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ORIGINAL PAPER

Informing marine protected areas in Bimini, Bahamas by considering hotspots for green turtles (*Chelonia mydas*)

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Abstract
Knowledge on the spatial distribution, habitat use and processes of site selection by marine turtles is fundamental to identify key habitats, critical resources, and discrete foraging aggregations for protection. This is particularly important for regions of known importance for marine turtles and where widespread habitat degradation is taking place. The waters surrounding Bimini, Bahamas, provide important foraging areas for threatened juvenile green turtles (*Chelonia mydas*) however, these habitats are being severely degraded by coastal development. To inform managers on the design of planned future no-take marine protected areas (MPA) in Bimini, we used a spatial planning approach and incorporated diverse methodologies (e.g., visual surveys, capture events, passive acoustic telemetry) to identify areas of high use by juvenile green turtles. We also assessed forage items to understand habitat use by green turtles. This information was compared with how various stakeholders use the local waters to identify priority areas for protection within Bimini to maximize conservation of green turtles, while minimizing impact to society, and to meet the conservation target previously stipulated by government officials. Two regions within Bimini (South Flats in south Bimini and Bonefish Hole on the north Island) were identified as important areas for protection and suggestions are made on their considerations for MPA implementation.

Keywords Conservation planning · Sea turtles · *Chelonia mydas* · Seagrass · Marxan · Telemetry/biologging · Mark-recapture/survey · Habitat use

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Introduction

Many marine turtle populations have been dramatically reduced worldwide through human activities, and as a result are now threatened throughout their ranges (Bjorndal et al. 1993; Wallace et al. 2011; Tapilatu et al. 2013). In response to these severe declines, considerable efforts have been made to protect these species of conservation concern. For example, in many countries it is now illegal to harvest, buy or sell any marine turtle product and efforts have been made to reduce bycatch and other direct threats (Gilman et al. 2006; Howell et al. 2008; Fuentes et al. 2015; Ortiz et al. 2016). However, relatively little attention has been given to mitigating habitat degradation (Wallace et al. 2011). Important habitats where marine turtles are known to forage such as coral reefs, seagrass beds and mangroves forests, are continuously damaged or entirely destroyed as a result of coastal development, sedimentation, nutrient run-off, tourism activities and damaging fishing techniques (Halpern et al. 2008; Waycott et al. 2009).

Knowledge of the spatial distribution, habitat use and processes that determine site selection by marine turtles is fundamental to identify key habitats, critical resources and discrete foraging aggregations for protection (Bailey et al. 2012; Schofield et al. 2013a, b).This is particularly important for regions of known importance to marine turtles where widespread habitat degradation is occurring. This is the case for the surrounding waters and coastline in the Bahamas, where many islands are impacted and provide important foraging areas for threatened marine turtles (Bjorndal and Bolten 1988; Bjorndal et al. 2003; Jennings et al. 2008, 2012). Bimini in particular, on the northwestern Great Bahamas Bank, is an important foraging area for threatened green turtles (*Chelonia mydas*) and has experienced large-scale development since 1997 (Gruber and Parks 2002; Jennings et al. 2008). This has caused a loss of 39% of the mangrove and 18% of turtle seagrass (*Thalassia testudinum*) in the North region of Bimini (Jennings et al. 2008; DiBattista et al. 2011), which provides important habitat and foraging for juvenile green turtles in the region (Bjorndal 1980; Gillis et al. 2018).

In 2000, the Bahamian Minister of Agriculture and Fisheries, recognizing the ecological and economic value of marine life, declared Bimini as one of five highest-priority sites in the Bahamas for proposed Marine Protected Areas (MPA), with the goal of implementation by June 2001 (Gruber and Parks 2002; Wise 2014). However, at the time of this announcement no management plans were outlined or boundaries defined (Dahlgren 2002). A series of community meetings followed to discuss MPA boundaries, restrictions and management. Potential sites within Bimini were proposed based on a set of socioeconomic and ecological factors, including impact from displacement of fishing activities, community support in management and potential economic benefits (Dahlgren 2002). Ecological parameters included habitat diversity and the importance of the area for supporting local fisheries (Dahlgren 2002).

In 2009, the North Bimini Marine Reserve was declared, however not gazetted by the government. In 2012, The Master Plan for the Bahamas Protected Area System assessed the network of MPAs in the Bahamas and determined that the country was drastically behind schedule on its commitment to protect 20% of biodiversity targets by 2020. Currently, less than 5% of marine turtle habitat is being protected (Dahlgren 2002; Wise 2014). As of 2018, the MPA in Bimini has yet to be established. Indeed, in 2015 a statement made by the Minister of Environment and Housing indicated that the MPA in Bimini was not included in the proposed expansion of MPAs for the Bahamas. Since then, there has been renewed support for an expansion and reconsideration of the current network of MPAs, including implementation of the previously suggested MPA in the eastern half of North Bimini. However, when suggested, this MPA did not consider the importance of the region as a foraging area for green turtles.

