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Effects of sea-level rise on manatees' seagrass habitat:

A case study of the northern Indian River Lagoon, Florida

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ABSTRACT

Changes in depth and temperature due to climate change are predicted to highly impact seagrass coverage and distribution. Seagrass is critical for many marine species, including the endangered West Indian Manatee. Predicting changes in seagrass abundance for several climate change trajectories will help inform manatees conservation and preservation. In this study, the SLAMM model was used to assess how sea-level rise would impact the northern Indian River Lagoon, on the Atlantic coast of Florida. This ecosystem is especially interesting as it is one of the places with the highest manatee abundance throughout the state. Using predicted changes in temperature and depth over the area, MaxEnt was run to assess predicted seagrass habitat suitability for 4 climate change scenarios. It was found that as emissions increase, seagrass coverage predictions were increasing too. To assess the seagrass areas that would be available to manatees, the preferred depth and temperature range of the species was estimated. Those estimations were used to map and quantify the areas of seagrass reachable by manatees in each prediction. The areas unreachable by manatees increase as emissions increase but the total seagrass areas that would be a part of their predicted range is highest than it is in present days for all scenarios. Both predictions of seagrass habitat suitability and changes in manatees’ foraging areas should be taken into account and inform seagrass restoration and manatees conservation projects.

CONTENTS

INTRODUCTION

As a response to natural forcings, Earth's climate is temporally and spatially variable, alternating between Ice Ages and interglacial periods (Ghil & Lucarini, 2020; Petit et al., 1999; Tzedakis et al., 1997). The intensification of human forcings and anthropogenic activities has led to human-induced changes in the climate system. The post-industrial period starting at the end of the 19^{th} century has been characterized by a fast increase in temperatures (Mann et al., 1998). Between 1975 and 2005, the global surface temperature increased by about 0.2°C per decade (Hansen et al., 2006). This human-induced climate change is due in most part to greenhouse gas emissions, especially carbon dioxide, as well as non-CO_2 emissions such as methane (Montzka et al., 2011; Lashof & Ahuja, 1990).

Climate change alters the balance of the Earth system and these atmospheric changes have cascading effects on land and at sea. The intensity and frequency of extreme weather events such as storms, hurricanes, droughts, and floods have increased (National Academies of Sciences, Engineering, and Medicine, 2016). Climate change is also causing rising sea-levels (Warrick et al., 1990). Indeed, warming air temperatures are causing the melting of glaciers and ice sheets, especially in the Arctic and Antarctica (Hansen et al., 2016) as well as increased water temperatures. As oceans are warming up, the volume of water is increasing due to thermal expansion (Wigley & Raper, 1987; Lombard et al., 2005), which in turn contributes to global sea-level rise.

These changes in ecosystems are highly impacting the marine biota causing, for example, range shifts with local extinctions and colonizations (Perry et al., 2005; Kleisner et al., 2017; Hare et al., 2016), disrupted synchronies due to phenological shifts (Poloczanska et al., 2016; Taylor, 2007; Appelqvist & Havenhand, 2016) or biological modifications (Hoegh-Guldberg et al., 2007; Whiteley, 2011). Climate change is also causing modifications in organisms' habitats, both because of physical variability as well as chain reactions ultimately causing habitat degradation and impacting all species.

Seagrass are essential marine habitats that are heavily impacted by climate change (Orth et al., 2006). As aquatic angiosperms, seagrass is found exclusively in the marine environment (Larkum et al., 2006). There are 12 seagrass genera which have different habitats and growth conditions (Ogden, 2006). The impact of climate change on seagrass has been widely documented. First, most seagrass species are found in shallow coastal waters because they need a sufficient amount of light to grow (Dennison, 1987; Duarte, 1991; Morris et al., 2022). As sea-levels continue to rise, depth and light limitation will increase causing changes in seagrass distribution and growth (Short & Neckles, 1999). Global ocean warming will also be impacting seagrass depending on their thermal range as rising temperatures have been shown to decrease rates of seagrass growth (Collier & Waycott, 2014; Bulthuis, 1987) as well as abundance and distribution (Chefaoui et al., 2019; Telesca et al., 2015). Finally, increased events of hypersalinity in coastal ecosystems due to climate change may affect seagrass coverage across oceans (Lirman & Cropper, 2003).

The consequences of climate change on seagrass distribution are reinforced by urbanization and coastal armoring. Sea-level rise does not necessarily mean decreased seagrass abundance. Indeed, as sea-levels are rising, the range of seagrass could shift towards the newly flooded areas to remain within its depth range. However, the threat of sea-level rise has led to the construction of shoreline structures that would protect urbanized areas in case of sea-level rise or extreme weather events (Duvat, 2013). Called coastal armoring, it takes the form of seawalls, dikes, breakwaters or ripraps. While protecting urbanized zones, these structures have important consequences on seagrass distribution and abundance. Indeed, these structures prevent the water from expanding on land. Therefore, as sea levels rise, water is not expanding as it is blocked by the structure, but depth is increasing. As mentioned before, seagrass is mainly found in shallow waters, less than 1.5 meters deep (Aoki et al., 2020). Therefore, this increased depth is locally causing a contraction of the seagrass geographic range rather than a shift (Esteves, 2015; Pontee, 2013). This phenomenon called coastal squeeze has been predicted to engender up to 90% of tidal habitat loss under the effects of sea-level rise (Glick et al., 2008).

The predicted loss of seagrass habitat due to sea-level rise and coastal squeeze is likely to have important consequences for the many species that depend on it. This is particularly the case of *Trichechus manatus*, also called the West Indian manatee (hereafter “manatee”). In the United States, this Sirenian species is mainly found in the state of Florida, even though its range is expanding towards the eastern states of the Gulf of Mexico under the impacts of climate change (Cloyed et al., 2022; Cloyed et al., 2021). As herbivores, manatees rely mainly on seagrass as an energy source. Because it is highly abundant, but a low energy source, manatees have been found to consume high amounts of seagrass per day: the amount could vary between 9 to 80 kilograms per day (Bengston, 1983; O’Shea & Reep, 1990). Manatees feed mainly on submerged seagrass but have also been seen feeding on floating or emergent seagrass in cases of reduced availability (Marsh et al., 2011; Marsh, 2022). Therefore, the spatial distribution of manatees is strongly tied to these seagrass ecosystems.

However, manatees are facing an increased number of threats and are now classified as threatened by the U.S. Endangered Species Act. Indeed, anthropogenic activities are already impacting manatee populations in Florida and these impacts will be aggravated by the effects of climate change. Because of their low metabolic rate, manatees have to stay in waters above 20°C or they are at risk of dying of cold-stress (Blair Irvine, 1983). Thus, during the cold season in Florida, manatees migrate to warm-water refugia, mainly to natural springs and near power plants releasing hot water (Deutsch, 2000; Laist et al., 2013; Shane, 1984). However, due to the increased use of fertilizers, wastewater treatments and the closing of power plants to move to cleaner energy sources, manatees are faced with a loss of warm-water refugia leading to increased cases of cold-stress deaths in the winter (Denizman, 2018, Hardy et al., 2019). Moreover, as seagrass areas have reduced over time in Florida, the manatee population has declined. Seagrass abundance has been highly impacted in the last decade by algae blooms reducing the amount of light available for seagrass and causing massive seagrass die-offs (Lapointe et al., 2020; Lapointe et al., 2015; Morris et al., 2020). These blooms have caused up to 50% declines in seagrass in some areas of Florida, impacting the food availability for manatees (Allen et al., 2022). Decreases of seagrass abundance and coverage are predicted to be amplified by the impacts of climate change which will lead to decreases of manatees' habitats. Therefore, between January 2021 and March 2023, it is estimated that about 2,000 manatees have died, mostly of starvation (FWC, 2023). As the latest manatee counts in Florida estimate that there are between 5,700 to 7,500 manatees left in the state of Florida, seagrass abundance has become a priority concern (FWC).

The impacts of seagrass habitat loss on manatee population trends are amplified by the movement behavior and their site fidelity. During the summer months, manatees aggregate in the places containing the highest percentage of seagrass (Berger, 2007). Manatees display high-site fidelity, meaning that they usually migrate to the same winter and summer sites throughout their lives (Deutsch, 2003). Because of these strong site-fidelity patterns, manatees stay near their summer and winter sites, even when the habitat conditions are not suitable anymore. It has been suggested that in the event of a power plant shutdown, only a moderate number of animals would move to new winter sites while most of them would stay around the former refugia and therefore increase their risk of dying of cold stress (Laist & Reynolds III, 2007). Seagrass being a strong predictor of manatees' distribution, site-fidelity coupled with coastal squeeze might lead to increased events of starvation and malnutrition.

On the Atlantic coast of Florida, the northern Indian River Lagoon concentrates high manatee density. Brevard County, which is the county where the lagoon is located (Fig. 1), gathers over 70% of the manatees on the Florida East Coast (Martin et al., 2015). This area having several no-boat zones as well as being a part of the migratory route of many manatees to their winter site (such as Blue Springs), it is widely used during the summer months by manatees. This area was also characterized by healthy and high seagrass abundance that could sustain the manatees' population (Morris et al., 2022). Most areas of the northern Indian River Lagoon being less than 2 meters deep, the seagrass species present in this lagoon are growing at a depth range between 0.5 and 2 meters deep (Dawes et al., 1995). The most abundant species are *Halodule wrightii* and *Syringodium filiforme* which are also the species most consumed by manatees (Provancha and Carlton, 1991; Dawes et al., 1995; Provancha & Scheidt, 1999; Thompson, 1978). However, due to repeated phytoplankton blooms caused by nutrient run-offs since 2011, seagrass abundance has declined by half over the last 10 years (Morris et al., 2020; Allen et al., 2022). This decline led to many conservation and restoration efforts in the area, with both manatees' feeding programs to prevent malnutrition as well as seagrass transplantation to increase seagrass areas (FWC, 2023; Galoustian, 2022).

