

Quantifying Florida Bay Habitat Suitability for Fishes and Invertebrates Under Climate Change Scenarios

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Abstract The Florida Bay ecosystem supports a number of economically important ecosystem services, including several recreational fisheries, which may be affected by changing salinity and temperature due to climate change. In this paper, we use a combination of physical models and habitat suitability index models to quantify the effects of potential climate change scenarios on a variety of juvenile fish and lobster species in Florida Bay. The climate scenarios include alterations in sea level, evaporation and precipitation rates, coastal runoff, and water temperature. We find that the changes in habitat suitability vary in both magnitude and direction across the scenarios and species, but are on average small. Only one of the seven species we investigate (*Lagodon rhomboides*, i.e., pinfish) sees a sizeable decrease in optimal habitat under any of the scenarios. This suggests that the estuarine fauna of Florida Bay may not be as vulnerable to climate change as other components of the ecosystem, such as those in the marine/terrestrial ecotone. However, these models are relatively simplistic,

looking only at single species effects of physical drivers without considering the many interspecific interactions that may play a key role in the adjustment of the ecosystem as a whole. More complex models that capture the mechanistic links between physics and biology, as well as the complex dynamics of the estuarine food web, may be necessary to further understand the potential effects of climate change on the Florida Bay ecosystem.

Keywords Climate change · Scenario modeling · Sea level rise · Fisheries

Introduction

Coastal estuaries and bays are of great ecological and economic significance (Pendleton 2010), and they produce a diversity of ecosystem services that benefit humans (Barbier et al. 2011). Their close proximity to human populations and high productivity make them some of the most heavily utilized and threatened ecosystems on the planet (Halpern et al. 2008; Lotze et al. 2006). Urban, suburban, and agricultural development of coastal watersheds have led to

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destruction of wetland habitats, as well as profound hydrological alterations that modify surface and groundwater dynamics and can in turn change salinity regimes “downstream” in receiving water-bodies (Estuar Coast Shelf S Special Section 2012).

Florida Bay (Fig. 1), which is located at the southern end of the Florida Peninsula and lies at the terminus of one of the world’s largest wetlands—the Everglades, is an example of an estuary whose hydrodynamics have been substantially altered by humans (Light and Dineen 1994; McIvor et al. 1994), especially with respect to salinity. The building of spoil islands along Florida Bay’s southern border for the construction of the Florida Overseas Railway in the early 1900s restricted circulation in Florida Bay (Swart et al. 1996). Likely more significant was the drainage and water management within the upstream Everglades ecosystem over the twentieth century, which decreased freshwater flow to Florida Bay by as much as 59 % (Smith et al. 1989) and increased salinity in parts of the bay closest to freshwater input locations by 14 psu (Marshall and Wingard 2012; Marshall et al. 2008). These changes to Florida Bay have resulted in more frequent and intense hypersalinity events (Fourqurean and Robblee 1999) as a result of the decreased freshwater runoff and long residence times in north-central Florida Bay (Lee et al. 2006). The current salinity regime has significant seasonal variability, with hypersalinity during the summer months and estuarine salinities in the fall and winter (Kelble et al. 2007). Hypersalinity events are especially pronounced (>50 psu), when the onset of the wet season is delayed, and these high salinities can lead to significant ecological impacts (Fourqurean and Robblee 1999).

In 1987, Florida Bay experienced a significant seagrass die-off, followed in the next few years by increased phytoplankton blooms and increased turbidity (Fourqurean and Robblee 1999). These changes significantly impacted the fauna of Florida Bay, resulting in decreased lobster populations and sponge die-offs (Butler et al. 1995). Conditions in the Bay have since improved (Boyer et al. 2009; Madden et al. 2009), but episodic bloom and die-off events have continued to occur through this decade, and there remain significant concerns that this ecosystem is at risk without more effective management actions.

Florida Bay provides a number of ecosystem services (Kelble et al. 2013b; Cook et al. 2014) and is frequently utilized by the human population, largely for recreational fishing (Tilmant 1989; Osborne et al. 2006). Although the recreational fishery targets a diversity of species, gray snapper (*Lutjanus griseus*), and spotted seatrout (*Cynoscion nebulosus*) account for over 60 % of the recreational finfish catch (Tilmant 1989). The fishery for the Caribbean spiny lobster (*Panulirus argus*) is the single most economically valuable fishery in Florida and the Caribbean

(Ehrhardt et al. 2010), and in Florida the recreational lobster fishery accounts for 20 % of all lobster landings. Recreational fishing of lobster is not permitted within the Everglades National Park boundaries of Florida Bay, but the southern portion of the bay is an important lobster nursery (Herrnkind et al. 1997).

A recent analysis of stressors impacting the Florida Bay ecosystem showed that changes in the physical environment were more impactful to the ecosystem as a whole than the recreational fishery. Specifically, it identified the dominant pressures to be fresh water delivery, sea level rise, and climate-related alterations in temperature and weather (Cook et al. 2014). Thus, tools are needed that allow us to better examine and predict the impact of climate change on the fauna of Florida Bay. The present study presents the integration and application of hydrodynamic and ecological models to examine the impact of the potential climate change scenarios as proposed in this issue (Obeysekera et al. 2014; Havens and Steinman 2013) on key species within Florida Bay. Understanding these impacts may allow for the implementation of management actions that address the likely impacts of climate change.

To quantify the potential change in habitat quality for key faunal species caused by climate change, we make use of a variety of habitat suitability index models. Habitat suitability index (HSI) models represent a quantitative synthesis of species-specific information on habitat utilization and/or preference. They are simple mathematical expressions, derived empirically from field and/or laboratory observations, that convey habitat quality for a particular species or population as a function of one or more environmental variables. Typically, HSI models are used to assess the quality of a given geographical area for a specific population when modified by some combination of anthropogenically driven environmental changes, and they are increasingly being used to examine potential climate change impacts on a diversity of organisms, including fishes (Chang et al. 2013; Cline et al. 2013; Jones et al. 2013). In coastal ecosystems, these modifications may include alterations of terrestrial landscapes, hydrology and/or sediment dynamics, as well as changes to nutrient, temperature, dissolved oxygen, and salinity regimes. By mapping HSI values, changes in suitable habitat area and configuration under different management or climate scenarios can be visualized and communicated to managers. Therefore, HSI models have utility in natural resource decision-making by improving understanding of species-habitat relationships and by serving as specific hypotheses that can be tested and improved via empirical studies.

In this study, we use a combination of new and existing HSI models relating temperature and salinity characteristics to habitat suitability for a variety of species that reside in Florida Bay, including juvenile fishes and lobsters. We

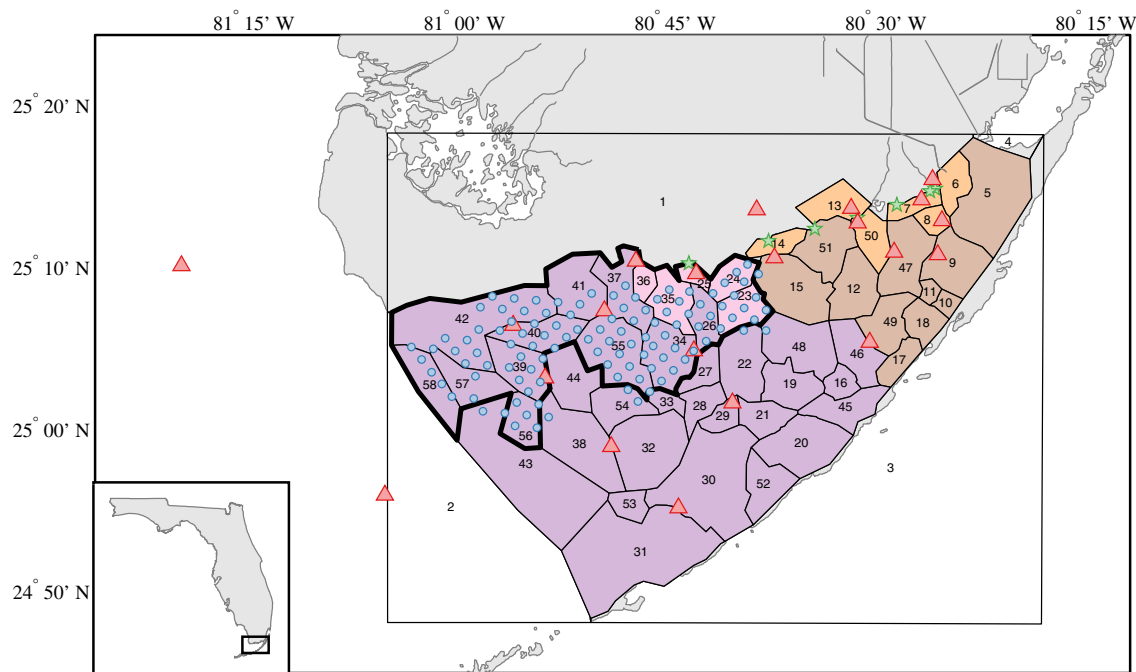


Fig. 1 The FATHOM model simulates exchange between 58 basins, which are indicated on the map as *black lines*. The basins outlined by the *thick black line* indicate the sampling region over which most of our HSI calculations were applied. Also shown are the locations of the juvenile fish data collection macrocells (*circles, blue*) and Marine Monitoring Network stations (*triangles, red*). Stars (*green*) along the

coastline indicate the locations of freshwater input to the Bay from coastal creeks; from west to east these are McCormick Creek, Taylor River, Mud Creek, Trout Creek, Stillwater Creek, West Highway Creek, and Highway Creek. The basins are colored according to the regions used to present our results: west *purple*, west inshore *pink*, east *brown*, and east inshore *orange*

then apply these habitat suitability models to the output of a time-dynamic mass-balance model that simulates the changing salinity conditions of the Bay under a series of climate change scenarios.

