Modeling and Mapping

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ABSTRACT

We conducted this study to assess the influence of changes in freshwater inflow on the distribution and relative abundance of estuarine species in Rookery Bay, Florida. Originally, freshwater entered the bay via sheet-flow. In the 1960s, the creation of a canal system, which funnels water through a weir situated on Henderson Creek, altered inflows. To assess the effect of these changes, we initiated monitoring in Rookery Bay and Fakahatchee Bay. The latter estuary served as a control, because it still has natural sheet-flow.

Bottom types and bathymetry in Rookery Bay were mapped using side-scan and QTC View sonar systems. Bottom types were verified via analyses of bottom-grab and core samples. Salinity, temperature, and dissolved oxygen data collected seasonally in the two estuaries were interpolated to map water-column habitats.

When this study was initiated, no long-term fisheries-independent monitoring (FIM) had been conducted in Rookery Bay. Consequently, we analyzed FIM data collected in Charlotte Harbor to determine habitat affinities for 22 life stages of 11 species of fish and macroinvertebrates. Suitability functions were derived by fitting splines to catch rates (CPUEs) across environmental gradients and by calculating mean CPUEs within bottom-type categories. Abundance indices transferred from Charlotte Harbor were applied to Rookery Bay habitat layers so that we could conduct raster-based habitat suitability modeling (HSM) for a dry season (spring) and a wet season (summer) in Rookery Bay with differing freshwater inflows. Predicted HSM maps depict suitability zones (low to optimum) across the estuary. The models were validated by calculating mean observed CPUEs (from monthly trawl sampling) within the predicted zones. Increasing mean observed CPUEs across the zones indicated that the models adequately predicted the spatial distributions of the species' life stages.

KEY WORDS: Fish habitat, GIS modeling, mapping, Rookery Bay

Modela y Traza la Relaciona de los Cambios an la Afluencia de Agua Dulce a Distribuciones de Especias en Rookery Bay, Florida

La Oportunidad del habitat que Modela y Traza la Relaciona de los Cambios En la Afluencia de Agua Dulce A Distribuciones de Especias en Rookery Bay, Florida. Realizamos este estudio para valorar la influencia de cambios en la afluencia de agua dulce en distribuciones y abundancia relativa de especias estuarinas en la Bahía de Rookery, Florida. Originalmente, agua dulce entró la bahía vía el sheet-flow. En la década de los 60, la creación de un sistema de canales, que encauza riega por un vertedero situado en Henderson Creek, y altero afluencias. Para valorar el impacto de estos cambios, nosotros iniciamos un muestreo en Rookery y Fakahatchee Bay, Florida. Fakahatchee Bay sirvió como un control, porque todavía tiene el sheet-flow natural.

Tipos de fondo y bathymetry en Rookery Bay fueron trazado utilizando side-scan y QTC View sistemas de sonar. Tipos de fondo fueron verificados por análisis de muestras inferioras de agarro y centro. Datos de salinidad, temperatura, y niveles disueltos de oxígeno se collecionaron durante differentes temporadas en los dos esteros y fueron interpolados para trazar los habitates de las columnas de agua.

Porque no hay muestro consistente de pescados en Rookery Bay a largo plazo, nosotros analizamos los datos de pescados colleccionados en Charlotte Harbor para determinar las afinidades del habitat para 22 etapas de vida de 11 especies de pescado y macro-invertibrados. Las funciones de la oportunidad fueron derivadas por tiras para agarrar los datos de la tasa (CPUE) a través de declives ambientales, y calculando las unidades de procesamiento centrales malas dentro de categorías de tipo fondo. Los índices de la abundancia transferidos de Charlotte Harbor fueron aplicados a capas de habitat de Rookery Bay para realizar la oportunidad trama-basado del habitat modelando (HSM) durante una temporada (primavera) seca y una temporada (verano) mojada en Rookery Bay. Los mapas predichos de HSM representan la oportunidad las zonas (bajo a óptimo) a través del estero. Los modelos fueron verificados calculando medio las unidades de procesamiento centrales observadas (de rastreo mensual que prueba) dentro de las zonas predichas. Creciente significa observó que las unidades de procesamiento centrales a través de las zonas indicaron los modelos predijeron correctamente las distribuciones espaciales de la especie' las etapas de la vida.

PALABRAS CLAVES: Habitat modelando, distribuciones espaciales, mapas predichos Rookery Bay

INTRODUCTION

Watersheds in South Florida have been extensively altered by the canalization of streams and by water diversions through canals. The effects of these changes on aquatic communities are not well understood (Sklar and Browder 1998). A number of studies in Florida clearly demonstrate the need to manage freshwater inflow into estuaries in order to protect marine resources (Browder and Moore 1981, Browder 1985 1991, Livingston et al. 1997 2000, Browder et al. 2002).