Seagrass transplantation and restoration should consider predictions of the areas that will be suitable for seagrass under different sea-level rise scenarios. This would ensure the long-term viability of the seagrass restoration projects. Similarly, understanding how sea-level rise would drive changes in seagrass habitat would also inform the predicted distribution and abundance of manatees. These predictions could then be used to guide the conservation efforts and anticipate the upcoming challenges. Yet no studies have looked at seagrass predictions under the impacts of sea-level rise scenarios in the northern Indian River Lagoon. Even fewer studies have used these impacts to foresee potential consequences on manatees' distribution, abundance, and health.

In this study, we use a Species Distribution Model (SDM) to model the distribution of seagrass and project predicted habitat suitability under 4 IPCC scenarios of climate change in the northern Indian River Lagoon. Based on manatees' distribution as a function of depth and temperature, these seagrass predictions are then used to produce high resolution maps assessing the future geographic distribution of manatees' preferred habitat. This study aims to provide an intermediate-scale framework that could be expanded to quantify the impacts of climate change on manatees over the rest of their range and inform management at the scale of the Florida state.

METHODS

Study area

The Indian River Lagoon on the Atlantic coast of Florida stretches from Ponce de León Inlet to Jupiter Inlet with a total area of 353 square miles (Fig. 1). The lagoon is connected to the ocean by 5 inlets distributed along this 156-mile-long water span. It is a very shallow area with an average depth of about 1.2 meters. The salinity of the water varies along the lagoon but is mainly brackish as the ocean saltwater coming through the inlets is mixing with freshwater coming down the streams and rivers. In this study, we focus on the northern part of the Indian River Lagoon. This area includes the northern part of the lagoon as well as Banana River and the southern part of Mosquito Lagoon, which are all adjacent to Merritt Island on which can be found both the NASA Kennedy Space Center and the Merritt Island National Wildlife Refuge. More precisely, the southern limit of the area is the Ernest Kouwen-Hoven Memorial Bridge, going from Melbourne to Indialantic and the northern limit is the city Ariel. The total research area covers 1882 km^2 and is 90 km long.

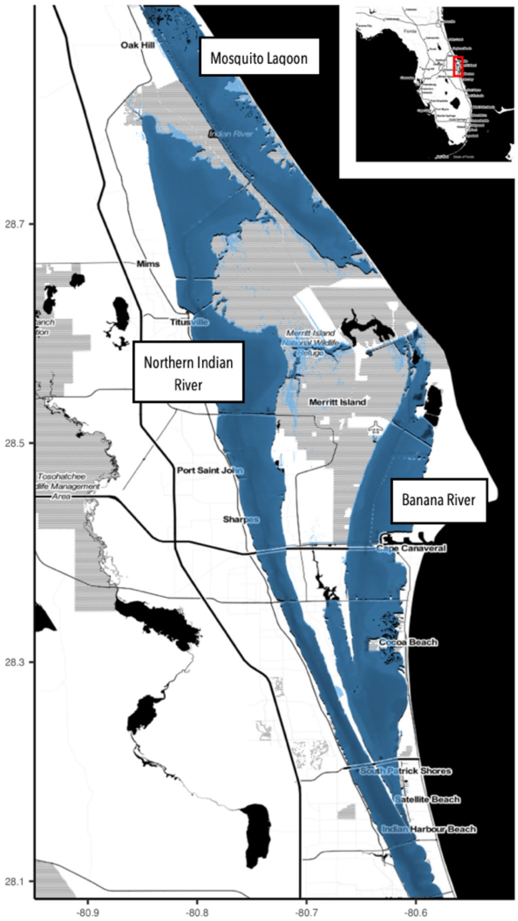

Figure 1. Map of the study area (blue). Land and ocean ocean are represented in white and black respectively. The area studied is shown with blue. The red rectangle on the inset map is showing the location of the northern Indian River Lagoon in the state of Florida.

Assessment of changes in wetland cover due to sea-level rise

Impacts of sea-level rise on wetlands and land cover were assessed using Sea-level Affecting Marshes Model (SLAMM) version 6.7. SLAMM is using a flexible decision tree to simulate wetland conversions in different long-term sea level-rise scenarios (Clough et al., 2016). Based on elevation, slope and current wetlands' distribution, the model computes the specific responses of wetlands to increased sea-level. Indeed, wetlands and especially tidal marshes are highly vulnerable to sea-level rise because of their low elevation. To stay in place and not be impacted by climate change, the rate of vertical accretion of sediment and organic matter of marshes has to take place at the same rate as sea-level rise (Reed, 1995). SLAMM accounts for these rates of accretion but also for the potential flooding of marshes if the rate of vertical accretion is lower than the rate of sea-level rise. The model was first developed in the 1980s and updated several times to reinforce accuracy. Its validity was tested using retrospective analyses in the states of Florida and Louisiana and the predicted wetland loss was similar to the observed wetland loss: 35% of predicted loss versus 39% of observed wetland loss in Louisiana for example (Geselbracht et al., 2011 ; Glick et al., 2013).

To apply SLAMM to the northern Indian River Lagoon area, three datasets were used as inputs: elevation, slope, and wetlands classification. Elevation data was collected from the NOAA National Centers for Environmental Information with a 1/9th Arc-second resolution and using units of meters (NOAA, 2020). The dataset is a continuously updated digital elevation model which was last updated in 2020. Using the Slope tool in ArcGIS Pro v.3.1.1, a slope dataset was derived from the digital elevation model. Finally, SLAMM requires a file of the current wetland type and distribution. The National Wetland Inventory (NWI) dataset created by FWS was used in this analysis and its extent was reduced to the northern Indian River Lagoon area (FWS, 2009). For this area, the data was collected and mapped in 2009. However, the wetland categories in the FWS dataset had to be adapted to match these used by SLAMM. Therefore, R version 4.2.2 was used to reclassify the data and obtain the SLAMM wetland categories. Based on the California SLAMM Categories to NWI Crosswalk published in the SLAMM Technical Document (Clough et al., 2016), the R dplyr package was used to associate each NWI category to one of the 17 SLAMM wetland categories in a new column. The NWI dataset being a shapefile, it was converted to a raster using the Polygon to Raster tool in ArcGIS Pro and its extent and resolution were matched with the elevation dataset. The three datasets (Elevation, slope and wetland types) were then converted to ASCII format using the Raster to ASCI tool in ArcGIS Pro as SLAMM only reads ASCII files.

Several parameters were then inputted to ensure better accuracy of the model. The initial time condition for the model is based on the date of the NWI dataset. The digital elevation model was calibrated to that date by the model using the historic trend of the sea-level rise parameter. For the northern Indian River Lagoon, the historic trend of sea-level rise was collected using NOAA's Tides and Current data for Trident Pier in Port Canaveral setting the parameter to 6.25 mm/year. The vertical datum used by SLAMM is Mean Tide Level while the elevation dataset is mapped using the NAVD88 vertical datum. Elevation data is corrected using the MTL-NAVD88 parameter. To determine its value, the following equation was used (Clough et al., 2016):

$$NAVD_{corr} = MTL - NAVD88$$

To calculate this parameter, the data from Trident Pier in Port Canaveral collected by NOAA was used (NOAA, 2023). As the mean tide level value is set to

0.570 meters and the NAVD88 value is 0.860 meters, the MTL correction inputted in SLAMM was -0.29 meters.

The SLAMM model was also parametrized to account for protection of developed dry land that is expected to lead to coastal squeeze. This functionality of the model takes all cells that are classified as developed and protects them from inundation in predictions.

Regarding sea-level rise scenarios, the model can be run using the set of sea-level scenarios published in 2001 in the Special Report of Emissions Scenarios by the IPCC which are included in the model, or the user can use customized sea-level rise scenarios. Because the use of the most recent data was preferred for this research, the high-resolution sea-level projections of the IPCC 6th Assessment Report relative to a 1995-2014 baseline were used (IPCC, 2022). The data was extracted from the NASA Sea-Level Projection Tool for Trident Pier in Port Canaveral for four Shared Socioeconomic Pathways (SSP): SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 (NASA, 2023). Each SSP corresponds to scenarios of socioeconomic trajectories leading to scenarios of greenhouse gas emissions. These scenarios have been widely accepted and used throughout the climate change research community and offer a common framework for climate change predictions. Both the 2050- and 2100-decades projections were extracted for each scenario to allow for temporal comparisons in each scenario.

Modeling seagrass habitat suitability using MaxEnt

A Species Distribution Model was used to model seagrass environmental correlates and predict seagrass habitat suitability in the northern Indian River Lagoon. MaxEnt is a presence-only model of species distribution, meaning that it models a species distribution based on locations where the species was present while absence positions are not known. After extracting environmental variables over these presence points and over a set of background point (a.k.a pseudo-absences), MaxEnt estimates probability densities and probabilities of habitat suitability (Elith et al., 2010; Phillips et al., 2006 ; Phillips, 2009).

MaxEnt was run twice at different scales for this study. It was run a first time for the state of Florida. For this run, the model was trained using ten environmental variables. The aim was to identify the potential predictors having the most impact on seagrass habitat suitability throughout Florida. Using these most impactful variables, MaxEnt was trained for a second run using datasets of these environmental variables for the Indian River Lagoon. The aim of this second run was to predict future seagrass habitat suitability under the effects of climate change based on the predicted changes for the variables that were identified as the most important drivers of seagrass occurrence across Florida.

Environmental drivers of seagrass occurrence

To use MaxEnt to predict seagrass habitat suitability in the northern Indian River Lagoon, the environmental variables that had the most impact on seagrass distribution were identified. To do so, presence data was extracted from the Seagrass Habitat in Florida dataset created by the Florida Fish and Wildlife Conservation Commission (FWC, 2022). This dataset is a compilation of seagrass data collected by several agencies and organizations throughout Florida. It is a polygon shapefile that is regularly updated with the latest data available. Using ArcGIS Pro, the polygon file was converted to a point shapefile to get the presence data of seagrass beds. The longitude and latitude coordinates were added to each point and the dataset was converted to a CSV file and inputted in MaxEnt. The resulting file had a total of 1,078 seagrass beds records.