To inform potential future MPA design in Bimini, information on the spatial ecology of green turtles and the distribution of their foraging items is necessary. To address this knowledge gap, we used a combination of visual surveys, marine turtle capture events, acoustic telemetry and conservation planning tools. Marine turtle ecological data were then combined with information on how various stakeholders use the waters around Bimini. As a result, we identified regions within Bimini in need of protection to maximize the conservation of juvenile green turtles, while minimizing impact to society and meeting the conservation target previously stipulated by government officials. Further, we investigated whether green turtle hotspots and foraging areas would be adequately protected if the suggested North Bimini MPA was implemented, and identified whether additional sites would need to be protected if the suggested MPA was established.

Materials and methods

Study area

This study was conducted in Bimini, Bahamas (Bahamas, 25°44′N 79°16′W), a small chain of subtropical islands approximately 85 km east of Miami, Florida, U.S.A. The Bimini Islands are comprised of two small islands (north and south Bimini) (Trave and Sheaves 2014) (Fig. 1). Bimini provides the only extensive mangrove and creek habitats on the western edge of the Great Bahamas Bank, and as such is an important habitat and nursery area for a diversity of species, including threatened green turtles, lemon sharks (*Negaprion brevirostris*), and the southern stingray (*Hypanus americanus*) (Feldheim et al. 2002; Afonso and Gruber 2007; Jennings et al. 2012; Trave and Sheaves 2014; Guttridge et al. 2015; Hansell et al. 2018; Gillis et al. 2018). Since 1997, the northern 50% of north Bimini has been subject to intense urbanization that involves the construction of an extensive touristic complex (Gruber and Parks 2002). The development of this resort and associated activities has substantially modified parts of the island and the surrounding marine environments (Gruber and Parks 2002; Jennings et al. 2008; Trave and Sheaves 2014). Additionally, a new port, wharf and golf course are being developed in contraindication to the United Nations Ramsar treaty signed by the commonwealth of the Bahamas in 1997 http://rockwellisland.com/the-project/; https://www.ramsar.org/wetland/bahamas).

Designing the conservation planning system—Marxan analysis

Marxan, a systematic conservation planning tool, was used to identify potential areas in the waters surrounding Bimini that maximize the conservation of green turtles, while minimizing impact to society, and meeting conservation targets previously stipulated by government officials. Marxan employs a minimum-set approach to identify planning units that achieve conservation targets at near-minimal financial cost (Ball and Possingham 2000). Marxan is the most widely used conservation planning software and has been used to design marine and terrestrial Protected Area networks in many countries (for examples see Smith et al. 2007; Ban et al. 2009). Our study area was divided into 1 Km^2 grid cell (1000 × 1000 m) planning units (pu), for a total of 228 pu, that were populated with values