Starting in the 1920s, the Big Cypress Swamp near Naples was altered with the creation of U.S. Highway 41 (Gardner 1988). The creation of the Southern Golden Gate Estates Canal system and the Faka Union-Remuda Ranch Canal system, to drain agricultural and residential areas during the 1960s, and the construction of major highways have altered the quantity, quality, and timing of freshwater entering the Rookery Bay system and other estuaries in the Ten Thousand Islands region. The canal systems, combined with deforestation and increasing urbanization, have reduced the amount of upland swamps, lowered the water table, and reduced regional rainfall, which in turn affected freshwater inflows to the estuaries (Carter et al. 1973, Browder and Moore 1981, Colby et al. 1985). Consequently, the Big Cypress Basin Board of the South Florida Water Management District (SFWMD) funded the present study to provide information to help manage freshwater inflows into Rookery Bay in order to protect the integrity of estuarine habitats and to conserve estuarine fish and macro-invertebrate species present in the estuary.

The Florida Fish and Wildlife Conservation Commission's (FWC) Fish and Wildlife Research Institute (FWRI) has developed habitat suitability models (HSM) using geographic information systems (GIS) to predict spatial distributions and relative abundance of estuarine species (Rubec et al. 1998, 1999, 2001, 2003a,b). One of the main strengths of using GIS is its ability to integrate data from a wide variety of sources. By transferring abundance relationships from estuaries with fisheries-independent monitoring (FIM) programs, the HSM can allow the prediction of species distributions in estuaries that lack long-term FIM programs.

The FWRI, Florida Department of Environmental Protection (FDEP) and the University of South Florida (USF) College of Marine Science collaborated to map habitats and model species distributions in relation to changes in environmental conditions in the Rookery Bay system. Data were collected across Rookery Bay and Fakahatchee Bay (control estuary). The environmental data points were interpolated to create habitat layers for use with the HSM model. Habitat affinities for key species were derived from FIM data previously gathered by FWRI in Charlotte Harbor. The predicted HSM maps determined changes in habitat suitability associated with salinity patterns related to different freshwater inflows. The study was conducted to provide water managers with information to help manage water flow through the weir situated at the head of Henderson Creek, which regulates inflow from the Henderson Creek canal to the Rookery Bay system. It demonstrates the use of HSM to assess the effects of changes in freshwater inflow on estuarine species.

METHODS

Study Area

The Rookery Bay National Estuarine Research Reserve (RBNERR), situated south of Naples, encompasses an area of 445 km^2. It includes the Rookery Bay system (424.4 hectares) and estuaries in the Ten Thousand Islands. Rookery Bay is surrounded by mangroves and has islands with bird rookeries, sand and mud substrates, oyster beds, and some areas with submerged aquatic vegetation (SAV). Most of Rookery Bay is quite shallow (< 2 m). The bay's high turbidity prevented us from using aerial photography to map SAV distributions in Rookery Bay.

Gear Standardization

One of the main goals of the present study was to map geographic distributions of marine fish and macro-invertebrate species by young-of-year (YOY), juvenile (Juv), and adult life stages during spring and summer seasons in Rookery Bay. The HSM requires as input indices of relative abundance across environmental gradients for each species' life stage. Ideally, these indices would be obtained from FIM in Rookery Bay. Although trawl sampling (4 - 5 samples per month) has been conducted since 2000, there was insufficient long-term FIM sampling in the bay. Consequently, we used the larger FIM datasets (600 to 1500 samples per season) obtained in Charlotte Harbor from 1989 to 1997 to create suitability functions (Rubec et al. 2003b).

To use all survey data in a comprehensive analysis, sample CPUEs were standardized across gear types to create gear-correction factors by species' life stages by using a modification of Robson's (1966) "fishing power" estimation method (Ault and Smith 2000). Gear-corrected CPUE data sets for Charlotte Harbor were created for the following species life stages: YOY (10 - 119 mm standard length-SL), Juv (120 - 199 mm SL), and adult (³ 200 mm SL) spotted seatrout (*Cynoscion nebulosus*); Juv (10 - 99 mm SL) and adult (³ 100 mm SL) pinfish (*Lagodon rhomboides*); Juv (15 - 29 mm SL) and adult (³ 30 mm SL) bay anchovy (*Anchoa mitchilli*); YOY (10 - 139 mm SL) Juv (140-239 mm SL) and adult (³ 240 mm SL) sheepshead (*Archosargus probatocephalus*); *duorarum*); and Juv (10 - 299 mm SL) red drum (*Sciaenops ocellatus*).adult (³ 110 mm SL) hardhead catfish (*Arius felis*); Juv (150 - 279 mm SL) and adult (³ 280 mm SL) common snook (*Centropomis undecimalis*); Juv (10-149 mm SL) and adult (³ 150 mm SL) sand seatrout (*Cynoscion arenarius*); YOY (10 - 149 mm SL) and Juv (150 - 199 mm SL) spot (*Leiostomus xanthurus*);
YOY (10 - 119 mm SL) and adult (³ 180 mm SL) southern kingfish (*Menticirrhus americanus*); Juv (5 - 17 mm carapace length-CL) and adult (³18 mm CL) pink shrimp (*Farfantepenaeus*