A review of the literature was conducted to identify the ten most important variables that potentially drive seagrass distribution. Among them, water temperature, phytoplankton, nitrate, current velocity, pH, photosynthetically available radiation, salinity, depth, chlorophyll and wetland type were identified as potential predictors (Duarte, 1999 ; Hemminga & Duarte, 2000 ; Larkum et al., 2006 ; Lee et al., 2007 ; Orth et al., 2006 Short et al., 1996 ; Short & Neckles, 1999). The National Wetland Inventory dataset for the state of Florida was used as the wetland layer. Depth data was extracted from the NCEI website by downloading all tiles of the state of Florida and merging them using ArcGIS Pro into one single dataset. The other environmental variables identified as potential predictors were obtained from Bio-Oracle version 2.2 at a resolution of 5 arcmins for the time period 2000-2014 (Tyberghein et al., 2011 ; Assis et al., 2017, Ming et al., 2022). Bio-Oracle is a database that compiled satellite-based datasets and in-situ measured data to create rasters of marine environmental variables such as the ones used in this study (Tyberghein et al., 2011 ; Assis et al., 2017, Ming et al., 2022). All the environmental files were clipped to the same 100 meters resolution, extent, and coordinates system. They were then converted to ASCII files and inputted in MaxEnt.

A threshold of 20% of permutation importance was chosen to identify the environmental variables having the most impact on seagrass distribution in Florida. MaxEnt was run using 10,000 background points and the AUC (Area Under Curve) was used to evaluate the performance of the model (Araújo et al., 2005). The value of the beta parameter was 1. MaxEnt' default settings were used to determine which feature classes to use to predict habitat suitability based on the number of presence points. Therefore, all feature classes were used (quadratic, hinge, linear, threshold and product) in this case because there were over 80 points of presence in the presence dataset (Merow, Smith & Silander Jr., 2013). With respectively 28.2% and 22% of permutation importance, depth and temperature came out as the most important variables in predicting seagrass distribution in Florida.

Predictions of seagrass habitat suitability

Being the two most important potential predictors in seagrass habitat suitability in Florida, it was chosen to use both depth and temperature to evaluate the impacts of climate change on seagrass habitat. To predict seagrass habitat suitability in the northern Indian River Lagoon based on these two variables, MaxEnt was trained using presence records in the Indian River Lagoon, from Jupiter Inlet to Ponce Inlet between 2008 to 2020. This ecoregion was chosen because of its similarity with the northern Indian River Lagoon which would prevent overfitting of the model to relationships found in this relatively small study area. The files were collected from the GIS database of the St John's River and Water Management District. The polygons were converted to points using ArcGIS Pro and all the datasets were merged to create a file of presence records of seagrass in Indian River between 2008 and 2020 (Fig. 2).

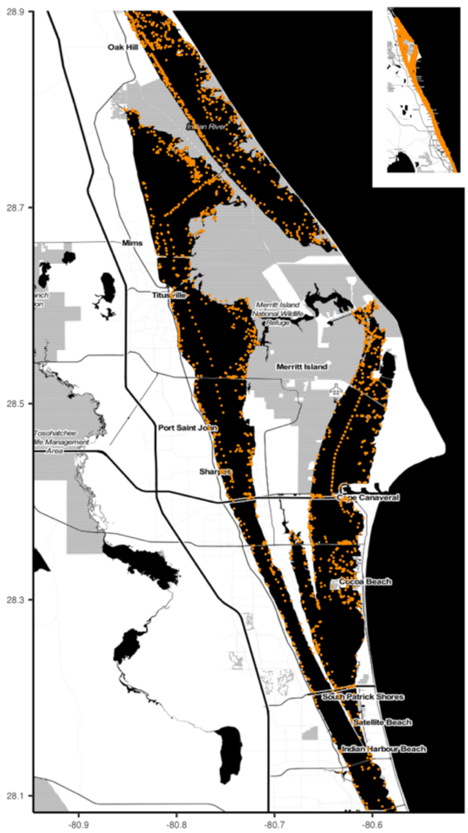

Figure 2. Seagrass presence records (orange points) for the extent of the training area (Indian River Lagoon) between 2008 and 2020. The inset map shows seagrass presence records for the whole training area while the main map shows a close-up of seagrass beds records for the northern Indian River Lagoon.

The data extracted from the NCEI website was used as the depth file with a resolution of 3 meters. For temperature, annual rasters of remotely sensed sea-surface temperature (SST) with a resolution of 1 kilometer collected by the Advanced

Very High-Resolution Radiometer (AVHRR) between 2008 and 2020 were gathered (NOAA, 2008-2020). Rasters were locally extrapolated using Focal Statistics in ArcGIS Pro to ensure that they were covering the extent of the Indian River Lagoon, especially when some coastal pixels were not measured by AVHRR. Annual rasters of sea-surface temperature were averaged together to obtain a raster of mean SST in the Indian River Lagoon at a 1-kilometer resolution for the 2008-2020 time-period. Both rasters were clipped to the same resolution and extent. The MaxEnt model was then trained using these two variables. The modelling of the contribution of each variable showed that the permutation importance of elevation was 70% while temperature had a permutation importance of 30% in predicting seagrass habitat suitability. MaxEnt was then run for each scenario using 10,000 background points and 500 iterations. AUC was used to validate the model. MaxEnt also performed jackknife tests to test for the impact of each environmental variable on the model (Elith et al., 2010). The model was set-up to produce ASCII outputs to ensure further analysis using ArcGIS Pro.

To predict habitat suitability, rasters of predicted environmental variables also need to be inputted into MaxEnt. These files were created for the 2050 and 2100 decades for each scenario. In the case of predicted bathymetry, the file of current depth in the Indian River Lagoon was updated with each predicted changes in sea-level rise collected from the NASA Sea-Level Rise tool and the SLAMM outputs. To get sea-surface temperature predictions, predictions of changes in sea-surface temperature (deltas) of the CMIP6 climate model for each scenario were extracted from the IPCC Interactive Atlas using a 1995-2014 baseline. Annual datasets of sea-surface temperature between 2008 and 2020 were collected from the AVHRR East Coast Watch Initiative (NOAA, 2008-2020). Each annual dataset was extrapolated using Focal Statistics in ArcGIS Pro to cover the entire study area. Annual rasters of sea-surface temperature were averaged together to obtain a 1-kilometer resolution raster of mean sea-surface temperature in the northern Indian River Lagoon between 2008 and 2020. The predicted sea-surface temperature deltas of each scenario were added to this dataset to produce high-resolution datasets of predicted sea-surface temperature for 2050 and 2100 (von Hammerstein et al., 2022). These datasets were clipped to the extent of the study area to prevent extrapolation.

Predictions of seagrass habitat suitability for the 2008-2020 period were also generated to compare to future predictions. To do so, the same presence points and environmental variables were used to train the model. As predictions, the raster of mean annual temperature for the 2008-2020 time-period over the area that was created as the high-resolution base layer to generate temperature predictions was inputted. The depth file inputted corresponds to the elevation file used for SLAMM, clipped to the extent of the study area. The output of the model was a map of predicted probability of seagrass habitat suitability for the 2008-2020 time-period over the northern Indian River Lagoon. To be able to compare MaxEnt predictions for present days to the actual seagrass coverage, a map of observed seagrass coverage was produced. It was generated using the “IRL Seagrass 2009 ; Shoreline 2008” shapefile created by the St Johns River and Water Management District (SJRWMD, 2009). It was chosen to use a dataset of 2009 because the Indian River Lagoon has been faced with many algae blooms since 2011 that have caused the loss of many seagrass areas. Using the 2009 seagrass dataset ensures that seagrass coverage is not altered by these blooms.

Assessment of seagrass available to manatees

The MaxEnt outputs of seagrass habitat suitability were visualized using ArcGIS Pro. Three different thresholds were applied to the predicted probabilities of seagrass habitat suitability (>0.5, >0.75 and >0.95) to estimate predicted spatial coverage of seagrass beds.

To identify the seagrass areas that would be available to manatees in each scenario, we assessed the distribution of manatees with respect to two environmental variables: depth and temperatures. To do so, manatees’ distribution data was extracted from the Manatee Synoptic Survey Observation Locations shapefile, collected by the Florida Fish and Wildlife Conservation Commission (FWC, 2021). Thirty-three aerial surveys were conducted between 1999 and 2021 using aerial surveys over the state of Florida. Each presence record was mapped as a point and added to the general dataset. For the purpose of this study, only the manatee observations recorded between 2003 and 2021 were used in order to match the time period of the temperature dataset. That dataset was then used to extract and analyze manatees distribution based on depth and temperature.

First, the preferred depth range of manatees was determined. Using the Florida bathymetry file produced by NCEI mentioned previously, a density plot of manatees’ distribution as a function of depth was produced in R. This density plot was used to identify the preferred depth range of manatees. Manatees could access seagrass beds that are less than 0.5 meters deep in case of starvation but it would require them to crawl so it was decided that all depths inferior to -0.5 meters would be outside of manatees’ preferred range.

Then, the preferred temperature range of manatees was assessed. Annual sea-surface temperatures were extracted from the Multiscale Ultra-High-Resolution Sea-Surface Temperature dataset (NOAA, 2003-2021) for the state of Florida between 2003 and 2021. The average of these datasets was calculated using ArcGIS Pro to obtain the average sea-surface temperature for this period with a resolution of 1 kilometer. The density plot of manatees’ distribution as a function of temperature was then generated.

Using these data, the preferred habitat of manatees was identified for the northern Indian River Lagoon in each scenario. This preferred habitat was laid over the output maps of MaxEnt to identify the seagrass beds that would be a part of this preferred habitat. This was used to create maps showing the seagrass that would be a part of the manatees' preferred habitat and therefore that would be accessible to manatees. The total areas of seagrass beds available to manatees for the three predicted probability thresholds used previously were calculated to quantify the amount of seagrass available to manatees in each scenario.