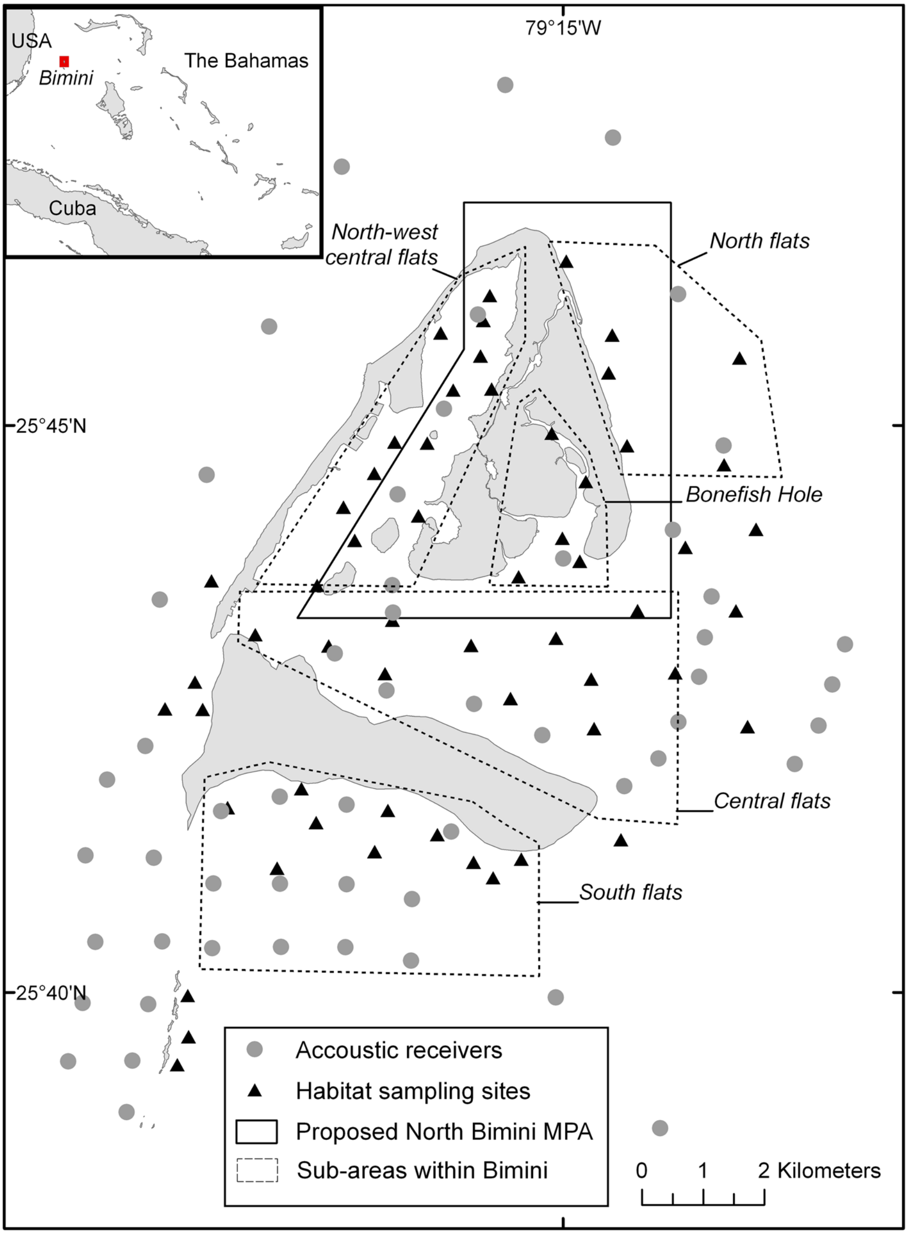

Fig. 1 Study site (Bimini, Bahamas), indicating the region for the proposed MPA in north Bimini, and the location of the acoustic receivers and the sampling sites for the forage composition and distribution conducted in 2016

for (1) turtle density (number of turtles per square kilometer), (2) coverage of forage habitat, and (3) stakeholder use (see below for description of these features). Surveys covered the whole extent of the planning units.

We ran Marxan for eight different scenarios (Table 1). First, we considered two different conservation targets for green turtle density and forage items: we used targets of 20% to align with the Bahamian government biodiversity targets and 30%, which is recommended by the International Union for Conservation of Nature (IUCN) (Broad and Sanchirico 2008). Two different cost metrics were considered. First, we assumed that each planning unit had a cost of 1, which was based on the surface area of each unit. Our second cost metric, was also based on surface area, but cost value increased by 50% based on human use of the area (as per Delavenne et al. 2012). Areas with no use received a value of 1, low use areas a value of 1.5, medium use areas a value of 2.25, and areas with high use a value of 3.375. A boundary-length modifier of 5 was used for a compact design. These scenarios were run twice, first (scenarios 1–4) assuming that none of the waters surrounding Bimini is protected (Table 1). For the second set of scenarios (scenarios 5–8), we assumed that the already declared but not gazetted area in north Bimini is protected and, therefore, we identified which additional areas would need to be protected to meet each of the targets under the two cost metrics. For each scenario we performed 500 runs of the Marxan software and we used only the results meeting all the conservation targets. The selection-frequency output was used to determine areas of high conservation value. Therefore, the identified areas may change between different analyses, and the extent of its near-optimality tends to increase with the number of runs used (Delavenne et al. 2012).

Conservation features

Turtle density

We searched for turtles across the study region using haphazard, unmarked, nonlinear transect (HUNT) surveys from a moving vessel (Bresette et al. 2010), across three sampling trips: June, 2016 (5 days), July, 2016 (9 days), and in May, 2017 (3 days). During HUNTs, we recorded turtle locations with a handheld GPS (Garmin 64 s) and made opportunistic captures using the 'rodeo' technique (Limpus and Walter 1980; Fuentes et al. 2006). Upon capture, each turtle was brought to the boat and morphometrics were taken including: straight and curved carapace length (±0.1 cm; SCL and CCL, respectively) following protocols described by Balazs (1999). Each turtle was marked with two Inconel flipper tags (National Band and Tag Company, Style 681) on the trailing edge of both front flippers and a passive integrated transponder (PIT tag, Biomark, GPT12) inserted sub-dermally in the

Table 1 Different scenarios considered for the Marxan analysis

Scenario	Conservation target (%)	Cost metric	Conservation consideration
1	20	Area based (value of 1)	No pre-protected area
2	20	Human use based (1–3.375)	No pre-protected area
3	30	Area based (value of 1)	No pre-protected area
4	30	Human use based (1–3.375)	No pre-protected area
5	20	Area based (value of 1)	North Bimini Marine Reserve established
6	20	Human use based (1–3.375)	North Bimini Marine Reserve established
7	30	Area based (value of 1)	North Bimini Marine Reserve established
8	30	Human use based (1–3.375)	North Bimini Marine Reserve established

front left flipper. Each turtle was given a unique number with an All-Weather PAINTSTIK Livestock Marker (LA-CO industries Elk Grove Village IL) to avoid re-capture within the same day. Capture data were recorded as point locations, where each point represented one turtle. The dataset was imported into ArcGIS 10.5 and converted into a shapefile, which was later merged with the filtered acoustic dataset (see below).

