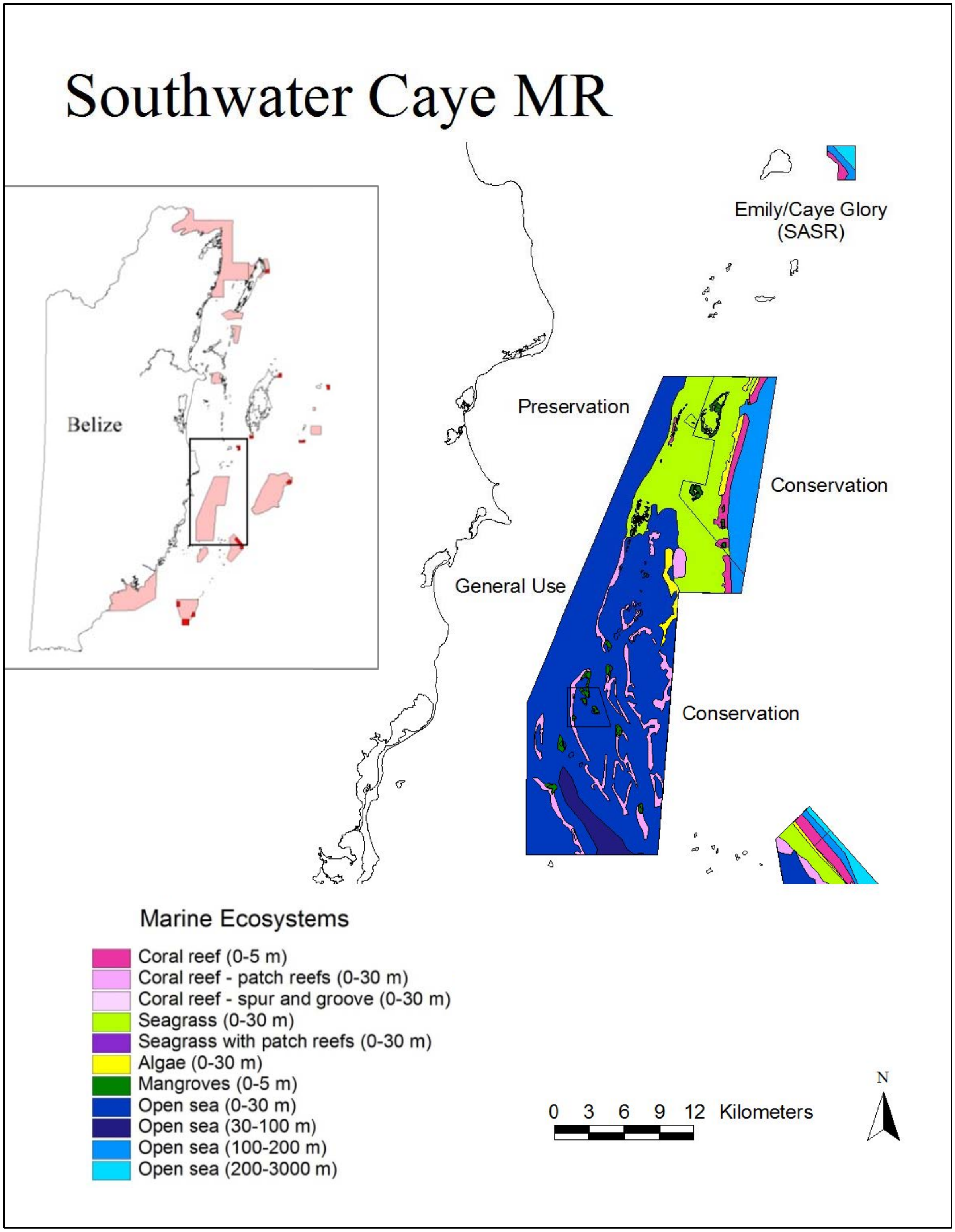

Figure 11. Marine ecosystems and management zones for Sapodilla Cayes Marine Reserve (includes Emily/Caye Glory SASR).