Suitability Functions

Habitat affinities for 11 species of fish and macroinvertebrates were determined from 8.5 years of FIM data gathered in Charlotte Harbor from 1989 to mid-1997. The analyses involved development of suitability functions by fitting splines across environmental gradients to mean gear-corrected catch rates (CPUEs) for each species' life stage (Rubec et al. 2003b). First, mean CPUEs were computed within each season for each environmental variable. Then, splines (variable lambda) were fitted to mean CPUEs across gradients of salinity, temperature, dissolved oxygen, and depth using JMP software (SAS 2002). Mean CPUEs were computed by 1 g/L (‰) salinity, 1°C temperature, 1-mg/L dissolved oxygen (DO), and 1 meter depth intervals. Seasonal-mean CPUEs were also computed by Sand, Mud, and SAV bottom-type classes. The mean CPUE values across each gradient were placed in look-up tables within a GIS to facilitate HSM analyses. We then transferred the suitability functions derived from Charlotte Harbor monitoring to Rookery Bay.

Habitat Mapping

The mapping of water-column and benthic habitats in Rookery Bay, required data collection, data integration, and the use of GIS-based software to interpolate raw data points. Bottom type and bathymetry were determined from data gathered by USF using sidescan and Quester Tangent QTC View sonar systems (Locker and Wright 2003). Salinity, temperature, and dissolved oxygen data were gathered seasonally in the two estuaries using a Hydrolab MiniSonde Model 4a data logger.

A skiff with the data logger mounted to the boat's gunnel, a differential global positioning system (DGPS), and a Furuno LS-6000 depth sounder linked to a Furuno 520ST–PWD transducer were wired to a rugged Argonaut laptop computer to gather environmental data. The data were merged on the computer using software developed for the project (Rubec et al. 2003b).

The boat cris-crossed Rookery and Fakahatchee bays during separate days to gather data believed to be representative of five seasonal time periods (June to August 2002, September to November 2002, December 2002 to February 2003, March to May 2003, and June to August 2003). The data logger was used to collect salinity, temperature, and dissolved oxygen data in Rookery Bay on August 22, 2002; October 30, 2002; February 20, 2003; May 2, 2003; and July 10, 2003. Data were collected in Fakahatchee Bay on August 23, 2003; October 31, 2003; February 21, 2003; May 1, 2003; and July 11, 2003.

The GeoStatistical Analyst module associated with ArcGIS 8.3 was used to interpolate the environmental data points in an iterative manner using simple punctual kriging (Johnston et al. 2001). Semivariograms were used to choose the most optimal interpolation for each environmental variable. Raster-based grids were created representing seasonal habitat layers for salinity, temperature, and dissolved oxygen in the two estuaries, as well as grids for bathymetry (depth) and bottom type in Rookery Bay derived from data gathered by USF.

Habitat Suitability Modeling

We used the Spatial Analyst extension in ArcMap associated with ArcGIS 8.3 to relate abundance indices from Charlotte Harbor, for the spring (March-May) and summer (June - August) seasons, with the habitat layers in Rookery Bay to conduct HSM analyses for Rookery Bay. The HSM analyses were conducted to spatially compare the effects of several inflow conditions on species' life stages at two time periods during the summer and at one period during the spring.

The geometric mean algorithm was used to compute composite suitability values in order to create predicted seasonal HSM maps for Rookery Bay. Composite HSM values within each 18.5 m^2 cell were computed as the geometric mean of the suitability values associated with the habitat layers for *n* environmental factors. Predicted HSM values were derived from abundance indices associated with five habitat layers, as follows:

$$HSM= (\Pi\ CPUE_i)^{1/n}$$

Separate HSM analyses were conducted for each time period to model species distributions by each species' life stage in Rookery Bay. The CPUEs in predicted HSM grids were scaled from 0 to 10. The predicted HSM grids were classified into equal CPUE ranges to create four suitability zones (Low, Moderate, High, and Optimum). This allowed us to compare the effects of changes in freshwater inflow into Rookery Bay. Percent changes in total area of Rookery Bay for the four HSM zones were used to determine whether the changes in salinity were beneficial or not for various estuarine species' life stages.

Three tables were associated with each HSM map depicted on the CD-ROM (Rubec et al. 2003b). The first table presented the observed densities (no./m^2) within predicted HSM zones and minimum and maximum CPUEs and the standard deviation for each zone. Provided there were observed data in the first table, a histogram was created as part of the validation analysis. The second table presented predicted densities (no./m^2) for the four HSM zones. The third table presented the areas, expressed in hectares, for each of the predicted HSM zones and percentages of the total area for each of the suitability zones in the estuary. Hence, the predicted suitability zones were summarized both in terms of their area and by the proportion of the total area each zone occupied in the Rookery Bay system.

The HSM analyses were conducted for two time periods with different inflow conditions (August 2002, July 2003) during the summer season. Changes in percentages of the total area with High plus Optimal suitability in the estuary were computed to determine whether changes in salinity distributions, associated with changes in freshwater inflow, were "suitable" for various life stages of estuarine species.