Acoustic tags (Vemco Inc. Bedford NS; V13, V16; battery life 1135 days to 10 years, interval 90–150 s) were deployed on a subset of 57 captured turtles following methods by Seminoff et al. (2002). Each tag transmitted a 69 kHz acoustic signal with a unique code for identifying individuals, which was recorded by an established array of passive acoustic receivers (n = 57 receivers at the time of this study, Vemco VR2W) (Fig. 1; see Guttridge et al. 2017). Acoustic data from turtles were recorded as number of individuals detected by each receiver. Detections were filtered by comparing each record with the capture/release dataset, based on the following rules: (a) an acoustic record was deleted from the dataset, if the turtle was detected within a 350 m radius from the capture/release location (Guttridge et al. 2017), (b) further detections of a turtle within the range of other acoustic receivers (other than the closest one to their capture/release location) were retained in the dataset, and (c) if a turtle was detected more than once on the same receiver, only the first record was retained. Captured turtles and filtered acoustic datasets were merged into a point shapefile. The combined dataset was then smoothed using the kernel-density tool in ArcGIS to create a raster layer of turtle density (number of turtles per square kilometer) with a 1 Km^2 resolution grid.

Coverage of forage habitat

Vegetation surveys were conducted in June 2016 to quantitatively describe the spatial distribution of marine flora available to foraging green turtles. Vegetation was assessed at 57 sites (Fig. 1), based on previous sites determined by (Hussey 2003), for eventual comparisons between current and past forage habitat. At each site, two 1 m^2 quadrats were thrown in opposite directions, for a total of four quadrats per site. For each quadrat, composition and percent coverage was determined for turtle grass, shoal grass (*Halodule wrightii*) and manatee grass (*Syringodium filiforme*), as well as green and red algae (as per Fuentes et al. 2006). Turtles in Bimini are known to forage on all of these items; with turtles in north Bimini exhibiting a more generalist omnivorous diet, selecting for green algae, whereas turtles in south Bimini have a more specialist herbivorous diet, primarily consuming seagrasses and selecting for red algae, when available (Gillis et al. 2018). Coverage of each forage item was imported into ArcGIS 10.5 as point shapefiles and smoothed using the kernel density tool to create a raster layer of coverage percentage per square kilometer of each of the five categories.

Stakeholder use

A stakeholder-elicitation meeting was conducted in July, 2017, where local stakeholders (e.g., dive companies, fishermen, ecotourism agencies) were invited to discuss local conservation issues with researchers. Eighteen stakeholders were invited to the meeting and 12 stakeholders attended from Bimini Big Game Club, Neal Watson's Bimini Scuba Center, Bimini Biological Field Station Foundation, Wild Quest, Bimini Healing Arts, Bimini Adventures and Atlantis Rejuvenation Center. During the meeting stakeholders were asked to indicate in a 1 Km^2 gridded map which areas they use (e.g., fishing, ecotourism activity).

Each survey map was digitalized, imported into ArcGIS 10.5 and georeferenced. A polygon shapefile of use by stakeholders was created for each survey map following the shapes of the used areas drawn in the map, which were weighted equally. The polygon shapefiles were converted into a gridded polygon layer (resolution 1 Km^2) and then converted to raster layers using the polygon to raster tool. All survey map raster layers were summed into a single layer to obtain the number of stakeholders that reported to use each grid cell. We categorized each grid cell as: (1) low use (<25% of participants use the area), (2) medium use (26–75% participants use the area), and (3) high use (>76% of participants use the area).

Results

Turtle density

We captured 77 and acoustically tagged 57 green turtles, ranging from 28.6 to 63.9 cm SCL (mean = 45.9 ± 8.1) and between 30.5 and 69.9 cm CCL (mean = 49.36 ± 8.7). Mean SCL of turtles from Bimini were compared to the mean SCL of known mature green turtle within the Northwestern Atlantic population (mean = 96.7 ± 5.1 cm; Goshe et al. 2010), which indicated that all turtles captured during the present study were immature.

Two areas of high turtle density were identified: (1) South Flats, an open coastal seagrass bed running parallel to the south coast of south Bimini and (2) Bonefish Hole, a mangrove tidal estuary located on the northeast point of Bimini (Fig. 2). Bonefish Hole is located within the proposed North Bimini MPA. Turtle density in both the South Bimini Flats and Bonefish hole varied from 1 to 26 turtles per square kilometer (Fig. 2).