RESULTS

Identification of seagrass occurrence predictors

A first run of MaxEnt was done to identify the most important predictors of seagrass habitat suitability in the state of Florida. Seagrass beds occurrence recorded a total of 678 presence points. The performance of the model was good as the area under the curve (AUC) score was 0.842. Among the 10 environmental variables used, elevation and temperature were the ones that contributed the most to seagrass habitat suitability, respectively by 28.2% and 22%. The variables with the less important contribution were wetland types (1%) and chlorophyll (0%).

Predictions of seagrass habitat suitability

MaxEnt was then used a second time using the most important habitat suitability predictors (here temperature and depth) to generate predictions of seagrass habitat suitability in climate change scenarios. For this run, seagrass beds occurrence recorded a total of 8,121 presence points collected between 2008 and 2020 throughout the Indian River. Among these occurrences, 25% were used for model testing and 75% for training. The area under the curve score of the model (AUC) was 0.748 ± 0.011. Depth was the variable contributing the most to seagrass habitat suitability (69.4%). The importance of temperature in the model was 30.6%. Predictions of habitat suitability were generated for the decades 2050 and 2100 for the extent of the study area (northern Indian River Lagoon).

The comparison of present seagrass coverage as well as MaxEnt predicted probabilities of habitat suitability for that same period show that Banana River and Mosquito Lagoon are the areas that both with the highest seagrass coverage (Fig. 3). This is corroborated by both maps of present seagrass coverage and MaxEnt predictions of present habitat suitability.

When it comes to predictions of climate change scenarios, MaxEnt showed an increase in habitats suitable for seagrass in the future, and even more so in the most extreme climate change scenarios. Both the scenarios and the decades had an impact on the predicted probability of seagrass suitable habitat (Fig. 4). The scenarios with the lowest emissions, mainly 2.6 and 4.5, are very similar in their 2050 and 2100 predictions, only showing relatively small areas with high predicted probabilities of habitat suitability. The 4.5 scenario has more extended areas with higher predictions of seagrass habitat suitability than the 2.6 scenario. On the contrary, the 7.0 and 8.5 scenarios, which are the highest emissions scenarios, are characterized by higher seagrass habitat suitability probabilities over larger areas. Both the 7.0 and 8.5 predictions also are similar, which is why two groups seem to form: the lowest emissions scenarios with low seagrass habitat suitability probabilities in most areas and the highest emissions scenarios with higher predicted suitability in more areas. The differences between the scenarios are mainly visible between these two groups than intra-groups. In terms of spatial differences, the areas with the highest predicted probabilities are the shallow coastal zones as well as some other shallow areas of the lagoon in the 8 predicted maps. Current dry areas that are predicted to get inundated by sea-level rise are the ones with the highest habitat suitability probabilities. Mosquito Lagoon as well as the most northern part of the Indian River are the areas that display the most predicted changes between the 2.6 scenario and the 8.5 scenario, mainly because they are the shallow areas (less than 1.5 meters deep) with the highest potential flooding range as they are less urbanized than the southern areas around Kennedy Space Center and Titusville. On the contrary, the Banana River and the most southern part of the study area, which are also among the deepest parts of the northern Indian River Lagoon, have a low predicted probability of habitat suitability in every scenario. This differs from the present days seagrass coverage as the Banana River was identified as the area with the highest seagrass coverage (Fig. 3).

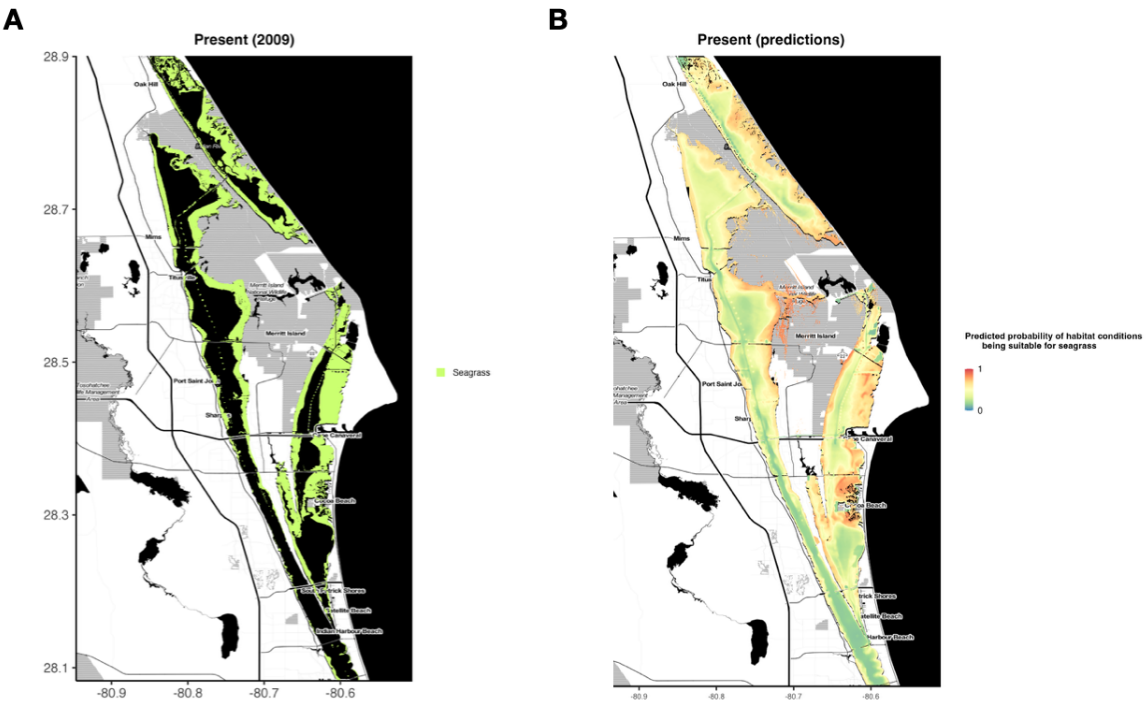

Figure 3. Seagrass coverage in the northern Indian River Lagoon in 2009 (A). MaxEnt predicted seagrass habitat suitability for the 2008-2020 time-period (B).

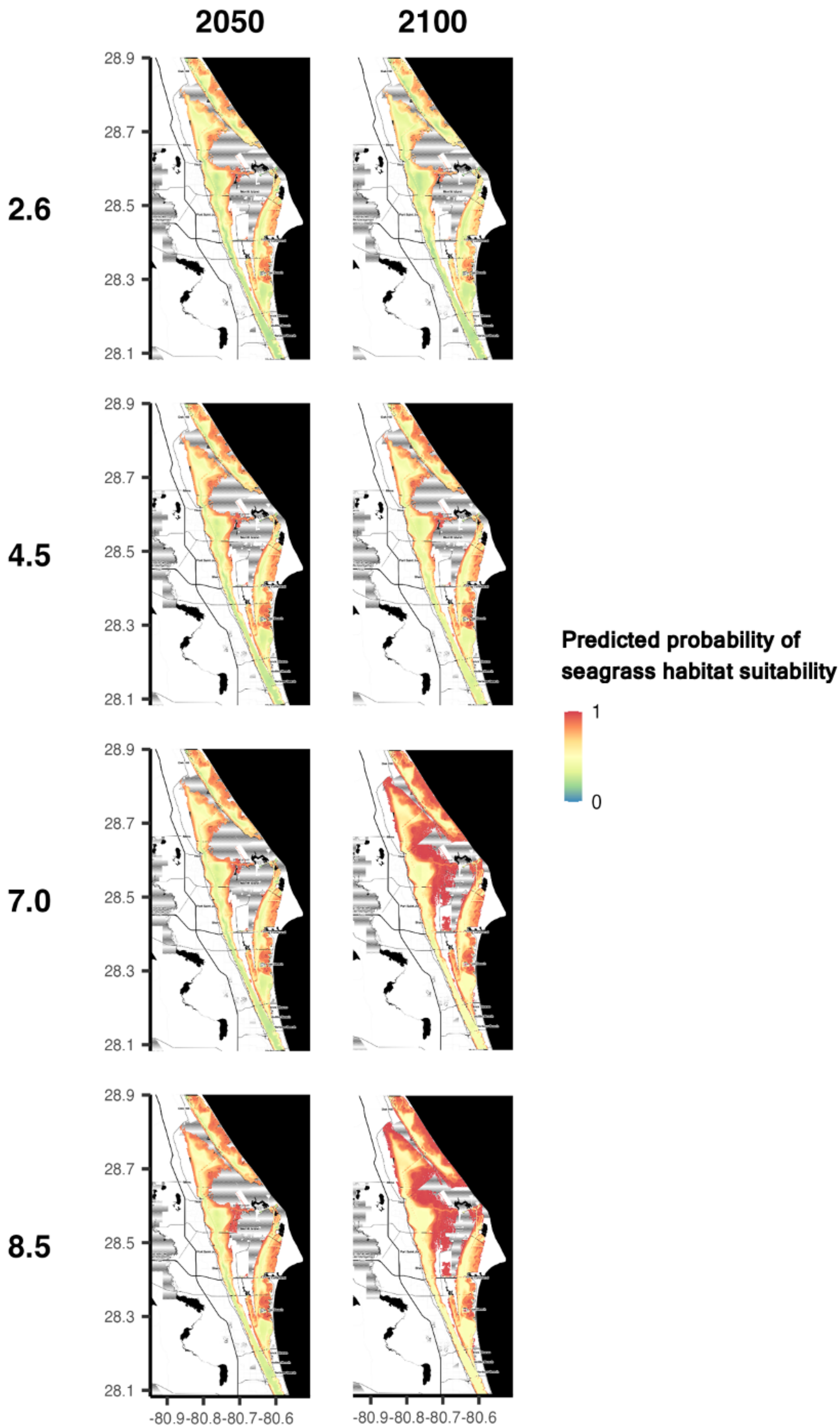

Figure 4. MaxEnt Predicted probabilities of seagrass habitat suitability in the northern Indian River Lagoon for each IPCC scenario.