Methods

Modeling the Physical Effects of Climate Change Scenarios on Florida Bay

We used the Flux Accounting and Tidal Hydrology at the Ocean Margin (FATHOM) model, a coastal model, to predict salinity conditions for Florida Bay. FATHOM is a spatially explicit box model that uses tidal forcing to move water across the multitude of shallow banks that separate Florida Bay into 58 discrete basins; the model has been demonstrated to reproduce observed salinity patterns throughout Florida Bay. (see Cosby et al. 2004, for details). The model operates at 1 min. time steps, calculating the transfer of water across the banks due to surface level differences between basins using the Manning equation for flow in shallow channels. At each time step, fresh water is either added or removed from each basin due to precipitation and evaporation, and then salinity is recalculated.

Because the model assumes well-mixed basins, model results are presented in monthly time steps.

The scenarios investigated using FATHOM are all modifications of a base scenario representing the observed conditions between 1965 and 2000. Input variables, including precipitation, evaporation, freshwater discharge, and sea level timeseries, were increased or decreased to reflect the conditions expected during future hydrologic regimes as projected by Obeysekera (2014), while maintaining the seasonal patterns in the original data set. Details of these modifications are provided in the scenario descriptors below. This approach allows the model to simulate future scenarios while including historical temporal variability. Throughout this paper, we refer to the various simulated climate scenarios using abbreviations for each environmental variable that was manipulated:

1. Sea level (SL): The baseline state (SL0) uses observed coastal water levels, marsh water levels, and salinity boundary conditions as input to the FATHOM model. The increased sea level state (SL+) applies an additional 18" (45.7 cm) to the water levels in all basins.
2. Evaporation rate (EVP): The baseline state (EVP0) evaporation rates were derived from air temperature variability measurements, as described in Cosby et al.

Table 1 Juvenile fish count trawl data

Common name	Scientific name	Number	Fraction	Average number
Spotted Seatrout <100 mm	<i>Cynoscion nebulosus</i>	3,615	0.0999	2.1
Gray Snapper	<i>Lutjanus griseus</i>	3,615	0.1524	2.6
Goldspotted Killifish	<i>Floridichthys carpio</i>	297	0.1279	9.3
Rainwater Killifish	<i>Lucania parva</i>	297	0.5758	64.4
Mojarra	<i>Eucinostomus spp.</i>	297	0.8956	55.1
Pinfish	<i>Lagodon rhomboides</i>	297	0.4983	37.6

Data include common and scientific name of each species, number of trawl datasets where a species was quantified, fraction of those datasets where the species was observed, and the average number of each species observed in the fraction of datasets where they were present

(2004) and references therein. The increased evaporation state (EVP+) forcing is based on the bulk aerodynamic flux equation (Pond et al. 1974) that has previously been employed in Florida Bay (Kelble et al. 2007; Smith 2000). The equation was adjusted to account for differences in evaporation due to a 1 °C temperature increase, and the resultant monthly time-series was provided as input to the FATHOM model.

3. Rainfall and runoff (RF): The baseline state (RF0) uses observed precipitation rates and observed discharge from coastal creeks. The increased state (RF+) adds a 10 % increase in precipitation rates and corresponding 5 % increase in freshwater flow from the coastal creeks. The decreased state (RF–) decreases precipitation rates by 10 % and decreases freshwater flows by 5 %. The 2:1 correction for freshwater flow from the coastal creeks located along northeastern Florida Bay (Fig. 1) was based on the relationship between precipitation data in the upstream marsh and measured creek discharge data (South Florida Natural Resources Center Everglades National Park 2013).
4. Water temperature (T): In addition to its effect on sea level, evaporation rates, and precipitation, the predicted change in air temperature will be accompanied by changes in water temperature that in turn directly influence the habitat quality of Florida Bay. To capture this, we added a fourth variable, water temperature, to the scenarios outlined by (Obeysekera 2014). Because the FATHOM model does not reliably simulate water temperature, we instead derived temperature values corresponding to the FATHOM simulations from monthly measurements taken at stations within Florida Bay (Fig. 1, triangles within the Bay). These timeseries

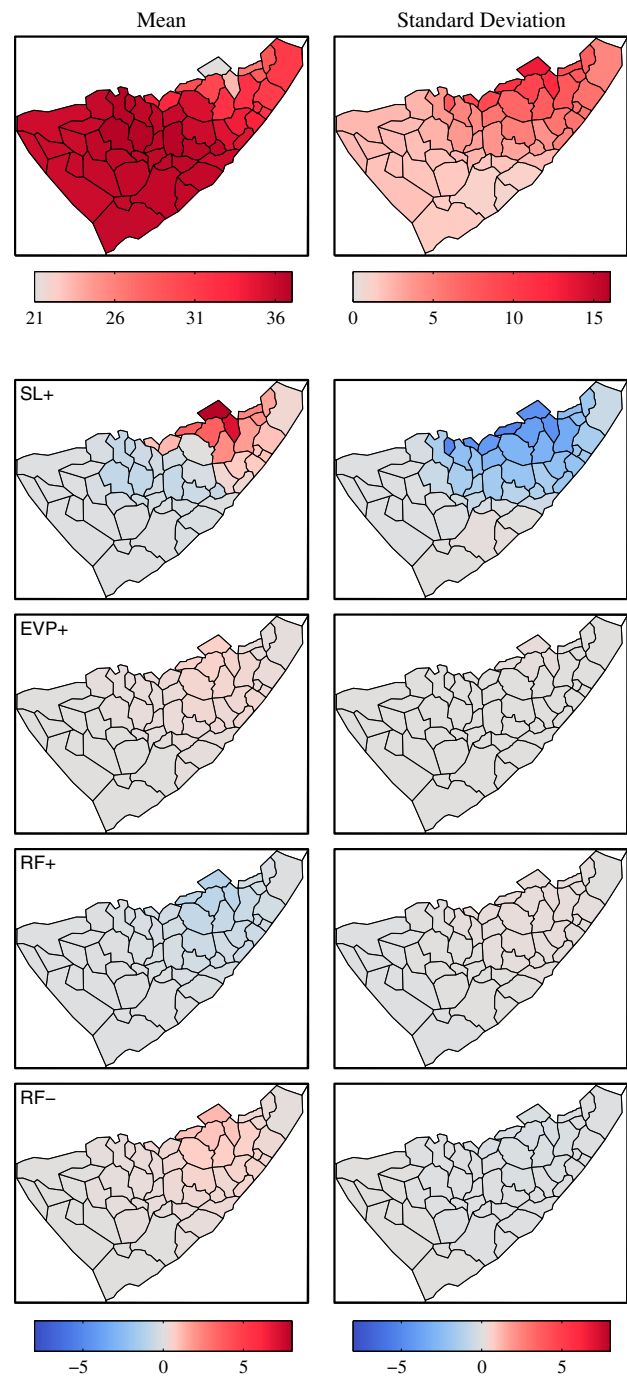
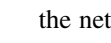


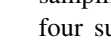
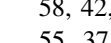
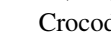
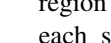
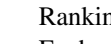
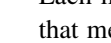
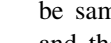
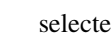
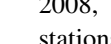
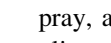
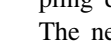
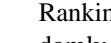
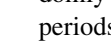
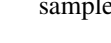



Fig. 2 Spatial change in salinity. The top two panels show the mean (left) and SD (right) of the baseline scenario. The remaining panels show the change in these properties that can be attributed to increased sea level, increased evaporation, and increased/decreased rainfall and runoff, derived by subtracting the results of scenarios that do and do not include the changes in each input variable

were available for the period of 1993–2005; for all missing years, we applied the monthly mean climatology values. Temperature varied little among the stations, so for the baseline case (T0), each model basin was simply assigned the timeseries corresponding to the

Table 2 Salinity statistics

Basin	Statistic	Sparkline	SL0	SL+	SL+	SL+	SL+
			EVPO	EVPO	EVP+	EVP+	EVP+
			RF0	RF0	RF0	RF+	RF-
			T0	T0	T0	T0	T0
Florida Bay	Mean		34.941	35.284	35.432	35.210	35.659
	Median		34.991	35.525	35.688	35.435	35.936
	Std. Dev.		3.286	2.421	2.438	2.480	2.397
Sampling region	Mean		36.156	35.936	36.014	35.905	36.123
	Median		36.403	36.137	36.213	36.102	36.343
	Std. Dev.		2.834	2.168	2.176	2.192	2.162
West	Mean		36.263	36.085	36.163	36.055	36.271
	Median		36.438	36.295	36.370	36.253	36.513
	Std. Dev.		2.090	1.829	1.836	1.849	1.824
East inshore	Mean		25.587	30.469	30.868	30.166	31.597
	Median		25.358	31.220	31.592	30.910	32.326
	Std. Dev.		10.118	6.598	6.682	6.826	6.526
West inshore	Mean		35.452	35.482	35.688	35.378	36.001
	Median		36.155	35.886	36.081	35.819	36.397
	Std. Dev.		6.507	3.204	3.223	3.348	3.098
East	Mean		32.446	33.565	33.893	33.392	34.406
	Median		32.483	33.869	34.189	33.649	34.662
	Std. Dev.		6.182	4.017	4.057	4.172	3.940

All statistics are calculated across time. For regions, values were first spatially averaged, weighting each contributing basin value by the area of the respective basin. Sparkline mini-plots show the relative trend across values in each row, normalized to the range of that row

nearest measurement station. For the increased temperature scenarios (T+), a step increase of 1 °C was applied across the entire timeseries.