Coverage of forage habitat

The spatial distribution and concentration of the five considered forage categories varied greatly, with green algae and turtle grass being the most widely distributed (Fig. 3). Green algae were found at 96.5% of the stations, followed by turtle grass (89.5%), manatee grass (47.4%), red algae (40.4%) and shoal grass (17.5%). Turtle grass was predominately found in Bonefish Hole, the South Flats and the north-west central flats (Figs. 1, 3a). Manatee grass was concentrated in the deeper waters south of the island (Fig. 3b), while shoal grass was found mainly on the central flats between the north and south islands (Figs. 1, 3c). Green algae were distributed across Bimini with higher concentration on the north flats (Figs. 1, 3d), while high concentration of red algae was found in Bonefish Hole (Figs. 1, 3e).

Stakeholder use

The interviewed stakeholders indicated to be using all areas around Bimini, with a focus on locations in the northwest of Bimini and within the west side of the south island, where a channel exists and most of the boat traffic takes place (Fig. 4). These areas are utilized for a variety of ecotourism activities, including but not limited to, dolphin encounters (*Tursiops truncatus* and *Stenella frontalis*), great hammerhead shark (*Sphyrna mokarran*) diving, snorkeling, fishing (rod, reel and spearfishing) and reef SCUBA dives (Guttridge et al. 2017; Haas et al. 2017).

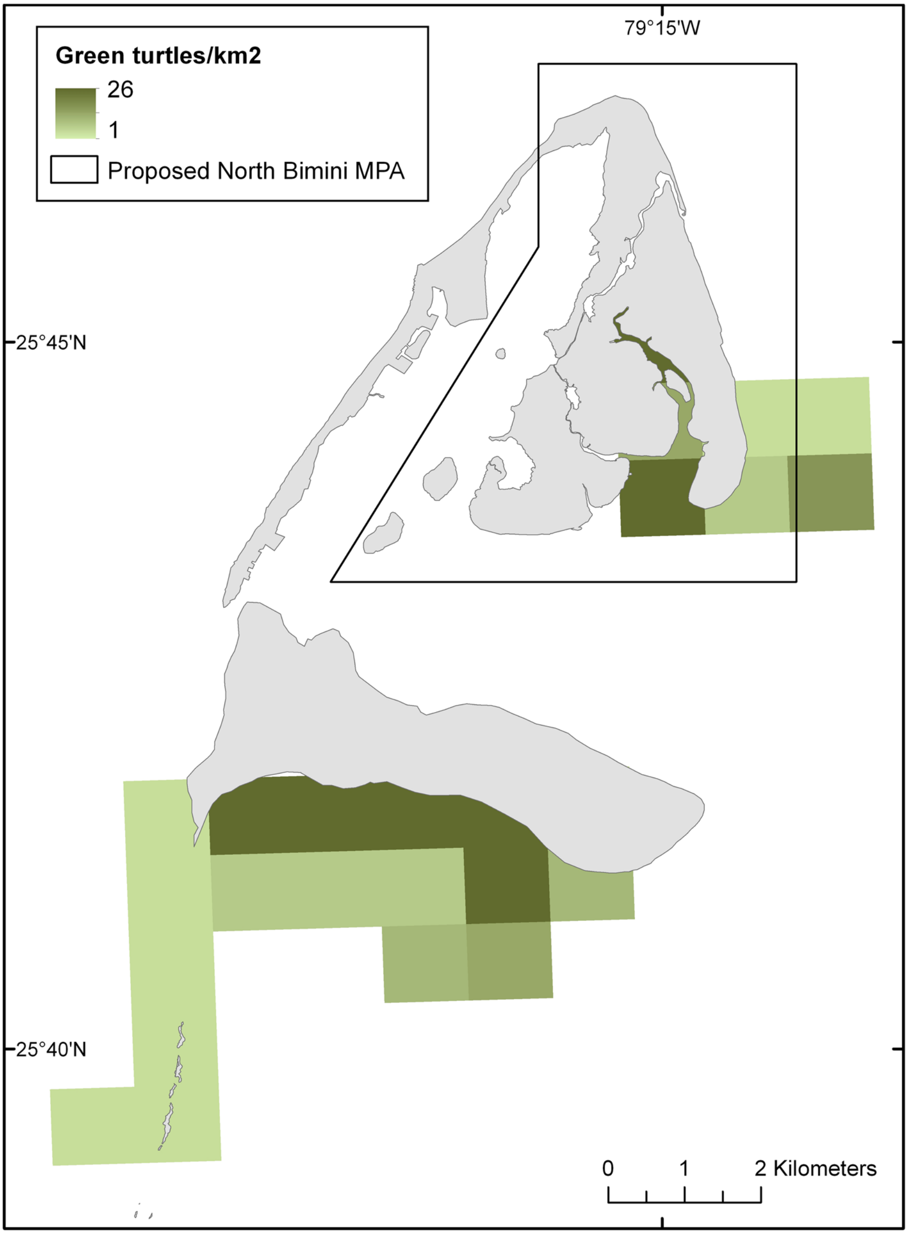

Fig. 2 Green turtle density (Km^2) across Bimini, from turtle data collected in 2016 and 2017 from turtle captures and acoustic telemetry data