Model Validation

The models presented are heuristic and qualitative in nature, thereby precluding any formal statistical testing of model efficacy (Rubec et al. 2001). A simple test was developed to assess the adequacy of the HSM analyses (Rubec et al. 2001, 2003a,b). If histograms of mean CPUE values that fall within the predicted zones increased from "Low" to "Optimum", then model performance was judged to be adequate.

CPUE data obtained by RBNERR staff from trawling on a monthly basis in Rookery Bay (from 2000 to 2003) were used to validate the predicted HSM maps (Rubec et al 2003b). The observed CPUE data (74 samples for spring and 65 samples for summer) were overlaid onto the predicted seasonal HSM maps. Then, mean CPUEs were calculated within the low to optimum suitability zones. Increasing mean observed CPUEs across the HSM zones indicate whether the models adequately predicted habitat suitability for each species' life stage.

RESULTS AND DISCUSSION

Habitat Mapping

The full results of the study are presented on a CD-ROM that accompanied a report to the SFWMD (Rubec et al. 2003b). There were 24 seasonal habitat maps created for salinity, temperature, and dissolved oxygen for Rookery Bay and Fakahatchee Bay, and one map each for bottom type and bathymetry in Rookery Bay.

Water Quality

In the bays proper (excluding tributaries), the ranges in water temperatures between the two estuaries were similar during the spring (26 - 28 ^{o}C) and during the summer (29 - 32^{o}C). Dissolved oxygen values ranged from 4 to 8 mg/L in Rookery Bay and 4 to 6 mg/L in Fakahatchee Bay during May 2003, 4 to 7 mg/L in Rookery Bay and 3 to 6 mg/L in Fakahatchee Bay during August 2002, and 1 to 6 mg/L in Rookery Bay and 2 to 5 mg/L in Fakahatchee Bay during July 2003. Low DO values (1 to 2 mg/L) extended out from the Fakahatchee River into the eastern part of Fakahatchee Bay during August 2002. Salinities were similar (30 - 33 g/L) in both estuaries during May 2003 (the dry season). Marked differences in salinity were found between Fakahatchee Bay (8 - 16 g/L) and Rookery Bay (30 - 31 g/L) during August 2002. Inflow data obtained from SFWMD indicates that the higher salinities in Rookery Bay during August 2002 were related to the fact that the weir situated at the head of Henderson Creek kept freshwater from entering Rookery Bay. There was heavy rainfall at the end of June, which lowered salinities in both estuaries during July 2003. Salinities ranged from 26 to 29 g/L in Rookery Bay and 16 to 19 g/L in Fakahatchee Bay during July 2003.

Affinities for Salinity

The ranges of salinities within which various species' life stages had the highest affinity (top 25% of each suitability function) in Charlotte Harbor during the spring are depicted in Figure 1. The following species' life stages had affinities for low salinity (< 10 g/L): YOY spot, Juv sheepshead, Juv sand seatrout, Juv red drum, Juv spotted seatrout, and Juv bay anchovy. Some species' life stages were found to have an affinity for moderate salinities (≥ 10 and < 25 g/L): YOY and adult kingfish, YOY spotted seatrout, and adult bay anchovy. Other species had an affinity for high salinities (≥ 25 g/L): Juv spot, YOY and adult sheepshead, Juv spotted seatrout, Juv and adult pink shrimp, adult hardhead catfish, Juv and adult snook, YOY and adult spotted seatrout, and Juv and adult pinfish. The predominate salinity range (30 - 33 g/L) in Rookery Bay proper and the available salinity range (18 - 33 g/L) in the Rookery Bay system (including both the bay and Henderson Creek) were unsuitable for the species with affinities for low salinity. Those species with moderate salinity affinity were restricted to a relatively small area in Henderson Creek. Only species whose life stages had affinities for higher salinities had ranges that overlapped with the predominate salinity range (30 - 33 g/L) available in Rookery Bay during the spring.

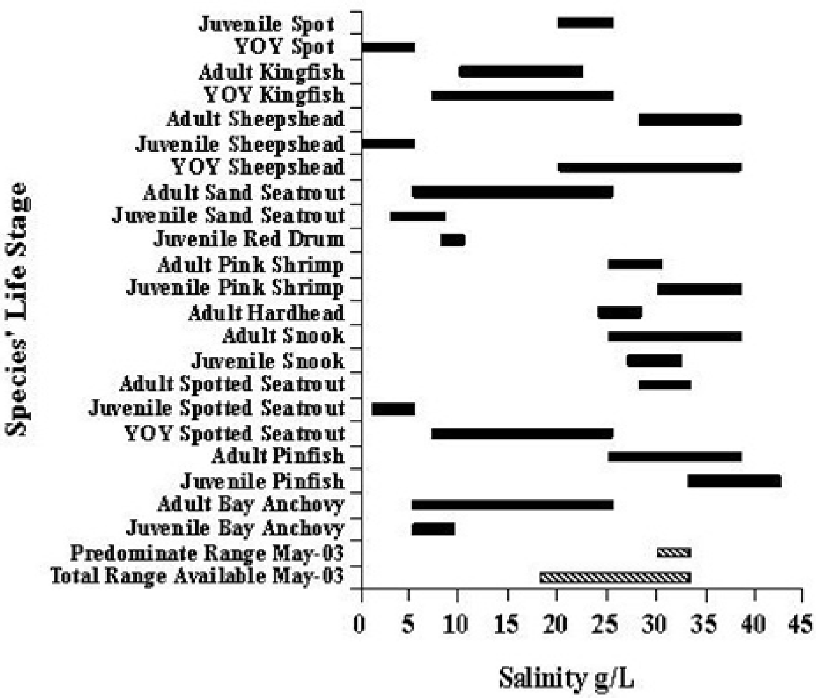

Figure 1. Salinity ranges over which various species' life stages had higher densities (CPUEs) during spring in Charlotte Harbor and the predominate (bay proper) and total salinity ranges (bay plus Henderson Creek) available in Rookery Bay during May 2003.