The FATHOM model was run for five different climate scenarios, starting with baseline conditions (SL0_EVPO_RF0_T0) and then incrementally adding sea level rise (SL+_EVPO_RF0_T0), increased evaporation (SL+_EVP+_RF0_T0), and either increased (SL+_EVP+_RF+_T0) or decreased (SL+_EVP+_RF-_T0) rainfall and runoff rates. These five FATHOM scenarios were then combined with the increased temperature conditions, for a total of 10 climate scenarios. While it is likely that water temperature changes would be coupled with changes in evaporation rates, the additional influence of potential changes in wind speed on evaporation rates could decouple the two properties (Obeysekera 2013; Misra et al. 2011). In addition, the inclusion of both the coupled and decoupled scenarios allows us to isolate the effects of salinity and temperature on habitat suitability. Therefore, we have chosen to present all 10 scenarios for analysis. Throughout this paper, when we refer to salinity-altered-only scenarios, we are referring to those simulations with baseline conditions for T but non-baseline conditions for SL, EVP, and/or RF.

Habitat Suitability Index Models for Juvenile Fishes

The field data utilized to develop the fish HSIs in Florida Bay were collected using an otter trawl to sample the

juvenile and small adult fish community (Thayer et al. 1999). The otter trawls consist of a net with 6 mm mesh in the net body and 3 mm mesh in the tail bag. The field data span the years of 2004–2012, and were conducted monthly from June through November of each year.

These tows were conducted using a stratified random sampling design. The sampling area was first divided into four sub-regions: West, (approximately FATHOM basins 58, 42, 57, 39, 56, 40, and 41, see Fig. 1), Rankin (basins 55, 37, and 36), Whipray (basins basins 34 and 35), and Crocodile Dragover (basins 23, 24, 25, and 26). Each sub-region was divided into macrocells that are 1,800 m on each side; this results in 50 macrocells in West, 23 in Rankin, 19 in Whipray, and 20 in Crocodile Dragover. Each macrocell was then further divided into 4 microcells that measured 900 m on each side. First, the macrocells to be sampled within a sub-region were randomly selected, and then within each macrocell a random microcell was selected to conduct the otter trawl. From 2004 through 2008, sixty otter trawls were conducted each month; 26 stations were sampled in West, 14 in Rankin, 10 in Whipray, and 10 in Crocodile Dragover. After 2008, the sampling design was modified based upon a power analysis. The new sample design samples all of the macrocells in Rankin, Whipray, and Crocodile Dragover, and 20 randomly selected stations in West each month. For both periods, a random microcell was sampled at each macrocell sample location.

Table 3 Habitat suitability model details for the six juvenile fish species

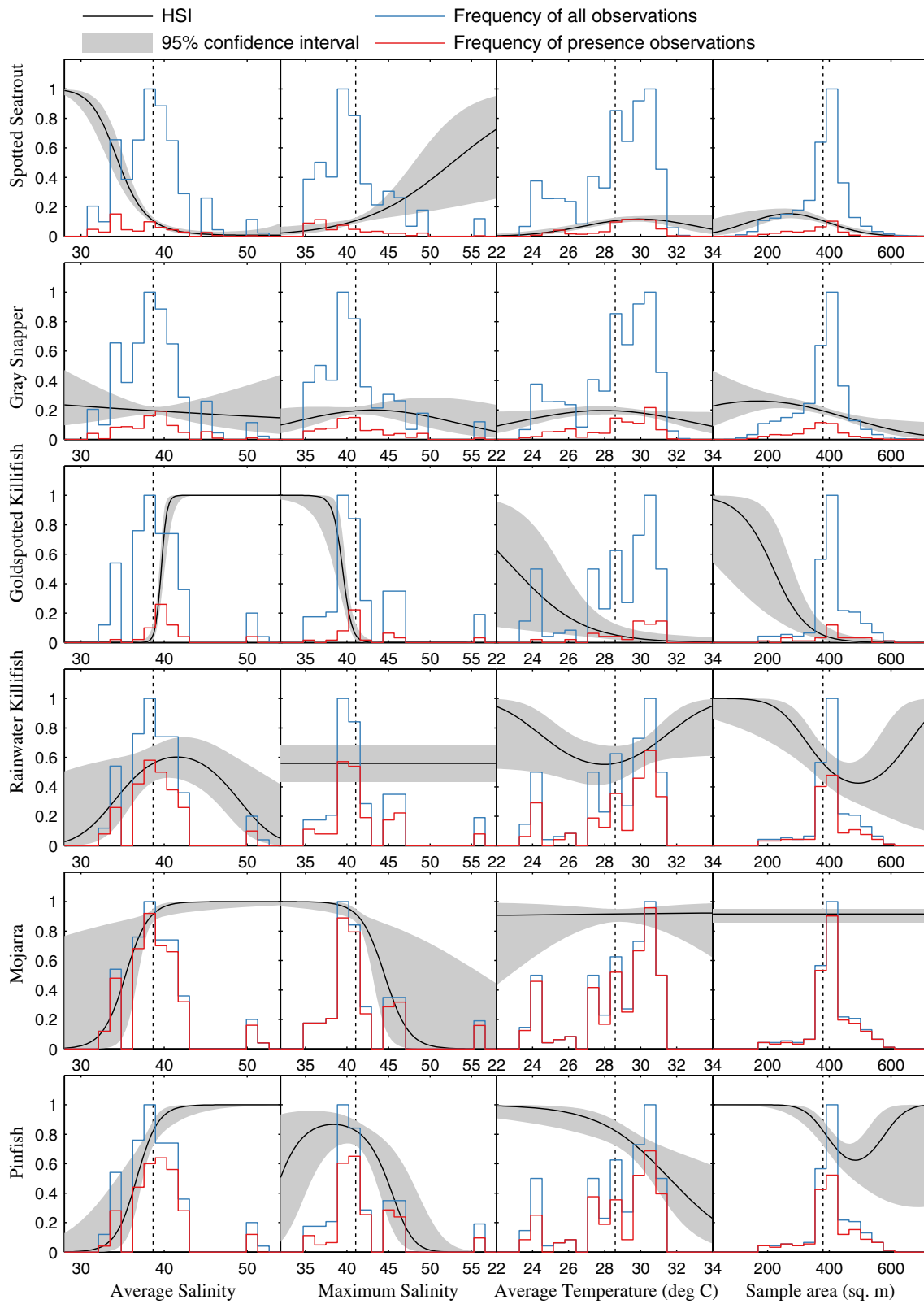
Coefficient	Estimate	SE	P value
Spotted Seatrout <100 mm			
$\text{logit}(H) = x_1 + x_2S_m + x_3A + x_4S_aT_a + x_5S_a^2 + x_6T_a^2 + x_7A^2$			
x_1	-69.92	13.57	2.59e-07
x_2	0.1837	0.06147	0.002812
x_3	0.01749	0.006083	0.004039
x_4	-0.04256	0.01394	0.002262
x_5	0.01716	0.002759	4.922e-10
x_6	-0.0604	0.0207	0.003517
x_7	-3.276e-05	9.227e-06	0.0003851
Gray Snapper			
$\text{logit}(H) = x_1 + x_2T_a + x_3S_aA + x_4S_mA + x_5S_m^2 + x_6T_a^2 + x_7A^2$			
x_1	-34.69	10.72	0.001215
x_2	1.415	0.697	0.04236
x_3	0.001165	0.0005359	0.02976
x_4	-0.001228	0.0004758	0.009881
x_5	-0.006708	0.002141	0.001726
x_6	-0.02531	0.01248	0.04253
x_7	-8.517e-06	5.591e-06	0.1277
Goldspotted Killifish			
$\text{logit}(H) = x_1 + x_2S_a + x_3S_m + x_4T_aA + x_5S_m^2$			
x_1	5.309	27.67	0.8479
x_2	2.997	0.6565	5.002e-06
x_3	1.64	1.019	0.1074
x_4	0.008947	0.002561	0.0004771
x_5	-0.04311	0.01282	0.0007706
Rainwater Killifish			
$\text{logit}(H) = x_1 + x_2S_a + x_3T_a + x_4A + x_5S_a^2 + x_6T_a^2 + x_7A^2$			
x_1	30.34	26.46	0.2515
x_2	1.809	0.7788	0.0202
x_3	-4.14	2.108	0.04959
x_4	-0.04143	0.01895	0.02885
x_5	-0.02177	0.009183	0.01777
x_6	0.07404	0.03754	0.04855
x_7	4.204e-05	2.221e-05	0.05836
Mojarra			
$\text{logit}(H) = x_1 + x_2S_a + x_3S_mT_a$			
x_1	194.1	87.4	0.02638
x_2	0.7187	0.3172	0.02347
x_3	0.1634	0.07334	0.02583
Pinfish			
$\text{logit}(H) = x_1 + x_2S_a + x_3S_m + x_4T_aA + x_5S_m^2 + x_6A^2$			
x_1	-20.07	21.64	0.3538
x_2	0.7782	0.2454	0.001517
x_3	3.5	0.7857	8.387e-06
x_4	0.003645	0.001906	0.05583
x_5	-0.04563	0.009916	4.196e-06
x_6	9.461e-05	3.796e-05	0.0127