Areas of high conservation value

Across all scenarios a total of 19 (8%) pu were selected for protection in Bimini (Fig. 5). Those pu were concentrated in South Flats and Bonefish Hole (Figs. 1, 5), which were

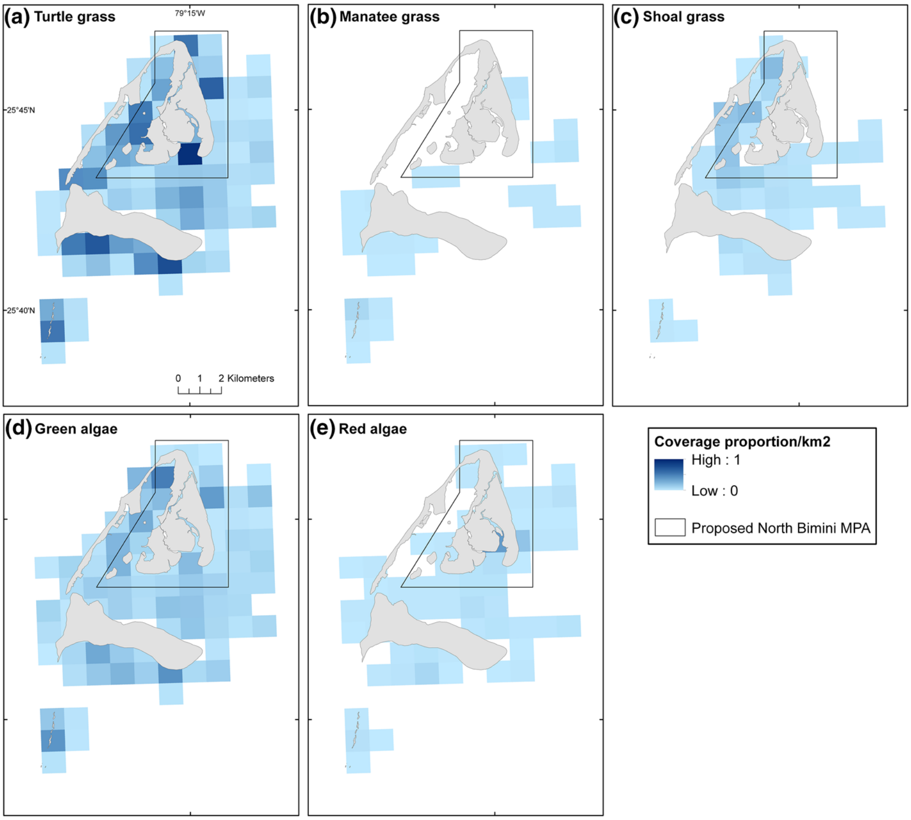

Fig. 3 Spatial distribution and percentage coverage of **a** turtle grass—*T. testudinum*, **b** manatee grass—*S. filiforme*, **c** shoal grass—*H. wrightii*, **d** green algae, **e** red algae, from habitat surveys conducted in 2016

identified as areas of high value for green turtle conservation as pu within both areas had a high frequency (> 51%) of selection for protection, with the most frequently (> 91%) selected pu in South Flats (Figs. 1, 5). Planning units within South Flats were also frequently selected for protection for scenarios that assumed the implementation of MPA in North Bimini (Figs. 1, 5e–h). When considering human use cost, the most frequent pu selected were also in South Flats (Figs. 1, 5b, d, f, h).

Discussion

Two regions within Bimini (South Flats in south Bimini and Bonefish Hole on the north Island) were identified as important areas for protection to meet government targets to maximize conservation of juvenile green turtles. This indicates that conservation targets would not be fully met with only the implementation of the proposed North Bimini MPA and that additional planning units within south Bimini should be protected. This is a reflection of the high turtle density in south Bimini and the occurrence of the principal forage items for juvenile green turtles in this region. Further, given the differences found in the distribution and abundance of green turtle forage items in this study and the variability in