These findings are corroborated by the calculations of total seagrass areas for three predicted probabilities thresholds: over 50%, over 75% and over 95% (Fig. 5). First, all scenarios have higher predicted total seagrass areas than both the present days predictions (294 km^2) and the present-days actual seagrass coverage (241 km^2). The same two groups of scenarios are confirmed by the areas' calculations for the 2100 predictions. In the case of the first group of lower emissions, there is no area of predicted suitable habitat with a probability over 0.95 for the 2.6 scenario and only 200 m^2 for the 4.5 predictions. However, the total predicted seagrass areas with a habitat suitability probability over 50% are similar in both scenarios: 307 km^2 in the 2.6 scenario and 385 km^2 in the 4.5 scenario. There is a bigger gap for the predictions with a probability over 75% as the total seagrass area in the 2.6 scenario is 73.5 km^2 against 178.8 km^2 in the 4.5 predictions. In the case of the 2050 predictions, all scenarios have a similar total seagrass area of predicted probability over 50% as it fluctuates around 400 km^2. There are more disparities for the predicted probabilities over 75% or 95% as the total seagrass areas increase as the emissions get higher. For the 2100 predictions of the group with the highest level of emissions, the areas with predicted probabilities of suitable habitat over 50% and 75% are similar, reaching respectively just above 600 km^2 and 400 km^2. This corresponds to more than a doubling of present days seagrass coverage. Total seagrass area with a predicted probability over 95% is marginally smaller in the 7.0 scenario but the difference is only 40 km^2.

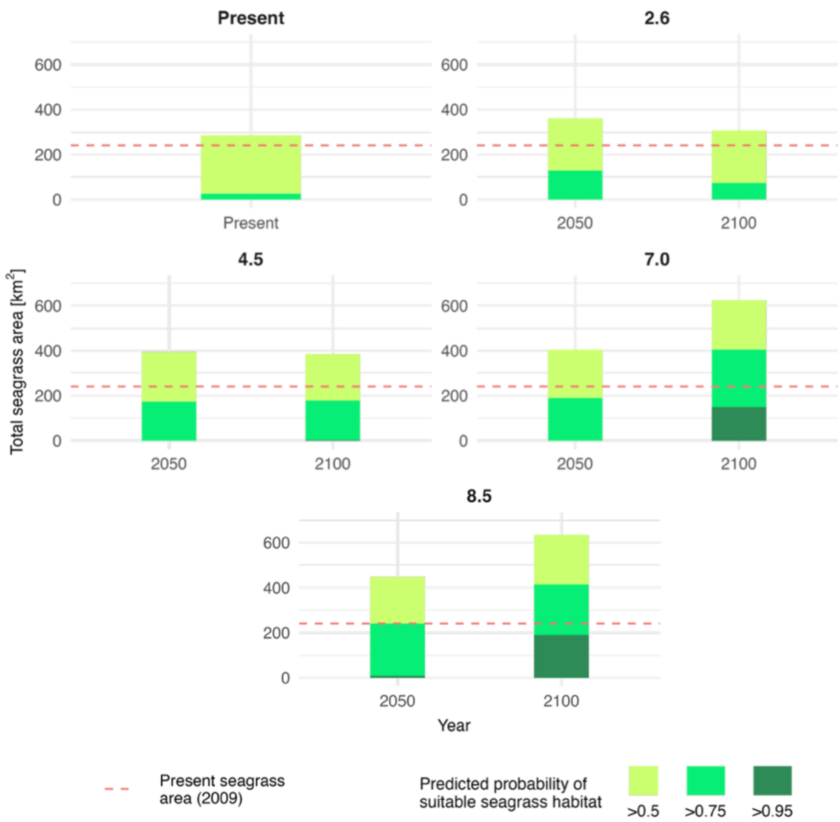

Figure 5. Total seagrass areas for three thresholds of predicted probabilities of habitat suitability (>0.5; >0.75; >0.95).

Assessment of manatees' preferred habitat

To identify manatees' preferred habitat, density plots of their distribution as a function of both depth and temperature were generated. Manatees' distribution data over the state of Florida was made of 63,655 occurrence points collected between 2003 and 2021. Manatees were mainly found in shallow waters, less than 2 meters deep (Fig. 6). The density of manatees shows a multimodal trend with peaks between 1.5 meters and 0.5 depths which suggests that their preferred depth range would be comprised between these two values. In the case of temperature, the density of manatees also shows a multimodal trend with peaks around 24°C, 25°C and 27°C (Fig. 7). The density as a function of temperature not showing any clear pattern of distribution, their preferred range of habitat was determined using the literature. As mentioned previously, manatees do not stay in waters below 20°C to prevent the risk of cold-stress death but higher temperatures have not been observed as impacting manatees' distribution. Therefore, the preferred temperature range of manatees was determined as waters above 20°C. In the case of the predicted scenarios of climate change, no areas of the northern Indian River Lagoon are predicted to have water temperatures below 20°C in the annual predictions. Thus, the sea-surface temperature was not used to predict manatees habitat as all the area was part of the manatees' preferred temperature range.

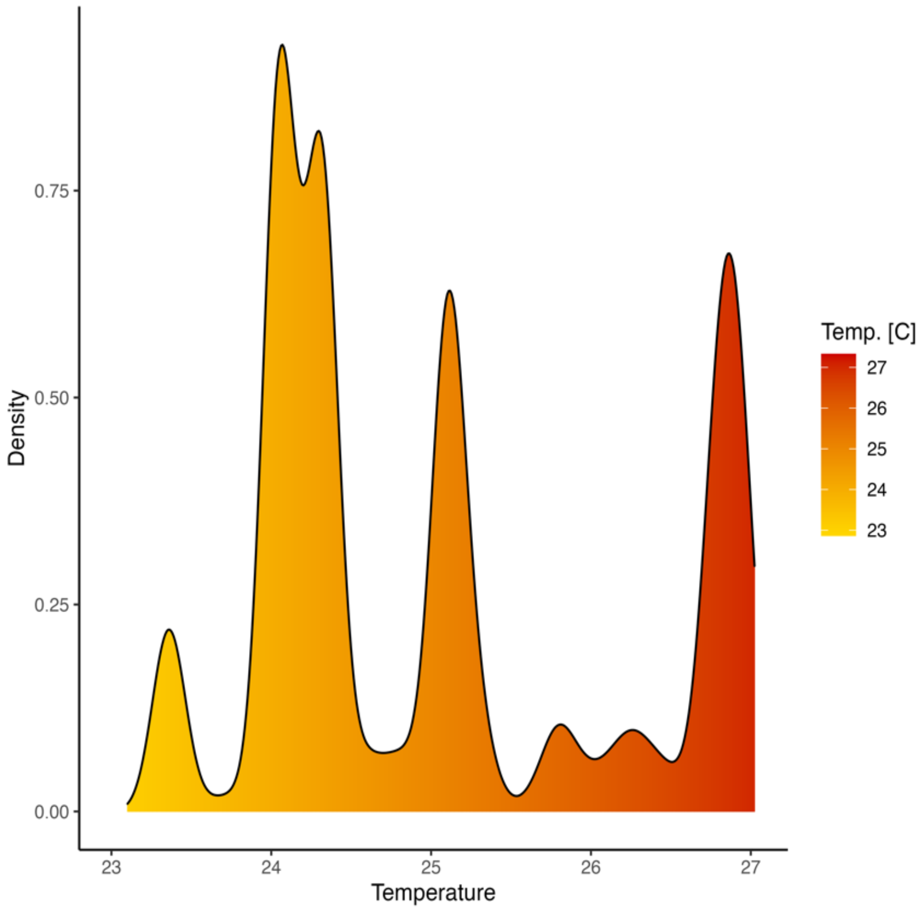

Figure 6. Manatees' density as a function of depth (in meters) in Florida Occurrence data was made of 63,655 presence records.

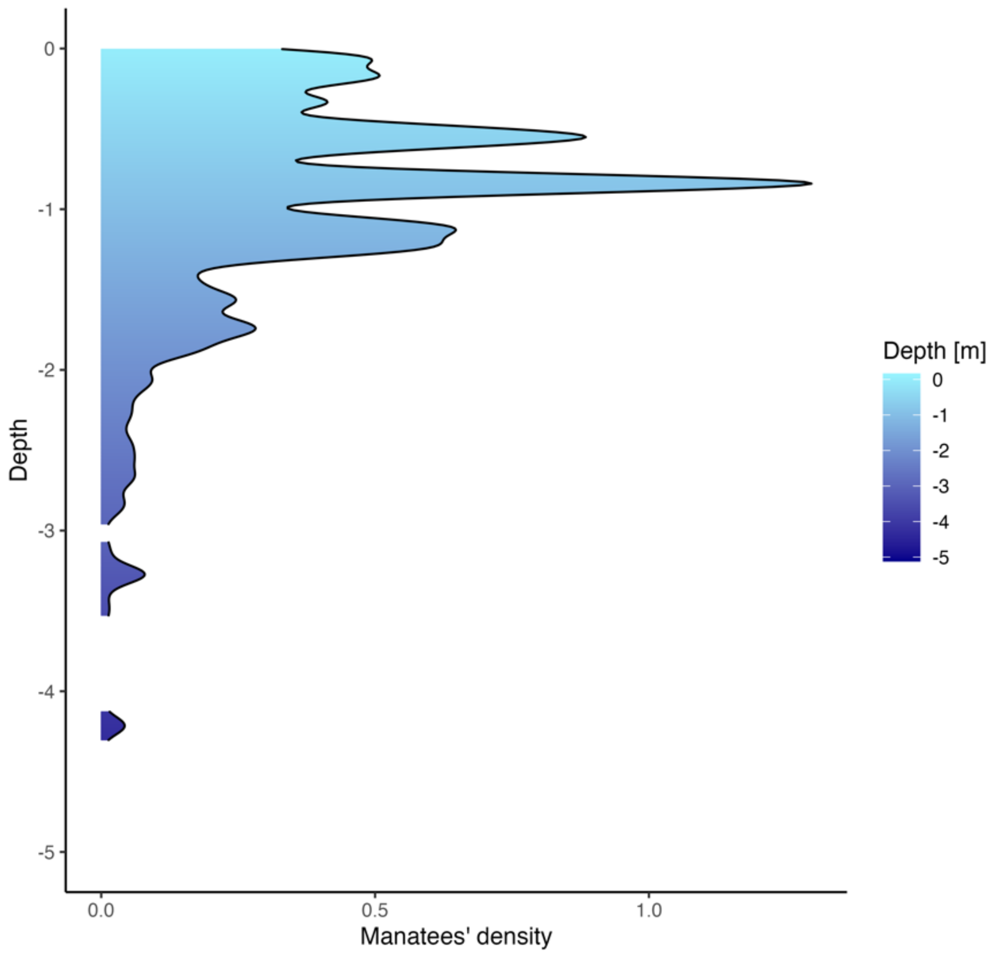

Figure 7. Manatees' density as a function of temperature (°C) in Florida. Occurrence data was made of 63,655 presence records.