All equations are written in terms of the logit function, such that the HSI value (H) is equal to $\frac{\exp(\text{logit}(H))}{1+\exp(\text{logit}(H))}$. The tables list the coefficient estimates, standard error of the coefficient estimates, and P values for the t statistic of each coefficient. The predictor variables include monthly-averaged salinity (S_a), monthly-maximum salinity (S_m), monthly-averaged water column temperature (T_a , in °C), and sampling area (A, in m²)

Fig. 3 Slices of each HSI function are shown, versus each predictor variable included in the models. The HSI predictions themselves are shown in black, with the shaded gray region depicting the 95 % confidence interval for the predictions. The outlined histograms indicate the distributions of each property associated with the juvenile fish sample counts, across all samples (blue) and just samples where the particular species was observed (red); both are normalized to the maximum all-observations value. The dotted black line indicates the mean value of each predictor variable in the observation dataset; for each slice, this indicates the value where the other predictor variables are set (e.g., the average salinity vs. HSI curve shows the predictions and confidence intervals when maximum salinity, average temperature, and sampling area are set to their mean-observed values)

Environmental conditions, including temperature and salinity at time of sampling, were measured alongside the trawl data. However, because the FATHOM model resolves its output as monthly statistical values rather than instantaneous values, we wanted to build our habitat suitability models using comparable environmental data. Under the Everglades National Park Marine Monitoring Network, salinity and temperature data have been measured at approximately 1-h resolution at 22 stations around Florida Bay (Fig. 1). We interpolated these timeseries to the locations of the juvenile fish collection stations using inverse distance weighting interpolation (see supplementary methods for full details). Using the resulting interpolated timeseries, we then calculated a variety of statistics on the 30-day section preceding each observation, including average salinity, average temperature, and maximum salinity values.

Of the 95 juvenile fish species quantified in the trawl surveys, we chose to focus on six for our habitat suitability models (Table 1). These include two major recreational fisheries target species: spotted seatrout (*Cynoscion nebulosus*) and gray snapper (*Lutjanus griseus*), as well as four of their most common prey species: goldspotted killifish (*Floridichthys carpio*), rainwater killifish (*Lucania parva*), mojarra (*Eucinostomus* spp.), and pinfish (*Lagodon rhomboides*). The seatrout and snapper were quantified as either present or absent for all trawls in the dataset, totaling 3615 observation points each. The four remaining species were only quantified at a subset of approximately 12 stations each month from 2009 through 2012, resulting in only 297 data points each. Logistic regression models were fit to the presence/absence data for each species, using average salinity, maximum salinity, and average temperature as potential predictor variables. Because there was some variation in the exact area covered by each trawl, we also included sampling (i.e., trawl) area as a predictor variable to eliminate any trends associated with this variable. Stepwise regression was performed on each species dataset using a Generalized Linear Model with logit link function, allowing for inclusion of linear, quadratic, and paired



product interaction terms. Terms were added or removed using the criterion that a term must decrease the Akaike information criterion (AIC) of the model in order to be included. The resulting logistic regression models calculate the probability of observing a particular fish species under the given conditions; we will refer to this quantity as the HSI value.

The resulting HSI models were mapped onto each climate change scenario using the FATHOM monthly-average and monthly-maximum salinity values for each basin coupled with the water temperature timeseries described in the section “[Modeling the Physical Effects of Climate Change Scenarios on Florida Bay.](#)” The sampling area variable of each HSI equation was set to 400 m², the approximate mean for the observation dataset, for all simulations, so the HSI values can be interpreted as the probability of finding a given species in a 400 m² portion of a basin.



















Juvenile fish are not typically found in the more eastern portions of Florida Bay, due to the lack of seagrass cover in this portion of the Bay. Therefore, extrapolating the HSI predictions beyond the basins from which the observations were gathered should be done cautiously. In this study, we

have applied the models to the entire bay, but have focused our analysis and conclusions on the 16 basins from which data were collected, hereafter referred to as the sampling region (Fig. 1, black line).

Survival Models for Juvenile Lobster



















Caribbean spiny lobsters are tropical marine organisms whose tolerance to the fluctuating temperatures and salinities found in estuaries is limited, particularly among the vulnerable early life history stages that occur in hardbottom nursery areas within Florida Bay. Laboratory studies using temperatures between 18 and 32 °C and salinities ranging from 25 to 50 psu indicate that postlarval and early benthic juvenile lobsters experience high mortality at salinities much different from seawater, especially at high summer temperatures (Field and Butler 1994). Large juvenile adult lobster life stages, which are less abundant in the Florida Bay nursery, tolerate a wider range of salinities and temperatures, but also respond to changes in environmental conditions by emigrating from the area (Herrnkind et al. 1997; Butler 2009). Postlarval lobsters also avoid water masses of low (<30 psu) or high (>45 psu) salinity during

Table 4 HSI statistics for Spotted Seatrout

Basin	Statistic	Sparkline	SL0	SL+	SL+	SL+	SL+	SL0	SL+	SL+	SL+	SL+
			EVPO	EVPO	EVP+	EVP+	EVP+	EVPO	EVPO	EVP+	EVP+	EVP+
			RF0	RF0	RF0	RF+	RF-	RF0	RF0	RF0	RF+	RF-
			TO	TO	TO	TO	TO	T+	T+	T+	T+	T+
Florida Bay	Mean		0.164	0.136	0.131	0.141	0.121	0.184	0.154	0.149	0.160	0.138
	Median		0.106	0.074	0.071	0.079	0.067	0.128	0.100	0.094	0.103	0.088
	Std. Dev.		0.166	0.150	0.145	0.155	0.135	0.172	0.157	0.152	0.162	0.143
Sampling region	Mean		0.128	0.105	0.102	0.108	0.097	0.143	0.119	0.116	0.123	0.110
	Median		0.059	0.052	0.051	0.053	0.050	0.069	0.069	0.067	0.071	0.066
	Std. Dev.		0.157	0.128	0.125	0.131	0.118	0.166	0.137	0.135	0.141	0.128
West	Mean		0.091	0.085	0.083	0.087	0.078	0.105	0.098	0.095	0.100	0.090
	Median		0.051	0.046	0.045	0.046	0.044	0.063	0.064	0.063	0.063	0.061
	Std. Dev.		0.110	0.098	0.096	0.102	0.090	0.119	0.107	0.104	0.110	0.098
East in-shore	Mean		0.553	0.407	0.395	0.419	0.369	0.591	0.445	0.432	0.456	0.404
	Median		0.632	0.239	0.216	0.261	0.180	0.693	0.331	0.302	0.375	0.252
	Std. Dev.		0.405	0.405	0.400	0.409	0.389	0.395	0.406	0.403	0.410	0.392
West in-shore	Mean		0.272	0.187	0.179	0.196	0.163	0.289	0.202	0.194	0.212	0.176
	Median		0.056	0.066	0.061	0.065	0.057	0.080	0.074	0.068	0.077	0.061
	Std. Dev.		0.337	0.248	0.242	0.258	0.225	0.343	0.254	0.248	0.264	0.231
East	Mean		0.305	0.241	0.228	0.252	0.205	0.345	0.275	0.260	0.287	0.234
	Median		0.120	0.095	0.087	0.100	0.080	0.183	0.132	0.122	0.138	0.111
	Std. Dev.		0.338	0.289	0.278	0.300	0.254	0.347	0.301	0.291	0.313	0.267

All statistics are calculated across time. For regions, values were first spatially averaged, weighting each contributing basin value by the area of the respective basin. Sparkline mini-plots show the relative trend across values in each row, normalized to the range of that row