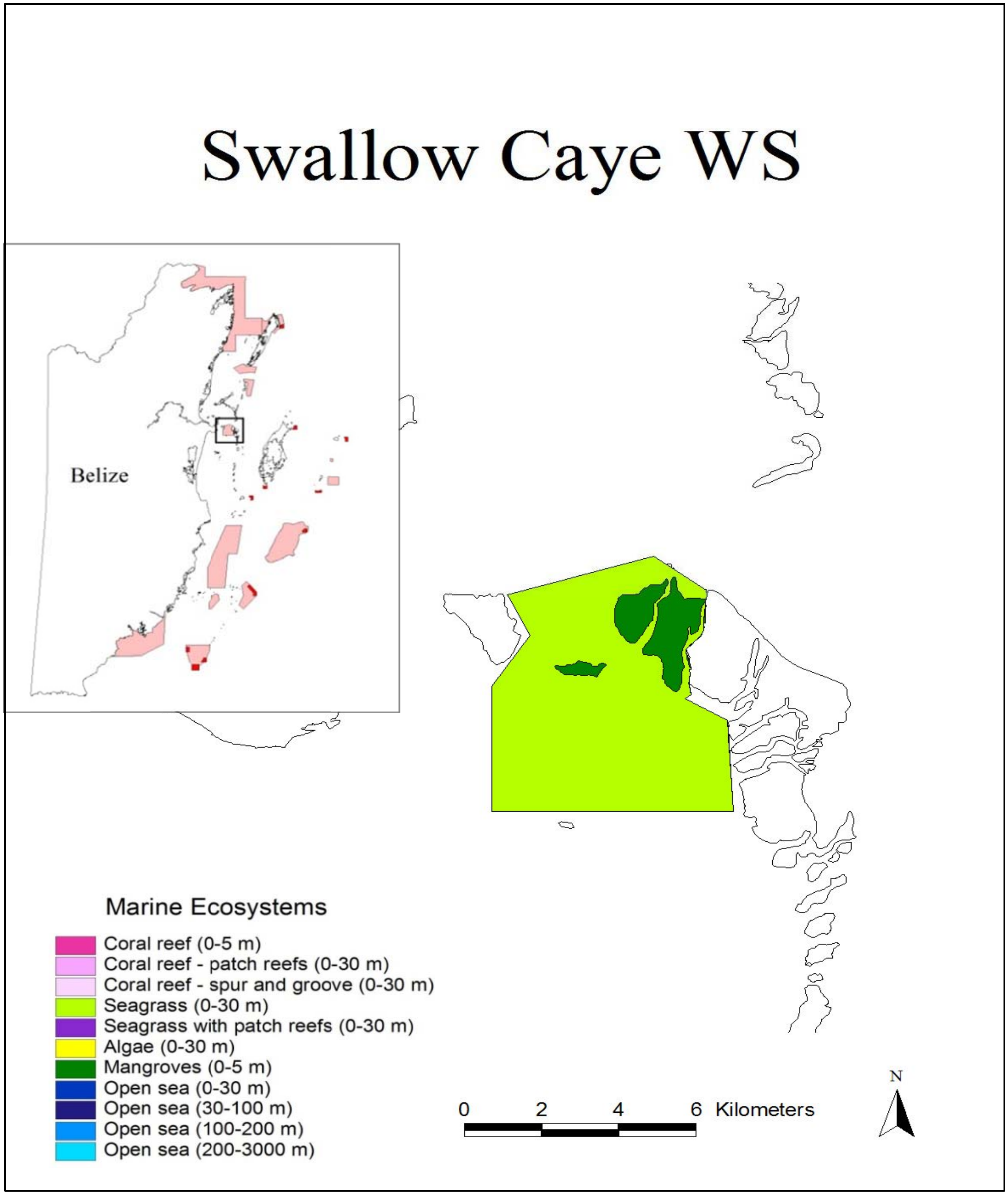

Figure 12. Marine ecosystems for Swallow Caye Wildlife Sanctuary.

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