Identification of seagrass areas available to manatees

Using manatees' preferred habitat, the seagrass areas that would be reachable by manatees in each scenario were identified. Current seagrass areas available to manatees are the largest in the Banana River while several seagrass areas of the Mosquito Lagoon are too shallow to be reached by manatees (Fig. 8). Almost all areas that were predicted by MaxEnt to have a probability of habitat suitability over 75% are not a part of manatees' preferred depth range.

Regarding climate change scenarios, MaxEnt predictions show that most areas with a high predicted probability of seagrass habitat suitability are located in the shallow coastal inundated areas (Fig. 9). Most areas with predicted suitability under 75% are more than 0.5 meters deep, making these areas reachable and available to foraging manatees. However, as the predicted probabilities increase, the proportion of areas less than half a meter deep increase too. In all 2050 predictions, the area of seagrass unavailable to manatees because they are too shallow remains largely unchanged. The extent of areas that are not a part of manatees' preferred habitat in the 2100 predictions increases as emissions increase. In all scenarios, the Banana River as well as the southernmost portion of the studied area have very few portions less than 0.5 meters deep and therefore unavailable to manatees. On the contrary and in accordance with areas of very high predicted probability of suitability (Fig. 1), the northernmost basin of the Indian River as well as some portions of Mosquito Lagoon are predicted to have more portions outside of the manatees' preferred feeding range, especially in the 7.0 and 8.5 scenarios. Finally, in all scenarios and decades, there is a portion of the northern Indian River Lagoon that has always less than a 50% predicted probability of habitat suitability. Being the central part of the lagoon, this area is also over 2 meters deep in all sea-level rise predictions, which gives an indication of seagrasses' depth range limits.

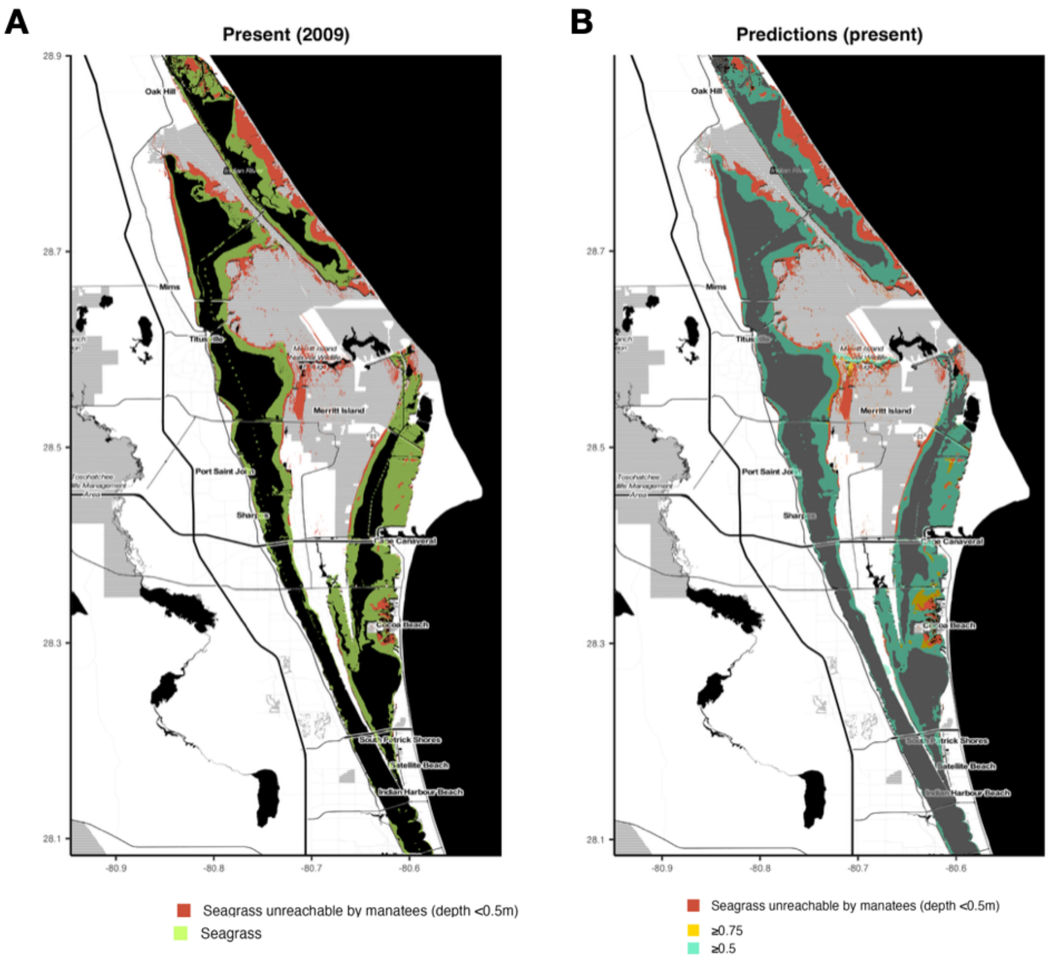

Figure 8. Seagrass reachable by manatees in the northern Indian River Lagoon in 2009 (A). Seagrass areas reachable by manatees and the associated predictive probabilities of habitat suitability for the 2008-2020 time-period (B).

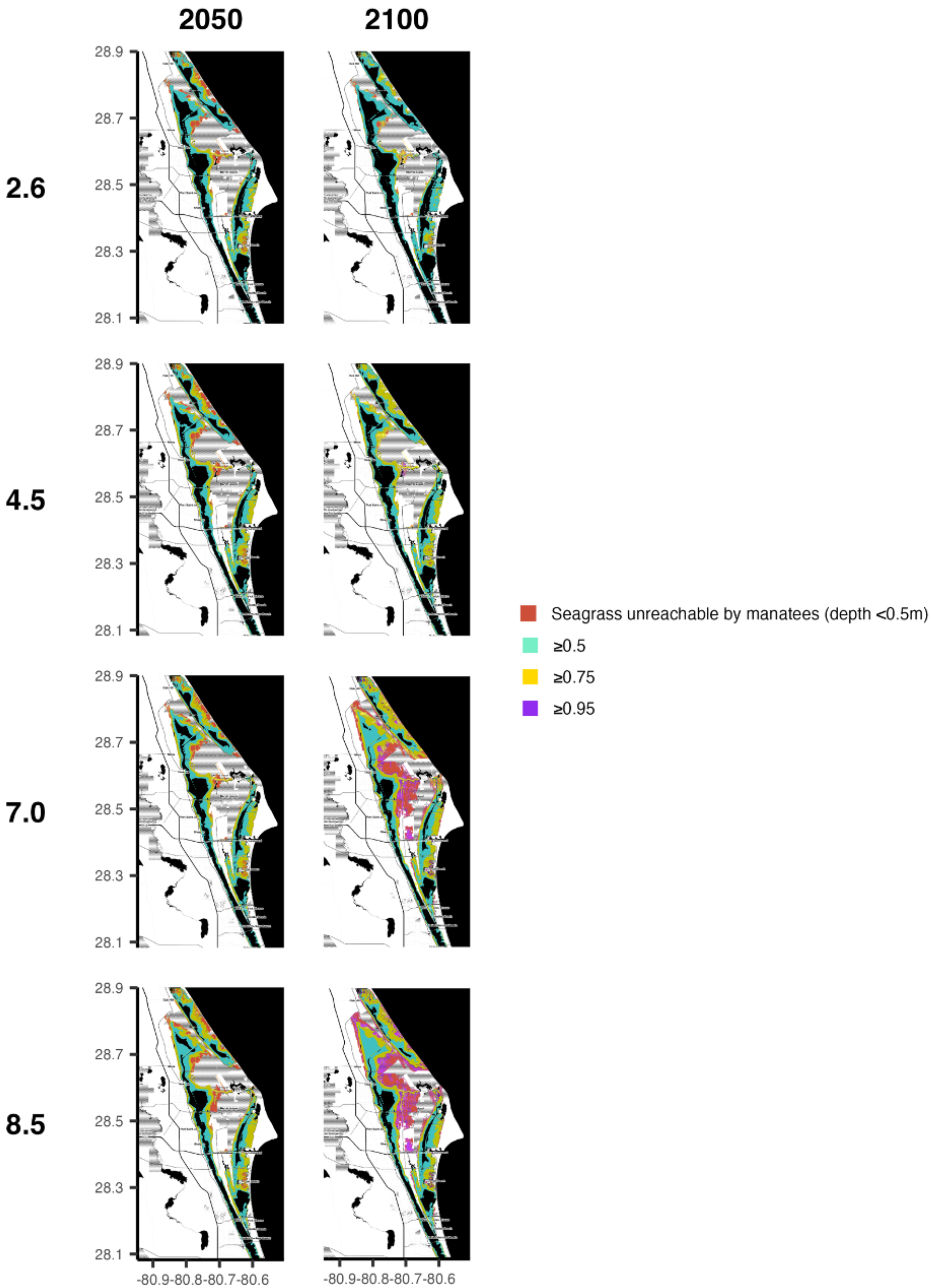

Figure 9. Seagrass areas reachable by manatees and the associated predictive probabilities of habitat suitability.