Table 5 HSI statistics for Gray Snapper

Basin	Statistic	Sparkline	SL0	SL+	SL+	SL+	SL+	SL0	SL+	SL+	SL+	SL+
			EVPO	EVPO	EVP+	EVP+	EVP+	EVPO	EVPO	EVP+	EVP+	EVP+
			RF0	RF0	RF0	RF+	RF-	RF0	RF0	RF0	RF+	RF-
			T0	T0	T0	T0	T0	T+	T+	T+	T+	T+
Florida Bay	Mean		0.111	0.114	0.115	0.113	0.116	0.113	0.116	0.117	0.116	0.119
	Median		0.118	0.122	0.123	0.121	0.125	0.114	0.117	0.118	0.116	0.120
	Std. Dev.		0.040	0.040	0.040	0.040	0.040	0.034	0.033	0.033	0.033	0.033
Sampling region	Mean		0.119	0.119	0.119	0.119	0.120	0.121	0.121	0.122	0.121	0.122
	Median		0.128	0.130	0.131	0.130	0.131	0.122	0.124	0.125	0.124	0.126
	Std. Dev.		0.039	0.040	0.040	0.040	0.040	0.032	0.033	0.033	0.033	0.033
West	Mean		0.120	0.119	0.120	0.119	0.121	0.123	0.122	0.123	0.122	0.123
	Median		0.131	0.131	0.132	0.131	0.132	0.126	0.126	0.127	0.126	0.128
	Std. Dev.		0.040	0.040	0.040	0.040	0.041	0.033	0.032	0.033	0.033	0.033
East in-shore	Mean		0.059	0.082	0.084	0.080	0.088	0.061	0.085	0.087	0.083	0.091
	Median		0.046	0.078	0.081	0.074	0.088	0.046	0.081	0.085	0.078	0.091
	Std. Dev.		0.051	0.050	0.050	0.051	0.050	0.052	0.050	0.050	0.050	0.048
West in-shore	Mean		0.110	0.118	0.119	0.117	0.121	0.112	0.119	0.120	0.118	0.122
	Median		0.113	0.121	0.123	0.121	0.125	0.111	0.116	0.117	0.116	0.120
	Std. Dev.		0.041	0.038	0.038	0.038	0.038	0.039	0.035	0.035	0.035	0.034
East	Mean		0.091	0.101	0.103	0.100	0.106	0.092	0.103	0.105	0.102	0.108
	Median		0.090	0.101	0.104	0.099	0.110	0.093	0.102	0.105	0.100	0.109
	Std. Dev.		0.049	0.044	0.044	0.045	0.044	0.047	0.040	0.040	0.041	0.039

All statistics are calculated across time. For regions, values were first spatially averaged, weighting each contributing basin value by the area of the respective basin. Sparkline mini-plots show the relative trend across values in each row, normalized to the range of that row

their onshore migration from the open sea (Goldstein and Butler 2009). For our modeling analysis, we focused on the lethal effects of changing salinity and temperature on the survival of benthic juvenile lobsters in Florida Bay, rather than the sublethal effects on lobster emigration and growth that are not captured by our HSI modeling. Therefore, weekly survival data from Field and Butler (1994) were used to derive a function describing the monthly relationship of survival (P_s) to salinity (S) and temperature (T):

$$P_s = 123.6e^{-\frac{1}{2} \left(\left(\frac{T-24.39}{5.565} \right)^2 + \left(\frac{S-35.31}{8.587} \right)^2 \right)} \tag{1}$$

We use this equation as our HSI model for juvenile lobster.

Results



















Salinity Under Changing Climate

Modeled salinity values of basins in Florida Bay, when averaged over time across the entire 36-year timeseries of monthly mean output values for each individual basin, resulted in temporal mean values ranging from

approximately 21.05 to 37.04 psu, with standard deviations over time ranging from 1.04 to 13.17 psu. To simplify the presentation of our results, we have categorized the basins into four groups: east, west, east inshore, and west inshore (see supplemental material for details of the clustering procedure). The western basins, which cover the most area of the four groups, are characterized by the highest mean salinity values (36.16 psu) and lowest temporal variability ($\sigma^2 = 2.09$ psu) under baseline conditions. The eastern basins are fresher and more variable than the western region, with a mean and SD of 32.45 and 6.18, respectively. The western inshore basins cluster around the mouth of McCormick Creek; they also have high mean salinity (35.45 psu), but higher temporal variability ($\sigma^2 = 6.51$ psu). Finally, the eastern inshore group is located closest to where Trout Creek and the Taylor River deliver the majority of the freshwater input to the estuary, and show the lowest mean (25.59 psu) and highest SD (10.12 psu) of all the regions under baseline conditions (Fig. 2).

Three of the variables manipulated by our climate change scenarios, including sea level (SL), evaporation rate (EVP), and rainfall/runoff (RF), affect the resulting salinity of

Table 6 HSI statistics for Goldspotted Killifish

Basin	Statistic	Sparkline	SLO	SL+	SL+	SL+	SL+	SLO	SL+	SL+	SL+	SL+
			EVPO	EVPO	EVP+	EVP+	EVP+	EVPO	EVPO	EVP+	EVP+	EVP+
			RF0	RF0	RF0	RF+	RF-	RF0	RF0	RF0	RF+	RF-
			T0	T0	T0	T0	T0	T+	T+	T+	T+	T+
Florida Bay	Mean		0.243	0.214	0.227	0.212	0.244	0.216	0.185	0.197	0.183	0.213
	Median		0.137	0.104	0.115	0.100	0.137	0.107	0.080	0.087	0.076	0.106
	Std. Dev.		0.259	0.245	0.253	0.245	0.259	0.243	0.226	0.234	0.226	0.241
Sampling region	Mean		0.282	0.240	0.248	0.238	0.258	0.254	0.208	0.216	0.207	0.225
	Median		0.167	0.117	0.127	0.117	0.141	0.129	0.090	0.096	0.088	0.107
	Std. Dev.		0.293	0.273	0.277	0.274	0.280	0.279	0.253	0.257	0.254	0.261
West	Mean		0.263	0.233	0.243	0.231	0.255	0.230	0.198	0.207	0.197	0.219
	Median		0.169	0.131	0.144	0.129	0.160	0.132	0.099	0.108	0.097	0.122
	Std. Dev.		0.267	0.253	0.258	0.253	0.261	0.248	0.230	0.236	0.231	0.240
East in-shore	Mean		0.106	0.123	0.140	0.119	0.165	0.099	0.113	0.130	0.109	0.154
	Median		0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.001
	Std. Dev.		0.242	0.244	0.259	0.243	0.275	0.231	0.232	0.247	0.231	0.263
West in-shore	Mean		0.335	0.259	0.278	0.257	0.301	0.320	0.234	0.253	0.233	0.274
	Median		0.052	0.041	0.054	0.038	0.080	0.038	0.030	0.039	0.027	0.058
	Std. Dev.		0.407	0.337	0.348	0.339	0.356	0.401	0.320	0.332	0.322	0.341
East	Mean		0.181	0.158	0.180	0.154	0.212	0.171	0.144	0.165	0.140	0.195
	Median		0.003	0.008	0.016	0.006	0.038	0.002	0.006	0.011	0.004	0.028
	Std. Dev.		0.294	0.259	0.273	0.259	0.285	0.285	0.246	0.261	0.246	0.274

All statistics are calculated across time. For regions, values were first spatially averaged, weighting each contributing basin value by the area of the respective basin. Sparkline mini-plots show the relative trend across values in each row, normalized to the range of that row

Florida Bay. Table 2 shows the temporal mean, median, and SD of salinity values in each basin group under each of the five scenarios that modify these three variables; the corresponding statistics for each individual basin can be found in the supplementary material, in Table S2. Increased sea level leads to increased mixing between basins and the coastal ocean, bringing the salinity of highly saline central basins down and that of the fresher eastern basins up; the net effect is a small increase (+0.343 psu mean, +0.534 psu median) in the bay-wide spatially averaged salinity and a decrease in temporal variability. Bay-wide SD decreases from 3.28 to 2.42 psu under these conditions, primarily due to a decrease in the frequency and duration of low salinity events. The effects of increasing evaporation rate and decreasing rainfall on salinity are similar in direction to that of sea level rise, increasing the spatially averaged mean and decreasing spatially averaged variability, but the magnitude of these changes is much smaller than those induced by sea level rise.

Spatially, the salinity changes are concentrated in those basins located closer to the shore and, consequently, to the freshwater input locations. These basins show increases in

temporal mean of 7–8 psu and decreases in temporal SD of 4–5 psu. However, the basins located in the western portion of the bay, which include the juvenile fish sampling region basins, show much smaller responses, with changes in mean and SD on the order of 0.1 psu or less.



















Habitat Change Under Changing Temperature and Salinity

The final HSI model equations for each of the juvenile fish species are described in Table 3, with a visualization of the regression models and the underlying data available in Fig. 3.