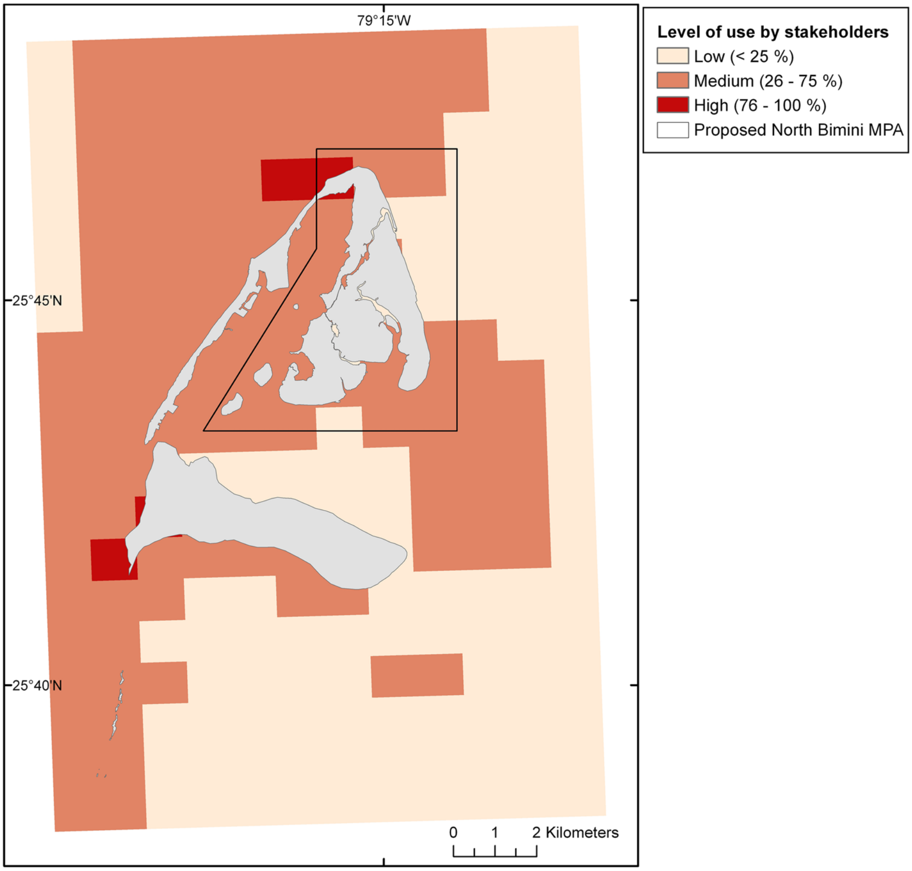

Fig. 4 Stakeholder use area across Bimini; low use (less than 25% of participants use the area), medium use (26–75% respondents use the area), and high use (more than 76% of participants use the area)

macrobenthic epifauna, species composition, and abiotic parameters between the two areas (Newman et al. 2007; Trave and Sheaves 2014), it would be desirable to protect both locations to ensure that a diverse range of habitats and species are conserved. South Bimini is also an important nursery area for various marine predators (e.g., juvenile lemon sharks and southern stingray) (Jennings et al. 2008; Guttridge et al. 2012; Wood et al. 2016; Hansell et al. 2018).Thus, protection of regions in south Bimini will not only benefit green turtles but can also benefit several elasmobranch species.

Future implementation of reserves in Bimini should consider lessons learned from the previous attempt to establish a MPA in the region (see Wise 2014). Despite initial support from the community (84%), the establishment of a MPA in north Bimini was delayed due to intra-agency conflict, tourist development priorities, economic uncertainty, lack of institutional support, a change in government and uneven participation (Wise 2014). While it is difficult to determine the exact cause of non-implementation, these combined factors created significant challenges for the implementation of the MPA and contributed to public uncertainty (Wise 2014). Future endeavors to restart discussions on MPA planning and implementation should highlight the potential economic benefits of protecting regions