The total seagrass areas available to manatees follow the same trends as the total seagrass areas (Fig. 5) except that the areas are smaller. They are higher than current seagrass coverage (both observed and predicted) in all climate change scenarios by both 2050 and 2100. The predictions with a probability over 50% for the 2050 decade vary between 320 km^2 and 398 km^2 (Fig. 10), increasing as emissions increase. The same trend is observed for the predicted probabilities over 75% as they vary between 91 km^2 and 190 km^2. Therefore, the differences between each scenario display only slight variances for the 2050 decade. However, the differences are predicted to be higher by 2100, with the variations between the 2050 and the 2100 predictions increasing as greenhouse gas emissions rise. First, no habitat that has a predicted probability of suitability over 95% available to manatees for the 2.6 scenario and only 2.8 km^2 for the 4.5 scenario. These probabilities get higher in the 7.0 and 8.5 predictions as they reach respectively 61 km^2 and 109 km^2. The trends are similar for the seagrass areas available to manatees having a predicted probability exceeding 50 and 75% as the areas get higher as emissions increase. Finally, it should be noted that the 2.6 scenario is the only scenario in which the total seagrass area available to manatees decreases between 2050 and 2100.

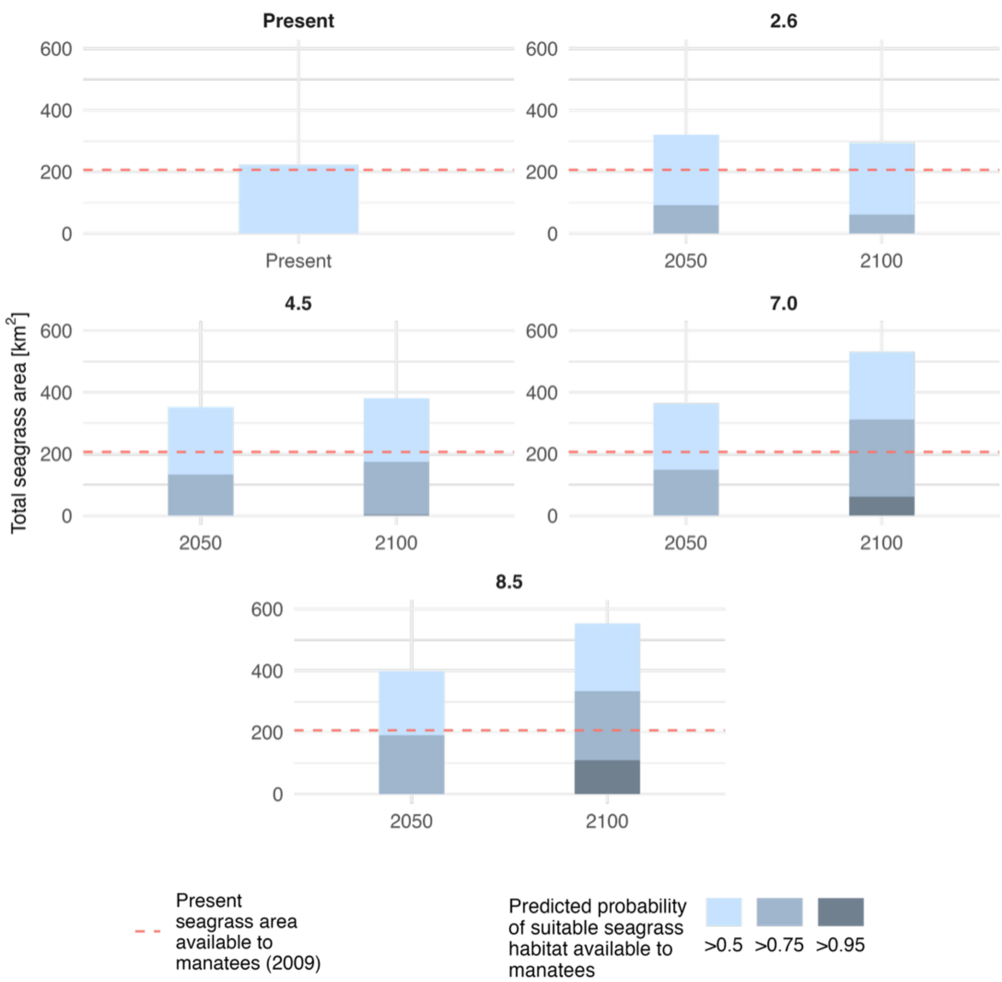

Figure 10. Total seagrass areas available to manatees in the northern Indian River Lagoon for three predictive probabilities thresholds.

DISCUSSION

This study showed that seagrass abundance in the northern Indian River Lagoon will be positively correlated to carbon emissions for future climate change scenarios. In cases of carbon emissions mitigation, seagrass coverage is likely going to be smaller than in cases of increased emissions. Seagrass areas will also be more likely and more expanded in the shallow northern parts of the study area, where the flooding range is higher than in the southern areas that are more urbanized. However, as manatees are large marine mammals, the shallower seagrass (less than 0.5 meters deep) is not a part of their preferred habitat, which reduces the amount of seagrass available to forage.

In 2017, the U.S. Fish and Wildlife Service downlisted the status of the West Indian manatee under the Endangered Species Act (ESA) from endangered to threatened which led to a reduction of legal protections. Since then, local organizations and governments campaign for a return to the endangered status, claiming that the manatee population declined dramatically since the downlisting. The study of the upcoming challenges that the species will have to face because of climate change and the intensification of anthropogenic activities help gain a better understanding of the upcoming threats or changes in their habitats.

Seagrass abundance increases as temperature increases but the depth range of habitat with high predicted suitability is always less than 2 meters deep and, in most cases, less than 1.5 meters deep. This depth range corresponds to the depth limits of the most common seagrass species in the northern Indian River Lagoon: *Halodule wrightii*, *Syringodium filiforme*, and *Ruppia maritima*. These three species have been found to be most abundant at low and mid-depth, usually between 0.2 and 2 meters (Dawes et al., 1995; Provancha & Scheidt, 1999). This explains why the areas of the lagoon with the highest predicted probability of habitat suitability are also the shallowest ones, located mainly in Mosquito Lagoon and the northern Indian River.

Seagrass abundance as a function of depth is also impacted by the effects of the coastal squeeze. This is especially the case in the Banana River. Indeed, current seagrass coverage shows that the Banana River is one of the areas with the largest extent of seagrass in the northern Indian River Lagoon. However, in the climate change predictions of seagrass habitat suitability, the Banana River is the waterway with the smallest spatial extent of high probability areas. This shift between present days and 2050 or 2100 can be explained by the impacts of the coastal squeeze that is causing a decrease of seagrass abundance. The east bank of the Banana River is mostly urbanized with the city of Cap Canaveral while the NASA Kennedy Space Center is located on Merritt Island, on the west bank of the Banana River. Land-cover of surrounding land is important since the potential for coastal squeeze has been found to be higher near urbanized areas and low-lying land because coastal armoring structures are built to prevent water to flood the developed land (Borchert et al., 2018). This phenomenon was accounted for when predicting the impacts of sea-level rise using SLAMM as developed areas were marked as “developed dry land” and could not be flooded in the predictions. As sea-level is predicted to rise, Banana River is going to get deeper because of the coastal squeeze. This area was already one of the deepest of the lagoon as there are only a few areas less than 0.5 meters deep that could not be reached by manatees. Seagrass growing mainly in shallow areas to get a sufficient amount of light, their range and abundance will be impacted by these changes in bathymetry. The area is not predicted to have high seagrass suitability because the depth of many areas will get closer or beyond the maximum depth limit of the seagrass species of the lagoon. This shows that if coastal armoring structures are built to protect the urbanized areas around the Banana River, they would prevent landward migration of seagrass and cause a contraction of seagrass coverage and abundance in the waterway.

In the case of temperature variability, several episodes of heat waves have shown that increased temperatures were leading to increased seagrass abundance (Rice et al., 1983). However, the maximum water temperature reached during these events was 30°C while the maximum temperature predicted for the worst-case climate change scenario is over 32°C. Previous seagrass die-offs have been linked to heat waves in other parts of the world (Strydom et al., 2020; Garrabou et al., 2022). In the case of the Indian River Lagoon, several studies have identified the upper thermal limit of the most abundant seagrass species of the lagoon to be comprised between 30°C to 35°C depending on the species (Marbá et al., 2022). However, the optimal range of these species has been determined as going from 22°C to 26/27°C (Mazzotti et al., 2007). A study predicting seagrass density in the same IPCC scenario in St Joseph Bay, in the Gulf of Mexico, showed that high temperatures in the highest emissions scenarios would lead to slight decreases in seagrass abundance (Lebrasse et al., 2022). However, this eco-region being very different from Indian River Lagoon, its findings are not necessarily generalizable. Thus, the response of these seagrass species to high temperatures in the highest emissions scenarios is not well assessed and should be further investigated.

Most of the seagrass habitat suitability variability inter-scenarios is visible in the 2100 predictions but not that much in the 2050 predictions. This is mainly because there is very little variability in the changes in sea-level rise and temperatures between scenarios for the 2050 predictions. Sea-level is predicted to rise by 0.28 meters for the 2.6 scenario and by 0.32 meters for the 8.5 scenario. Similarly, in the case of temperature predictions, they only change by 0.28°C between the lowest and highest emissions scenarios. Therefore, the changes are not strong enough to lead to high differences in habitat suitability. However, as these predicted changes intensify between the 2050 decade and the 2100 decade, variations between scenarios become more pronounced.