The HSI values resulting when these equations, along with (1), are applied to the output of the 10 different FATHOM scenarios are presented in Tables S3 to S9 ; summary statistics for the basin groups are shown in Tables 4, 5, 6, 7, 8, 9 and 10.

The climate scenarios led to relatively small changes in HSI values across the bay, particularly in the western basins, where the majority of the sampling region is located

Table 7 HSI statistics for Rainwater Killifish

Basin	Statistic	Sparkline	SLO	SL+	SL+	SL+	SL+	SLO	SL+	SL+	SL+	SL+
			EVPO	EVPO	EVP+	EVP+	EVP+	EVPO	EVPO	EVP+	EVP+	EVP+
			RF0	RF0	RF0	RF+	RF-	RF0	RF0	RF0	RF+	RF-
			T0	T0	T0	T0	T0	T+	T+	T+	T+	T+
Florida Bay	Mean		0.539	0.561	0.567	0.557	0.578	0.526	0.547	0.554	0.543	0.564
	Median		0.523	0.537	0.543	0.533	0.551	0.519	0.541	0.545	0.538	0.552
	Std. Dev.		0.210	0.214	0.213	0.216	0.209	0.186	0.188	0.187	0.189	0.185
Sampling region	Mean		0.588	0.597	0.600	0.595	0.605	0.576	0.585	0.588	0.582	0.594
	Median		0.575	0.576	0.580	0.577	0.586	0.561	0.573	0.579	0.569	0.586
	Std. Dev.		0.223	0.213	0.212	0.215	0.209	0.197	0.189	0.188	0.190	0.186
West	Mean		0.609	0.610	0.614	0.608	0.619	0.597	0.598	0.601	0.596	0.607
	Median		0.588	0.580	0.584	0.579	0.590	0.589	0.587	0.591	0.586	0.597
	Std. Dev.		0.206	0.204	0.203	0.205	0.200	0.182	0.180	0.179	0.181	0.177
East in-shore	Mean		0.225	0.334	0.346	0.325	0.368	0.206	0.309	0.322	0.300	0.346
	Median		0.087	0.263	0.294	0.248	0.341	0.091	0.265	0.294	0.252	0.340
	Std. Dev.		0.275	0.311	0.313	0.312	0.312	0.253	0.280	0.282	0.280	0.282
West in-shore	Mean		0.503	0.555	0.564	0.548	0.579	0.497	0.553	0.563	0.546	0.579
	Median		0.535	0.563	0.569	0.565	0.578	0.535	0.560	0.572	0.554	0.588
	Std. Dev.		0.297	0.247	0.245	0.253	0.236	0.275	0.223	0.221	0.228	0.214
East	Mean		0.371	0.442	0.457	0.433	0.480	0.355	0.423	0.439	0.414	0.463
	Median		0.362	0.443	0.459	0.435	0.490	0.357	0.447	0.468	0.440	0.491
	Std. Dev.		0.279	0.273	0.270	0.277	0.261	0.262	0.247	0.245	0.251	0.237

All statistics are calculated across time. For regions, values were first spatially averaged, weighting each contributing basin value by the area of the respective basin. Sparkline mini-plots show the relative trend across values in each row, normalized to the range of that row

(Figs. 4, 5). Because the absolute changes are small, and the HSI ranges vary widely between species, we chose to quantify some of our analysis in terms of quantile values based on the baseline conditions in the sampling region. Cumulative distribution functions of area vs HSI value were calculated across all baseline output values (i.e., 432 time steps and 16 sampling basins) and then divided into quartiles. For the remainder of this paper, these quartile intervals will be used to define poor (first quartile), fair (second quartile), good (third quartile), and optimal (upper quartile) habitat.



















The effect of the climate scenarios varied in both magnitude and direction across the seven species (Table 11; Fig. 6). Within the sampling region, optimal habitat for spotted seatrout is predicted to decrease under the salinity-altered-only scenarios but increased under the temperature-altered-only scenario, with the combined effect leading to a decrease of -4.58 km^2 (3.4 % change). The mojarra also saw opposite effects from salinity and temperature, with the salinity alterations leading to an increase in optimal habitat and the temperature increase leading to a decrease. Like the seatrout, the combined

effect resulted in a decrease in optimal habitat for mojarra. Juvenile lobster benefited most strongly of all the species from the changing salinity characteristics; lobsters are predicted to experience a small decrease in optimal habitat under the temperature only scenario, but an increase of at least 20 km^2 (a 10–13 % increase) in all other scenarios. Gray snapper may see only a small decrease in optimal habitat as a result of salinity alterations, but lose between 15.4 and 16.99 km^2 under the temperature-altering scenarios. The remaining species (goldspotted killifish, rainwater killifish, and pinfish) lose optimal habitat as a result of both the salinity and temperature alterations.

We also examined the shifts in seasonal habitat availability under various scenarios. Figure 7 depicts the quartile distribution, averaged over each month, under the scenarios that provided the best (i.e., largest increase or smallest decrease in yearly-averaged optimal habitat area) and worst (i.e., largest decrease or smallest increase in optimal habitat) scenario.

The juvenile fish sampling design aims to effectively sample the period of the year with optimal abundances of juvenile spotted seatrout, which are typically found from

Table 8 HSI statistics for Mojarra

Basin	Statistic	Sparkline	SLO	SL+	SL+	SL+	SL+	SLO	SL+	SL+	SL+	SL+
			EVPO	EVPO	EVP+	EVP+	EVP+	EVPO	EVPO	EVP+	EVP+	EVP+
			RF0	RF0	RF0	RF+	RF-	RF0	RF0	RF0	RF+	RF-
			TO	TO	TO	TO	TO	T+	T+	T+	T+	T+
Florida Bay	Mean		0.918	0.939	0.941	0.936	0.945	0.884	0.900	0.904	0.897	0.911
	Median		0.977	0.990	0.989	0.990	0.988	0.967	0.981	0.979	0.980	0.979
	Std. Dev.		0.116	0.097	0.093	0.101	0.085	0.164	0.151	0.145	0.155	0.135
Sampling region	Mean		0.917	0.949	0.950	0.947	0.953	0.889	0.916	0.918	0.913	0.923
	Median		0.964	0.990	0.990	0.990	0.990	0.960	0.984	0.985	0.984	0.985
	Std. Dev.		0.108	0.081	0.079	0.084	0.074	0.151	0.131	0.128	0.135	0.121
West	Mean		0.958	0.965	0.966	0.964	0.968	0.930	0.936	0.938	0.934	0.942
	Median		0.986	0.993	0.993	0.993	0.992	0.979	0.987	0.987	0.987	0.987
	Std. Dev.		0.064	0.055	0.053	0.057	0.049	0.110	0.102	0.098	0.105	0.092
East in-shore	Mean		0.705	0.788	0.791	0.780	0.803	0.661	0.726	0.732	0.720	0.745
	Median		0.965	0.982	0.977	0.981	0.975	0.914	0.965	0.962	0.962	0.960
	Std. Dev.		0.390	0.330	0.323	0.338	0.307	0.415	0.384	0.378	0.390	0.364
West in-shore	Mean		0.753	0.875	0.879	0.868	0.890	0.726	0.824	0.831	0.816	0.845
	Median		0.886	0.982	0.980	0.980	0.980	0.877	0.975	0.975	0.974	0.976
	Std. Dev.		0.297	0.211	0.205	0.220	0.190	0.327	0.268	0.261	0.277	0.245
East	Mean		0.867	0.899	0.904	0.893	0.914	0.809	0.834	0.842	0.826	0.858
	Median		0.982	0.990	0.988	0.989	0.987	0.969	0.979	0.976	0.978	0.977
	Std. Dev.		0.228	0.181	0.173	0.191	0.154	0.300	0.267	0.256	0.278	0.233

All statistics are calculated across time. For regions, values were first spatially averaged, weighting each contributing basin value by the area of the respective basin. Sparkline mini-plots show the relative trend across values in each row, normalized to the range of that row

May through October (Kelble et al. 2013a). Despite this weakness, the HSIs predicted seasonal peaks in habitat quality that correlated well with observational data for spotted seatrout, snapper, mojarra, and pinfish throughout Florida Bay (Powell et al. 2007). The HSI models were not as good at reproducing seasonal distributions of rainwater killifish and goldspotted killifish. In the case of goldspotted killifish, this weakness could result from the model being parameterized with data from west and north-central Florida Bay, whereas the peak densities of gold spotted killifish are observed in northeastern Florida Bay.



















The climate change scenarios resulted in an extension of the seasonal distributions of good habitat for gray snapper and spotted seatrout. However, these benefits will only be realized by the populations of gray snapper and spotted seatrout if their spawning season encompasses these months in which habitat suitability improved. For spotted seatrout, spawning occurs from March through October in Florida Bay, and there is a sufficient density of larval spotted seatrout under current conditions for the improvements in habitat suitability predicted in April and November to likely result in an increase in the population (Powell 2003). Spawning habits of the other species are not

well-documented enough in Florida Bay to enable insights into whether the changes in habitat quality predicted under climate change would also require a change in spawning patterns to allow for juveniles to be present in the system when habitat conditions are optimal.