During the summer, YOY kingfish, Juv sand seatrout, Juv red drum, Juv and adult pink shrimp, and adult hardhead catfish in Charlotte Harbor had affinities for low salinity (Figure 2). Juvenile spot, adult kingfish, adult sand seatrout, Juv pink shrimp, Juv and adult spotted seatrout, Juv and adult bay anchovy had affinities for moderate salinity. Species with affinitiesfor high salinity included YOY, Juv, and adult sheepshead; Juv and adult snook; and Juv and adult pinfish. Examining the predominate salinity range (30 - 33 g/L) and total salinity range (18 - 33 g/L) available during August 2002, it is apparent that salinities in most of Rookery Bay did not match the salinities preferred by the low or moderate salinity species' life stages.

With increasing rainfall during June and July 2003, the predominate salinity range available (26-29 g/L) matched the ranges preferred by the high salinity species (Figure 2). However, the expansion of the total range of salinities (2 - 29 g/L) indicated that there was more area available in Henderson Creek with a salinity range preferred by species' life stages having affinities for low to moderate salinities.

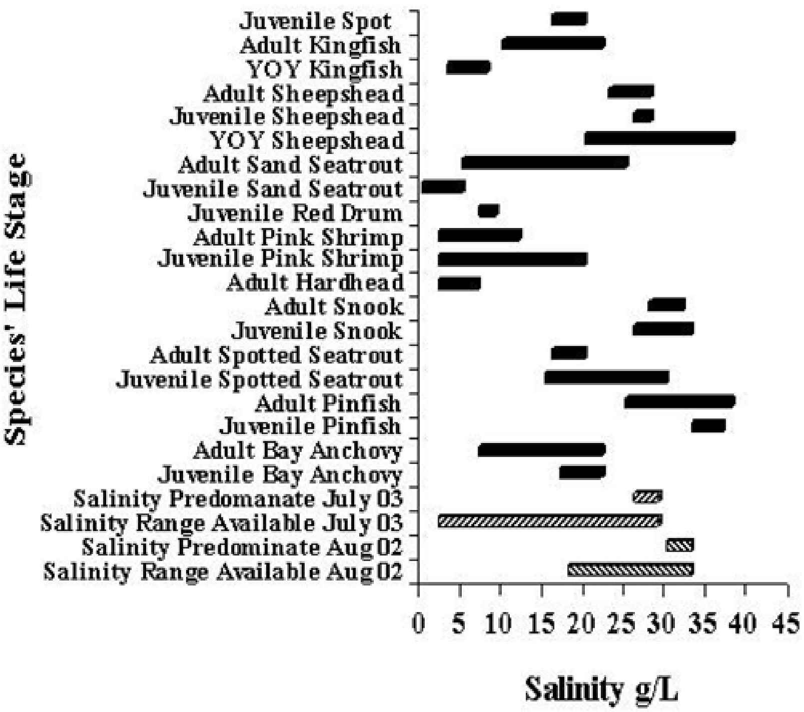

Figure 2. Salinity ranges over which various species' life stages of fish or macroinvertebrates had higher densities (CPUEs) during summer in Charlotte Harbor and with predominate (bay proper) and total salinity ranges (bay plus Henderson Creek) respectively available in Rookery Bay during August 2002 and July 2003.

Percentage of Total Area Suitable for Species' Life Stages

To simplify the interpretation, we summed the areas determined to be High and Optimum from the HSM analyses to determine the proportions of the total areain Rookery Bay that were "suitable" for each species' life stage during the three time periods (Table 1). Although all environmental factors played a role in determining suitability, it is evident that salinity changes between time periods were important in influencing the total area of Rookery Bay predicted to be suitable for various species' life stages. Differences in both water temperature and salinity appear to have been important in influencing the differences in predicted suitability found between the spring and summer time periods.

Table 1. Percentage of the total area determined to be "suitable" for various species' life stages associated with increasing freshwater inflows during three time periods in Rookery Bay.