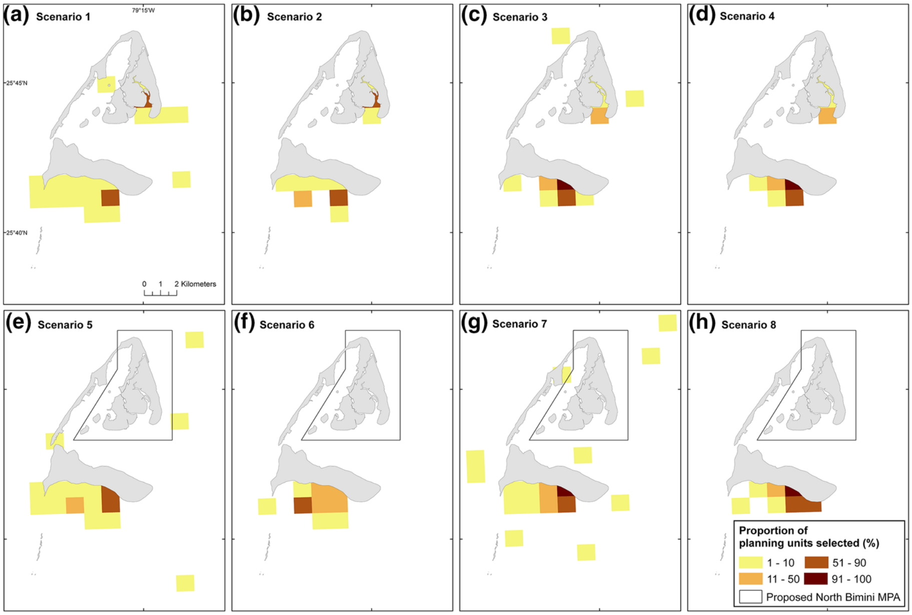

Fig. 5 Proportion of conservation units selected for each scenario; **a** scenario 1, 20% target, area based cost, no pre-selected protected area; **b** scenario 2, 20% target, human use based cost, no pre-selected area, **c** scenario 3, 30% target, area based cost, no pre-selected protected area; **d** scenario 4, 30% target, human based cost use, no pre-selected area; **e** scenario 5, 20% target, area based cost, North Bimini Marine Reserve established; **f** scenario 6, 20% target, human use based cost, North Bimini Marine Reserve established; **g** scenario 7, 30% target, area based cost, North Bimini Marine Reserve established; **h** scenario 8, 30% target, human based cost use, North Bimini Marine Reserve established

within Bimini to avoid competition with future development and the prospect of jobs. Economic benefits could include job creation from the harvest of resources, such as fish and conch, which would benefit from MPA implementation (Dahlgren 2002, 2004) and increased tourism and recreational activities (Dixon 1993; Haas et al. 2017). Importantly, acceptance of marine reserves will require consultation with local communities during all stages of planning and implementation, ensuring that all groups, gender and stakeholders are represented (Dahlgren 2004). In the past, stakeholder engagement appeared to ignore women as resource users, instead focusing on men as direct extractors (Wise 2014). Thus, any future engagement process should ensure a greater representation of previously under-represented groups.

The areas identified in need of protection to maximize the conservation of green turtles were selected based on how well they represented green turtle occurrence as well as their foraging items. Thus, our results only meet objectives of representation as they were informed by quantitative targets of species presence and their prey items. However, for more robust protection and the long-term maintenance of biodiversity, it is also necessary to have a more holistic approach and consider other species and objectives that account for the persistence of species and that influence conservation requirements (Sarkar et al. 2006; Pressey et al. 2007; Carwardine et al. 2009). For this, among other factors, it is necessary to incorporate biodiversity processes (e.g., dispersal), life history characteristics and dynamic threats into our marine conservation planning analysis

(Pressey et al. 2007; Carwardine et al. 2009). In the case of green turtles and in the context of a foraging area, such as Bimini, we should consider objectives that relate to: (1) protecting areas used by turtles with different size-classes and potentially life-stages (e.g., recently recruited juvenile and sub-adult turtles), (2) implementing measures that will mitigate specific threats (e.g., habitat degradation, fishing, pollution, harvest), and (3) considering approaches that account for multiple functions (e.g., foraging areas, movement corridors). No significant difference was found in the size class distributions of turtles between south and north Bimini, however a higher proportion of small turtles (< 35 cm,) was observed at Bonefish Hole, whereas a higher proportion of larger turtles was observed in south Bimini (> 60 cm) (Gillis et al. 2018), indicating that north Bimini may provide habitat for turtles that recently recruited to the region. Thus, future studies should identify where turtles with different life-stages are found to ensure that those areas are represented accordingly in any MPA implementation. Similarly, information on threatening processes to turtles and their habitat should be identified and incorporated into our analysis (Wilson et al. 2005). Given that marine turtles are fully protected in the Bahamas since 2009 (Bjondal and Bolten 2009), a focus should be on impacts to their habitat. Of concern are the impacts to seagrass beds from propeller scaring, coastal development and pollution (Waycott et al. 2009; Govers et al. 2014; Sweatman et al. 2017). Thus, any suggested/implemented MPA, with the aim of protecting green turtles, should prohibit or aim to minimize anthropogenic activities that impact seagrass beds in the region. With this in mind future analysis should identify areas that are most vulnerable to these processes and strategies to mitigate those threats.

Consideration should also be given to the socioeconomic, cultural and political context of the areas being proposed for protection, including the logistical feasibility of implementing reserves, costs and acceptability and impact to the local community and end-users (Lundquist and Granek 2005; Charles and Wilson 2009; Fuentes et al. 2015). Attention should be given to the design criteria for these areas, including size, shape, spacing and connectivity of planning units (Pressey et al. 2007). Nevertheless, our results provide valuable information into important areas to protect in Bimini given existent datasets and may be used to inform current and future marine protection delineation and implementation in the region, serving as a case study to the remaining of the Bahamas. Indeed, similar to our study, several other studies have demonstrated how spatial data can be used successfully to guide the delineation, implementation and management of MPAs (Schofield et al. 2013a, b; Maxwell et al. 2016; Dawson et al. 2017). As information becomes available on the spatial distribution and abundance of the other marine species that are found in Bimini (e.g., lemon sharks, southern stingray, great hammerhead), including loggerhead and hawksbill turtles which were observed in very small numbers, our analysis can be readily updated to incorporate these datasets and identify areas for protection under a multi-species conservation approach. This will ensure that more species are protected and a more holistic approach is undertaken.

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