Discussion

The practice of adaptive management calls for managers to rely on science to reduce uncertainty, and thus provide alternative management strategies with reduced variability. Yet, some problems, such as that of managing ecosystem resources under changing climate conditions, are often left unexplored due to the inherent high uncertainties. Conditions that may emerge under a changing climate provide a suite of ambiguities that have been difficult to integrate into existing terrestrial, coastal, and marine planning efforts, despite the recognition by many managers that the changing conditions are real. In this respect, scenario planning has emerged as a useful approach for envisioning potential alternative futures under conditions of high

Table 9 HSI Statistics for Pinfish

Basin	Statistic	Sparkline	SLO	SL+	SL+	SL+	SL+	SLO	SL+	SL+	SL+	SL+
			EVPO	EVPO	EVP+	EVP+	EVP+	EVPO	EVPO	EVP+	EVP+	EVP+
			RF0	RF0	RF0	RF+	RF-	RF0	RF0	RF0	RF+	RF-
			TO	TO	TO	TO	TO	T+	T+	T+	T+	T+
Florida Bay	Mean		0.488	0.485	0.498	0.480	0.516	0.440	0.431	0.444	0.427	0.462
	Median		0.484	0.467	0.490	0.460	0.524	0.416	0.382	0.404	0.374	0.432
	Std. Dev.		0.303	0.312	0.312	0.313	0.310	0.302	0.308	0.310	0.309	0.310
Sampling region	Mean		0.548	0.527	0.535	0.525	0.546	0.498	0.470	0.478	0.469	0.489
	Median		0.578	0.541	0.556	0.539	0.576	0.496	0.437	0.451	0.436	0.470
	Std. Dev.		0.335	0.334	0.333	0.335	0.330	0.337	0.331	0.331	0.333	0.330
West	Mean		0.557	0.541	0.550	0.538	0.564	0.499	0.479	0.489	0.477	0.501
	Median		0.587	0.550	0.568	0.543	0.591	0.490	0.446	0.464	0.441	0.487
	Std. Dev.		0.314	0.316	0.315	0.318	0.311	0.316	0.316	0.316	0.317	0.313
East in-shore	Mean		0.194	0.264	0.283	0.258	0.311	0.179	0.241	0.260	0.235	0.287
	Median		0.001	0.030	0.047	0.024	0.080	0.001	0.020	0.032	0.016	0.061
	Std. Dev.		0.319	0.348	0.356	0.347	0.363	0.306	0.331	0.340	0.331	0.348
West in-shore	Mean		0.500	0.480	0.497	0.475	0.521	0.473	0.437	0.454	0.434	0.477
	Median		0.455	0.440	0.485	0.430	0.538	0.375	0.343	0.382	0.331	0.433
	Std. Dev.		0.419	0.385	0.385	0.389	0.380	0.418	0.380	0.381	0.383	0.378
East	Mean		0.305	0.334	0.359	0.327	0.395	0.279	0.300	0.325	0.294	0.359
	Median		0.127	0.193	0.241	0.170	0.322	0.094	0.141	0.186	0.124	0.261
	Std. Dev.		0.354	0.346	0.350	0.348	0.348	0.341	0.331	0.336	0.332	0.337

All statistics are calculated across time. For regions, values were first spatially averaged, weighting each contributing basin value by the area of the respective basin. Sparkline mini-plots show the relative trend across values in each row, normalized to the range of that row

uncertainty and high impacts (Schoemaker 1995). Under this approach, managers can visualize a suite of potential future outcomes and develop adaptation strategies to deal with them.

The scenarios we examined bracket the expected future conditions, and thus provide a framework for managers to examine responses of species under different conditions. When a species is projected to respond similarly under varying scenarios, strategies are simpler to envision and craft. Alternatively, when a species response is different under different projected outcomes, the adaptation strategies may become divergent.



















Climate change will not be detrimental to all species, and there are likely to be winners and losers, as well as some species and some areas that show minimal impact (Somero 2010; Loya et al. 2001; Fabricius et al. 2011; Fulton 2011). In this study, goldspotted killifish and pinfish appear to be the only clear losers in all scenarios, with both species showing a greater than 15 % decrease in optimal habitat under all scenarios (Table 11). Rainwater killifish also lose optimal habitat under all scenarios, though their combined

good plus optimal habitat is relatively unchanged under all potential changes. Habitat for juvenile lobsters increased under all of the climate change scenarios except the temperature increase-only scenario, whereas habitat suitability for the remaining species varied between improved or degraded conditions in the different scenarios.

Temperature increases alone negatively affected the availability of optimal habitat for all species, except that of juvenile spotted seatrout. This is likely because many of the species are already living near their thermal optimum. The impact of sea level rise and the other variables that affected salinity was less clear. Both mojarra and lobster benefited from the expansion of their optimal habitat and a decrease of their poor habitat areas. The middle quartiles of habitat suitability expanded for all of the other species, whereas their areas of both optimal and poor habitat declined to varying degrees (Fig. 6).

Scenarios with both salinity and temperature changes resulted in varying responses among the species. Salinity had little effect on the habitat suitability distributions of spotted seatrout and remained very similar to those where

Table 10 HSI statistics for juvenile lobster

Basin	Statistic	Sparkline	SL0	SL+	SL+	SL+	SL+	SLO	SL+	SL+	SL+	SL+
			EVPO	EVPO	EVP+	EVP+	EVP+	EVPO	EVPO	EVP+	EVP+	EVP+
			RF0	RF0	RF0	RF+	RF-	RF0	RF0	RF0	RF+	RF-
			T0	T0	T0	T0	T0	T+	T+	T+	T+	T+
Florida Bay	Mean		0.601	0.655	0.655	0.652	0.657	0.547	0.594	0.594	0.591	0.596
	Median		0.717	0.797	0.797	0.792	0.805	0.655	0.729	0.729	0.729	0.743
	Std. Dev.		0.325	0.347	0.348	0.346	0.349	0.371	0.397	0.397	0.398	0.396
Sampling region	Mean		0.637	0.683	0.682	0.682	0.682	0.579	0.617	0.616	0.616	0.616
	Median		0.767	0.850	0.849	0.850	0.850	0.721	0.787	0.787	0.786	0.787
	Std. Dev.		0.341	0.358	0.358	0.358	0.358	0.388	0.407	0.407	0.407	0.407
West	Mean		0.677	0.696	0.695	0.695	0.694	0.615	0.631	0.631	0.630	0.630
	Median		0.843	0.894	0.889	0.894	0.887	0.814	0.839	0.844	0.834	0.851
	Std. Dev.		0.351	0.357	0.357	0.357	0.358	0.402	0.409	0.409	0.409	0.410
East in-shore	Mean		0.289	0.441	0.442	0.431	0.453	0.271	0.410	0.411	0.401	0.419
	Median		0.114	0.280	0.289	0.268	0.326	0.070	0.205	0.229	0.191	0.256
	Std. Dev.		0.330	0.394	0.389	0.394	0.382	0.333	0.410	0.406	0.409	0.402
West in-shore	Mean		0.452	0.616	0.614	0.612	0.616	0.411	0.547	0.545	0.544	0.546
	Median		0.372	0.871	0.863	0.859	0.858	0.218	0.560	0.561	0.557	0.564
	Std. Dev.		0.377	0.403	0.402	0.403	0.402	0.397	0.432	0.432	0.432	0.431
East	Mean		0.441	0.571	0.574	0.560	0.584	0.403	0.518	0.520	0.509	0.529
	Median		0.304	0.637	0.629	0.607	0.658	0.254	0.463	0.491	0.451	0.545
	Std. Dev.		0.359	0.365	0.364	0.367	0.361	0.380	0.403	0.403	0.404	0.401

All statistics are calculated across time. For regions, values were first spatially averaged, weighting each contributing basin value by the area of the respective basin. Sparkline mini-plots show the relative trend across values in each row, normalized to the range of that row

temperature alone increased. Salinity and temperature effects appear to cancel out one another in the response of mojarra to the scenarios incorporating both factors, with habitat suitability distributions slightly worse than the baseline scenario. Gray snapper and rainwater killifish both experienced an expansion of the middle quartiles and decrease in optimal and poor habitat quartiles for the scenarios with both salinity and temperature changes compared to the baseline scenario and the scenarios that only adjusted salinity or temperature. Optimal habitat for lobsters increased in response to salinity changes, but poor habitat area increased in response to temperature. The responses with both temperature and salinity reflected this as an expansion of both poor and optimal habitat and a contraction of fair and good habitat (Fig. 6).

In some cases, the effect of climate change was most pronounced during months that are currently just outside the period when a species is most likely to be observed. For example, *C. nebulosus* experience expansions of habitat in both April and October in the SL+_EVP+_RF+_T+ scenario, while currently the timing of their spawning

season leads to most juvenile *C. nebulosus* being observed from May through October. This may indicate that some scenarios will expand the recruitment season for juvenile spotted seatrout or other species. This expansion of recruitment is likely for November, because juvenile *C. nebulosus* are currently observed at high frequencies in November in some areas of Florida Bay, if conditions are near optimal (Kelble et al. 2013a). However, the temporal distribution may be limited by the timing of spawning that may or may not undergo a phenological shift as a result of changes in physical habitat.