Species' Life Stage	*Percentage* High + Optimum May-03	*Percentage* High + Optimum Aug-02	*Percentage* High + Optimum July-03
Juvenile Bay Anchovy	21.03	1.61	38.42
Adult Bay Anchovy	99.7	43.37	10.28
Juvenile Pinfish	96.4	99.00	97.8
Adult Pinfish	98.9	98.40	92.9
YOY Spotted Seatrout	97	99.80	87.7
Juvenile Spotted Seatrout	46.3	53.41	23.66
Adult Spotted Seatrout	97.3	44.64	0.31
Juvenile Common Snook	85.1	37.57	30.3
Adult Common Snook	99.7	95.30	97.3
Adult Hardhead Catfish	99.61	18.53	66.8
Juvenile Pink Shrimp	99.8	62.83	99.6
Adult Pink Shrimp	99.9	13.16	38.17
Juvenile Red Drum	58.9	5.46	1.17
Juvenile Sand Seatrout	1.1	6.54	35.99
Adult Sand Seatrout	23.33	39.87	24.49
YOY Sheepshead	99.4	97.60	96.9
Juvenile Sheepshead	92.3	8.77	4.91
Adult Sheepshead	46.4	12.44	16.89
YOY Kingfish	5.17	0.37	2.27
Adult Kingfish	3.19	1.52	2.22
YOY Spot	99.8	95.80	77.63
Juvenile Spot	63.06	3.78	25.49

We consider the two summer time periods (August 2002 and July 2003) to be the most comparable because the same suitability functions were used for the HSM modeling for both time periods. There was little difference in the temperature and dissolved oxygen levels monitored and mapped between the two summer time periods. Hence, we believe that changes in salinity are the most important in explaining the differences in computed habitat suitability between these two periods.

Heavy rainfall that occurred at the end of June 2003 increased the area of lower salinity found on July 10, 2003 in Rookery Bay. The increase in the area predicted to be suitable (Table 1) for Juv bay anchovy (1.61% in August 2002 to 38.42% in July 2003) appears to be related to the reduction in salinity in the estuary. In contrast, the percentage of the area determined to be suitable for adult bay anchovy decreased (43.37% to 10.28%). Some species' life stages with affinities for higher salinity, such as Juv and adult pinfish, adult common snook, and YOY sheepshead did not show marked percent changes in areas estimated to be suitable over the three time periods (the higher salinities present for all time periods were highly suitable). Other species with affinities for higher salinity (Juv and adult spotted seatrout, Juv common snook, Juv sheepshead, and YOY spot) were found to have decreases in the areas predicted to be suitable, associated with the reduction in salinity during July 2003. The HSM analyses predicted increases in areas with suitable habitat during July 2003 for species' life stages (Juv spot, adult hardhead catfish, Juv and adult pink shrimp, Juv sand seatrout, and adult sheepshead) with affinities for low or moderate salinities.

Low percentages of suitable habitat during both summer time periods were predicted for some species such as Juv red drum, Juv sheepshead, and YOY and adult kingfish. The low suitability of the bay during the two summer time periods predicted for Juv and adult kingfish appears to be related to the affinity these fish have for low salinity (lower than what was generally available in Rookery Bay). The low suitability of Rookery Bay predicted for Juv red drum and Juv sheepshead may be related to their high affinity for SAV (the sparse, short-bladed beds of SAV present in Rookery Bay may not provide sufficient cover for larger fish).

Model Validation

We produced 66 HSM maps to predict species distributions in Rookery Bay during the spring (May 2003) and summer (August 2002, July 2003) seasons (Rubec et al. 2003b). Because, the trawl used for monthly sampling in Rookery bay caught only juvenile fish (exceptions were adult bay anchovy and adult hardhead catfish), the validation test was conducted using those species' life stages. The histograms, created by overlaying the observed data from the species caught in Rookery Bay onto the predicted HSM zones, were found to have increasing relations across the zones in 14 of 23 (60.87%) of the cases tested. These results confirmed our ability to adequately predict habitat suitability in Rookery Bay using suitability values transferred from Charlotte Harbor.

CONCLUSIONS

Large differences in salinity were found between Rookery and Fakahatchee bays during the summer and fall wet-seasons (Rubec et al. 2003b). This may be partly related to natural and hydrological differences in rainfall, canal runoff, and the size of the drainage basins for the two estuaries. There was less monthly rainfall recorded near Rookery Bay (Naples) than near Fakahatchee Bay (Copeland) from 1990 to 2003. Based on data published by Carter et al. (1973), the average total annual rainfall at Copeland from 1970 to 1972 was 206.13 cm (n = 3) and the average annual rainfall recorded at Naples over the same time period was 134.53 cm (n = 3). By comparison, the average annual rainfall near Fakahatchee Bay at Copeland from 1990 to 2003 (n = 13) was 155.30 cm (SFWMD reports), and the average annual rainfall at Naples near Rookery Bay over the same time period was 138.38 cm (n = 14) (NOAA National Weather Service on-line data (http://www.dnr.state.sc.us/ water/ climate/sercc/index.html).

Another factor influencing the lower salinities monitored in Fakahatchee Bay in the present study appears to be the high flows of freshwater coming out of the Faka Union Canal system. Salinities lower than those in Rookery Bay were mapped in the northwestern part of Fakahatchee Bay, which adjoins Faka Union Bay, during August 2002, October 2002, and July 2003 (Rubec et al. 2003b).