The quantification of seagrass habitat suitability in each scenario shows that about 2/9 of the total present studied area displays a predicted probability of suitability over 50% for the 2 lowest emissions scenarios while the area for the two highest emission scenarios is just under 1/3 of the total present area. However, as sea-level rises and leads to the flooding of the shallow areas, the total area studied expands which leads to a reduced proportion of seagrass habitat suitability compared to the total water area in each scenario. The 7.0 and 8.5 2100 predictions are also the only predictions in which some areas are characterized by a predicted probability of habitat suitability over 95%. Areas having predicted probabilities over 95% are labelled as having a very high probability of having suitable habitats (Hastings, Cummins & Holloway, 2020; Beca-Carretero et al., 2020). Several studies that retrospectively tested the validity of the MaxEnt model on marine species showed that areas with very high probabilities of habitat suitability were later on characterized by a high density of the species (Smith, Kelly & Renner, 2021; Anderson et al., 2016). Therefore, it can be predicted that it is likely that the areas with over 95% predicted probability of habitat suitability will be characterized by high seagrass density if the climate trajectory was to follow these scenarios. That means that if the 7.0 or 8.5 emission levels were attained by 2100, there could be a minimum total seagrass area of 150 km^2 for the 7.0 trajectory and just below 200 km^2 for the 8.5 scenario. Similarly, in all climate change scenarios, the predicted seagrass area is higher than both the present days seagrass coverage and the predicted areas for the 2008-2020 time-period. This suggests that seagrass coverage will slowly increase in all future emissions scenarios, but the magnitude of the increase will depend on the actual climate change trajectory.

However, the values of seagrass areas do not represent the total seagrass areas that are a part of manatees' preferred habitat. The study of manatees' preferred habitat in terms of temperatures and depth informs their feeding range. Indeed, it was found that manatees' density was higher at temperatures over 20°C and that their density did not seem to be impacted by high temperatures. Their lower thermal range is based on manatees' low metabolic rates which makes them at risk of dying of cold-stress in waters below 20°C (Blair Irvine, 1983; Deutsch et al., 2003; Shane, 1984). There has been no assessment of manatees' upper thermal limit. Indeed, heatwave events have reduced the habitats range of manatees and dugongs, another Sirenian species, but do not seem to have caused direct mass mortality (Edwards, 2013; Marsh et al., 2022). Thus, despite the impacts of higher temperatures on their habitats, manatees may not be faced with a reduction of their range because of higher sea-surface temperatures.

Nevertheless, manatees' preferred habitat and especially their preferred feeding range are determined by depth. We found that manatees' density was the highest at depths comprised between -1.5 and -0.5 meters. These findings are congruent with the literature as studies indicated that manatees are characterized by shoal aversion (Hartman, 1979). It has also been found that feeding usually occurs at places less than 1.6 meters deep and in relatively shallow waters that are over 0.4 meters deep (Lefebvre et al., 1999; Marsh et al., 2011). This preferred feeding range can be correlated to manatees' dietary habits as they prefer to feed on submerged aquatic vegetation rather than emergent (Reich & Worthy, 2006). Thus, the preferred habitat chosen to identify the seagrass areas available to manatees is corroborated by the literature.

As all seagrass suitable habitats that will be less than 0.5 meters deep will be outside of manatees' preferred feeding range, the total areas of seagrass available to them is less than the general total seagrass area. Especially, the newly flooded areas of the 7.0 and 8.5 2100 predictions will not be a part of that range. Therefore, only half of the total area of suitable habitat with a predicted probability over 95% will be reachable by foraging manatees. However, all climate change predictions display an increase in total seagrass areas compared to present days coverage.

The locations of extended areas with high predicted habitat suitability might inform the future distribution of manatees in the northern Indian River Lagoon. Manatees have been described as opportunistic feeders that tend to aggregate in places where seagrass has the highest spatial cover and where there are the least human disturbances (Berger, 2007; Deutsch, 2003; Ledder, 1986; Mignucci-Giannoni & Beck; 2006). As the areas with the highest predicted habitat suitability in each scenario are Mosquito Lagoon and the northernmost basin of the Indian River, we hypothesize that these areas may be the ones with the highest manatees density in the upcoming years. These estimations are corroborated by the actual distribution of manatees in the study area as the population of manatees in Banana River and the southern portion of the study area has dramatically decreased over the last 7 years (Scheidt, 2021). Therefore, this distributional shift of manatees might intensify in the upcoming decades under the impacts of climate change with areas of high manatees density in the same areas that have a high predicted probability of seagrass habitat suitability.

Although the increased seagrass meadows available to manatees in the highest emissions scenarios might seem like a positive finding for the protection of the species, it should be nuanced by the potential climate-induced changes in manatees' biology and distribution. Indeed, manatees consume about 8% of their body weight in aquatic plants per day, which means that they consume between 9 and 80 kgs of seagrass per day (Best, 1981; Bengston, 1983; O'Shea & Reep, 1990). When feeding in the Indian River Lagoon, manatees disturb up to 40% of the seagrass beds and remove between 80% and 95% of the short shoot biomass and 50 to 67% of the rhizome and root biomass of seagrass (Lefebvre et al., 1999). In consequence, seagrass abundance quickly decreases when there is a high density of manatees in the area which is what is anticipated for the upcoming decades depending on the climate change trajectory. Thus, the high predicted probabilities of seagrass habitat suitability do not mean that it will be sufficient to feed the increased population of manatees in the northern Indian River Lagoon. Similarly, increases in sea-surface temperature might reduce the amount of time spent in winter sites and lead to increased use of summer sites and migration routes such as the northern Indian River Lagoon (Aven, 2016). Longer residence times in the northern Indian River Lagoon combined with an increased manatees density would highly impact seagrass abundance. Therefore, findings of high abundance in the highest emissions scenarios should be balanced.

Similarly, other external factors linked to increased temperatures and sea-level rise could impact seagrass abundance, especially in the 7.0 and 8.5 scenarios. Indeed, the northern Indian River Lagoon has had several phytoplankton blooms since 2011, caused partly by nutrient run-offs. These algae blooms caused the loss of about 58% of seagrass cover in the Indian River Lagoon between 2011 and 2019 (Morris et al., 2022). Forming mats at the surface of the water, very little light can penetrate leading to the death of seagrasses (Orth et al., 2006). These harmful algae blooms (HAB) are more frequent during the summer months or during El Niño periods when the high temperatures are combined with low precipitations (Phlips et al., 2020; Phlips et al., 2021). As climate change leads to increased temperatures and longer events of droughts, HAB might become more frequent and intense, leading to extensive loss of seagrass beds (Wells et al., 2015). Declines in seagrass coverage lead to high manatees mortality events because they tend to stay close to the area because of high-site fidelity (Littles et al., 2019; Preen & Marsh, 1995). Thus, high predicted probabilities of seagrass suitable habitat should be approached with a nuanced perspective as uncertainties linked to climate change could alter seagrass abundance.

Hence, more research is needed to further the findings of this study. Using other environmental variables that would be impacted by climate change such as salinity would be helpful to develop more accurate predictions of manatees' seagrass habitat. A mapping effort of the dikes and seawalls of the northern Indian River Lagoon could improve the understanding of the effects of the coastal squeeze that was only accounted for using urbanized areas boundaries.

More specialized studies could also reinforce the seagrass abundance predictions. Indeed, the same methodology could be applied to each seagrass species found in the northern Indian River Lagoon to reveal potential changes at the species level. These results could then be combined with manatees' dietary preferences to evaluate the potential changes in manatees' diet. Similarly, separate predictions could be made for the summer season and for the winter season. Seagrass abundance has been shown to be highest during the warm season (Dawes et al., 1995). The St Johns River Water Management District has monitored seagrass abundance along 74 transects throughout the Indian River Lagoon for both the warm season and the cold season since 1994. Using a presence-absence model such as a Generalized Additive Model (GAM) or a Generalized Linear Model (GLM), predictions of seagrass habitat suitability could be done for both seasons in each scenario. Such predictions would improve the understanding of potential variability in manatees' habitats.

Finally, to estimate future changes in manatees' population, it would be needed to assess the carrying capacity of the northern Indian River Lagoon. The carrying capacity is a useful metric to understand what is the maximum number of individuals that an ecosystem can sustain. Due to their high consumption of seagrasses, evaluating the carrying capacity of the area in each scenario would put in perspective the results and help gain more clarity as to the future of manatees' population and feeding situation in the northern Indian River Lagoon.

CONCLUSIONS AND PERSPECTIVES

This work aimed to provide an intermediate-scale framework that could be used to improve the understanding of the impact of climate change on the manatees' seagrass habitat. As anticipated, predictions of seagrass habitat suitability suggest a shift in seagrass' range, migrating towards the flooded areas, as well as increased seagrass abundance under the effects of high sea-surface temperatures. Therefore, manatees' seagrass habitat is predicted to improve with increased emissions in this study, but these results should be put in perspective with the intensification of extreme climate events that could lead to altered and highly variable seagrass abundance.

These findings should be used to guide conservation actions, especially the restoration of seagrass meadows in the northern Indian River Lagoon. The transplantation effort should focus on areas that are predicted to have long-term seagrass habitat suitability to ensure that the transplanted meadows sustain and survive for a longer time-period. Similarly, the transition from hardened shorelines to alternative resources such as living shorelines would reduce the impact of the coastal squeeze and increase the seagrass areas available. Regarding manatees, their habitat will be highly modified by the impacts of climate change as higher emissions will be associated with higher seagrass areas. The threats that they will face will highly depend on the upcoming climate change trajectory and actions of preservation should be prepared to adapt to all possibilities. As ecosystems undergo changes in their physical and biological environment, further studies predicting the potential impacts of intensified anthropogenic activities on species are needed to better inform conservation practices and enable adapted measures to preserve and protect biodiversity.

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