Differences in the ratios of drainage area to bay area may also help to explain the observed differences in salinity patterns between Rookery and Fakahatchee bays during the wet seasons. Historically, the Belle Meade watershed feeding water to Henderson Creek was similar in size and habitat composition as the Fakahatchee Strand watershed feeding water to Fakahatchee Bay. The creation of the canal system during the 1960s diverted freshwater from the upper part of the Belle Meade watershed through the Golden Gate Canal to Naples Bay (Yokel 1979, Browder and Moore 1981).

Yokel (1979) concluded that excessive freshwater discharges from the Golden Gate Canal through the Gordon River into Naples Bay had caused a rapid decline in salinities to near freshwater conditions from June through September. In the lower part of Naples Bay, the freshwater discharge from the Golden Gate Canal suppressed plankton development, which in turn resulted in a low relative abundance of midwater fish.

In the present study, we conducted HSM modeling to predict spatial distributions and relative abundances of estuarine species' life stages in Rookery Bay over three time periods ordered as they relate to progressively decreasing salinity in the estuary (Rubec et al. 2003b). The modeling found that most of the 22 life stages of the 11 species modeled responded to changes in salinity, related to changes in freshwater inflow. The results demonstrated our ability to predict habitat suitability associated with the changes in salinity in Rookery Bay. It appears that a number of estuarine species' life stages would benefit if the Rookery Bay system received more freshwater inflow during both the dry (winter and spring) and wet seasons (summer and fall). Further research is needed to define the salinity conditions that might be achieved in the Rookery Bay system by water diversions through the canal system in the Belle Meade watershed and by fine-tuning the weir on Henderson Creek.

Based on the large differences in salinity ranges observed between Rookery Bay and Fakahatchee Bay during the wet seasons, it is probably not feasible to augment freshwater inflows to Rookery Bay to exactly match the salinity ranges observed in Fakahatchee Bay. A more realistic management goal would be to use Fakahatchee Bay as a reference site, to help account for the hydrological differences between the two systems, and then set freshwater inflow targets for each season in Rookery Bay. This should broaden the range of salinities, and provide a more natural timing and variation in patterns of freshwater inflow into Henderson Creek, thereby creating more suitable habitats for various species' life stages.

Further studies are needed to develop a circulation model that takes into account monthly freshwater inflows and tidal variation in each estuary. By linking the HSM to both the circulation model and to stream gauging at the upstream weir, it will become possible to predict habitat suitability directly from inflow patterns. We recognize that seasonal patterns of salinity variation (measured by stationary data loggers) are also important (Shirley et al. 2004). Protecting biodiversity in the estuary should also become a management goal, through spatial evaluation of diversity-related indices such as species richness and evenness (Drake et al. 2002). We plan to conduct biodiversity-based HSM analyses to help predict the volumes and timing of freshwater inflows needed in Rookery Bay to mimic freshwater inflow patterns found in Fakahatchee Bay associated with natural sheet-flow.

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LITERATURE CITED

Ault, J.S. and S.G. Smith. 2000. *Extensions to Gear Inter-calibration Methods for Fishery-independent Catch-per-unit-effort Data*. University of Miami, Rosenstiel School of Marine and Atmospheric Science, Technical Report to Florida Marine Research Institute, Florida Fish and Wildlife Conservation Commission Contract No. 99020. 67 pp.

Browder, J.A. 1985. Relationship between pink shrimp production on the Tortugas grounds and water flow patterns in the Florida Everglades. *Bulletin of Marine Science* **37**(3):839-856.

Browder, J.A. 1991. Watershed management and the importance of freshwater inflow to estuaries. Pages 7-22, in: S.F. Treat and P.A. Clark (eds.). *Proceedings Tampa Bay Scientific Information Symposium 2*, Tampa Bay Regional Planning Council, St. Petersburg, Florida USA.

Browder, J.A. and D. Moore 1981. A new approach to determining the quantitative relationship between fishery production and flow of fresh water to estuaries. Pages 403-430 in: R.D. Cross and D.L. Williams (eds.). *Proceedings of the National Symposium On Freshwater Inflow To Estuaries*. FWS/OBS-81/04. U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C. USA .

Browder, J.A., Z. Zein-Eldin, M.R. Criales, M.B. Roblee, S.Wong, T.L. Jackson, and D. Johnson. 2002. Dynamics of pink shrimp (*Farfantepenaeus duorarum*) recruitment potential in relation to salinity and temperature in Florida Bay. *Estuaries* **25** (No. 6B): 1355-1371.

Carter, M.R., L.A. Burns, T.R. Cavinder, K. R. Dugger, P.L. Fore, D.B. Hicks, H. Lavon Revells, and T.W. Schmidt. 1973. Ecosystems analysis of the Big Cypress Swamp and estuaries. Atlanta, Georgia: United States Environmental Protection Agency, Region IV; June 1973, EPA 904/9-74-002, Report No. PB 233 070.

Colby, D., G. Thayer, W. Hettler, and D. Peters. 1985. A comparison Of forage fish community in relation to habitat parameters In Faka Union Bay, Florida, and eight collateral bays during the wet season. NOAA Tech. Report NMFS SEFC-162. Southeast Fisheries Center, Beaufort-Laboratory, Beaufort, North Carolina. 87 pp.

Drake, P., A.M. Arias, F. Baldé, J. A. Cuesta, A. Rodríguez, A. Silva-García, I. Sobrino, D. García-Gonzalez, and C. Fernández-Delago. 2002. Spatial and temporal variation of nekton and hyperbenthos from a temperate European estuary with regulated freshwater inflow. *Estuaries* **25**(3):451-468.

Gardner, T. 1988. Rookery Bay and Cape Romano-Ten Thousand Islands aquatic preserves management plan. Report prepared by The Florida Department of Natural Resources, Bureau of Aquatic Preservers, Division of State Lands, June 28, 1988. 143 pp.

Johnston, K., J.M. Ver Hoef, K. Krivoruchko, and N. Lucas. 2001. *Using ArcGIS Geostatistical Analyst.* Environmental Systems Institute Inc., Redlands, California USA. 300 pp.

Livingston, R.J., X. Niu, F.G. Lewis, and G.C. Woodsum. 1997. Freshwater input to a Gulf estuary: long term control of trophic organization. *Ecological Applications* **7**: 277-299.

Livingston, R.J., F.G. Lewis, G.C. Woodsum, X.-F. Niu, B. Galperin, W. Huang, J.D. Christensen, M.E. Monaco, T.A. Battista, C.J. Klein, R.L. Howell IV, and G.L. Ray. 2000. Modelling oyster population response to variation in freshwater input. *Estuarine, Coastal and Shelf Science* **50**:655-672.

Locker, S.D., and A.K. Wright. 2003. Benthic habitat mapping for habitat suitability modeling in Rookery Bay National Estuarine Research Reserve. Final Report submitted by the University of South Florida, College of Marine Science to the Florida Fish and Wildlife Conservation Commission, Florida Marine Research Institute under contract No. POS7701617863.

Robson, D.S. 1966. Estimation of the relative fishing power of individual ships. *International Commission Northwest Atlantic Fisheries Research Bulletin* **3**:5 - 14.

Rubec, P.J., M.S. Coyne, R. H. McMichael, Jr., and M.E. Monaco. 1998. Methods being developed in Florida to determine essential fish habitat. *Fisheries* **23**(7):21 - 25.

Rubec, P.J., C.W. Bexley, H. Norris, M.S. Coyne, M.E. Monaco, S.G. Smith, and J.S. Ault. 1999. Suitability modeling to delineate habitat essential to sustainable fisheries. *American Fisheries Society Symposium* **22**:108 - 133.

Rubec, P.J., S.G. Smith, M.S. Coyne, M. White, A. Sullivan, D. Wilder, T. MacDonald, R.H. McMichael, Jr., M.E. Monaco, and J.S. Ault. 2001. Spatial modeling of fish habitat suitability in Florida estuaries. Pages 1-18, in: G.H. Kruse, N. Bez, A. Booth, M.W. Dorn, S. Hills, R.N. Lipcus, D. Pelltier, C. Roy, S.J. Smith, and D. Witherell (eds.). *Spatial Processes and Management of Marine Populations,* Alaska Sea Grant College Program AG-SG-01-02. Fairbanks, Alaska USA.

Rubec, P.J., S.D. Whaley, G.E. Henderson, J. Lewis, M. White, A.M. Sullivan, R.L. Vadas Jr., R. Ruiz-Carus, D.T. Wilder, C. Westergren, and T.M. MacDonald. 2003a. *Development And Evaluation of Methods for Habitat Suitability Modeling In Florida Estuaries*. Report submitted to U.S. Fish and Wildlife Service, Atlanta, Georgia associated with Grant Number F-96 to the Florida Marine Research Institute, 69 pp. + CD-ROM.

Rubec, P.J., M.A. Shirley, J. Lewis, P. O'Donnell, S.D. Locker, G.E. Henderson, T. Mo, and C. Westergren. 2003b. *Spatial Modeling to Determine Optimal Freshwater Inflows into Estuarine Habitats in the Rookery Bay System*. Report submitted by the FWC Florida Marine Research Institute to the Big Cypress Basin, South Florida Water Management District, associated with SFWMD Grant No. C-13253, 83 pp. + CD-ROM.

SAS 2002. *Statistics and Graphics Guide: JMP Statistical Discovery Software*. SAS Institute Inc., Cary, North Carolina USA 707 pp.

Sklar, F.H., and J.A. Browder. 1998. Coastal environmental impacts brought about by alterations to freshwater flow in the Gulf of Mexico. *Environmental Management* **22**:547-562.

Shirley, M.A., V. McGee, T. Jones, B. Anderson, and J. Schmid. 2004. Relative abundance estimates of stenohaline and euryhaline oyster reef crab populations as a tool for managing freshwater inflow to estuaries. *Journal of Coastal Research* **45**:195-208.

Yokel, B.J. 1979. Section E Biology. Pages E1-E10, in: *The Naples Bay Study*. The Collier County Conservancy, Naples, Florida USA.

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