Areas of Florida Bay that are forecast to change habitat quality in response to climate change may be inaccessible to the juveniles for the species of interest (Fig. 4). However, sea level rise may provide the additional benefit of making more areas of Florida Bay accessible to these juveniles. Lobsters, in particular, are likely to benefit due to sea level increase because habitats that are currently inaccessible due to physical barriers associated with the banks within Florida Bay (Field and Butler 1994) may overwash with increasing frequency. This may facilitate

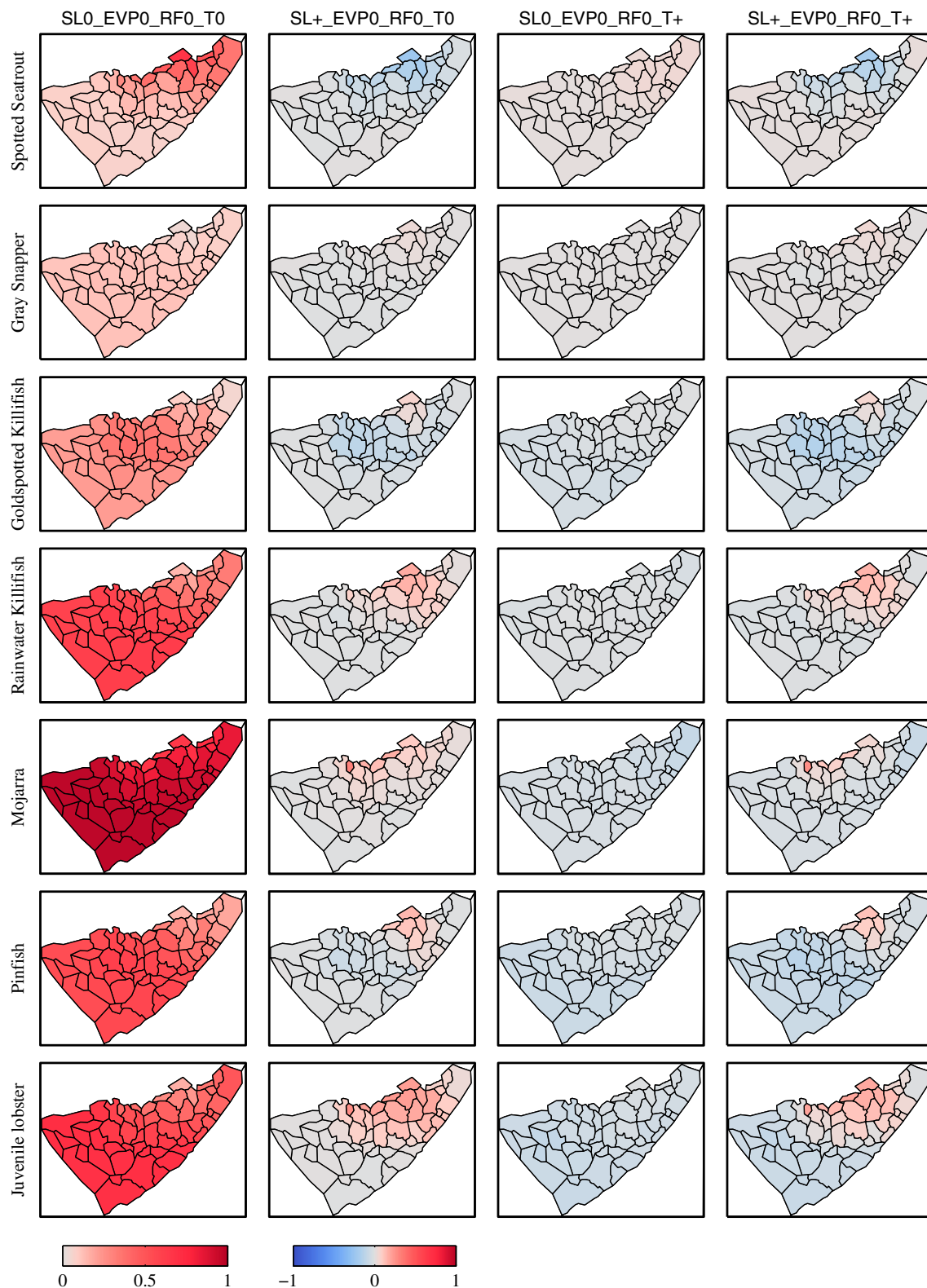


Fig. 4 Change in spatial distribution of mean HSI values. The *first* column of plots shows the mean HSI values in each basin under the baseline conditions. The *remaining three* columns show the change

between that scenario and the increased sea level only, increased temperature only, and increased sea level and temperature scenarios

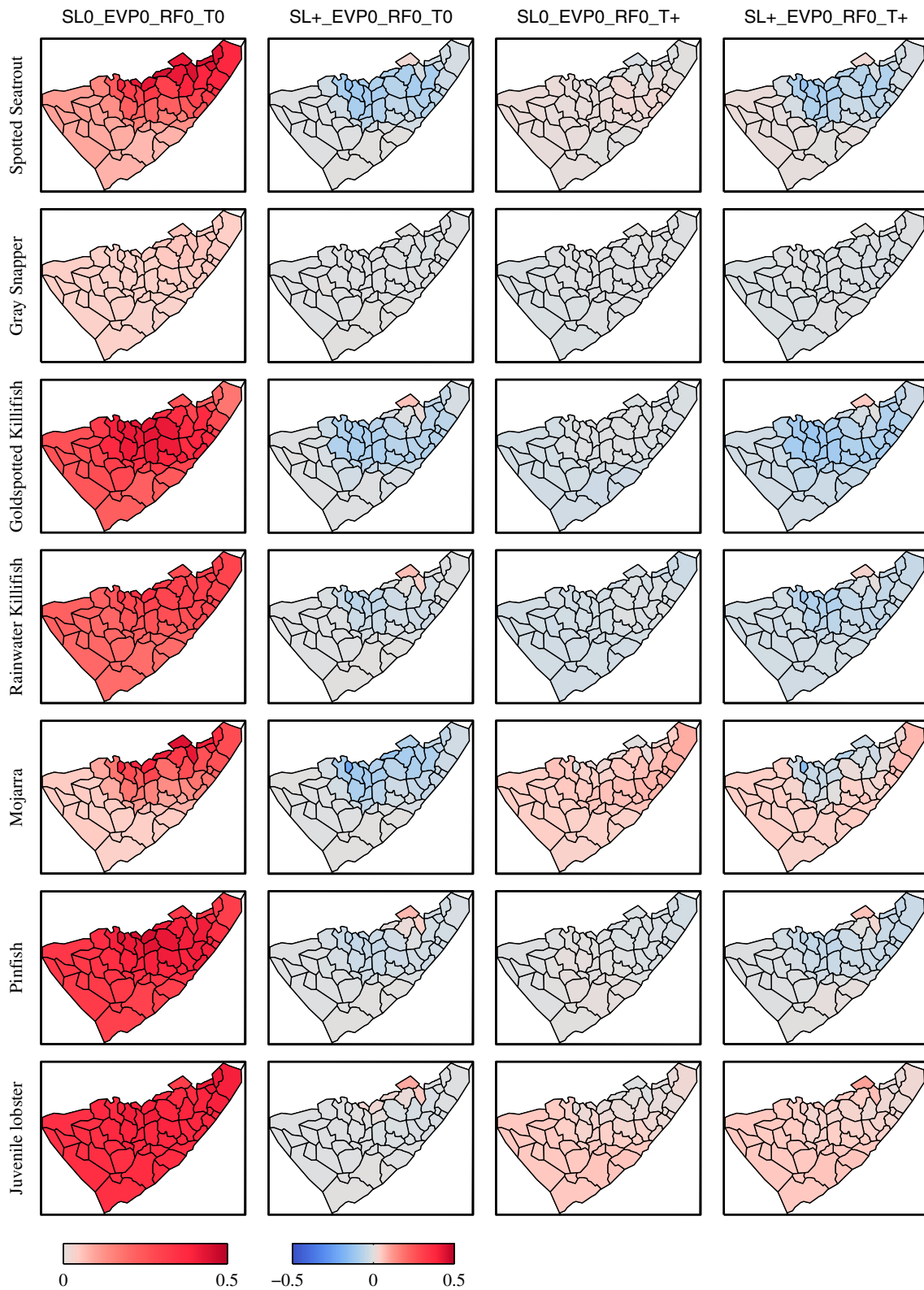


Fig. 5 Change in spatial distribution of SD of HSI values, arranged as in previous figure

Fig. 6 Change in mean yearly distribution of sampling region area (totaling 535.86 km²) between the four quartiles, with *dark orange*, *light orange*, *light purple*, and *dark purple* representing poor, fair, good, and optimal habitat, respectively. The *dotted gray line* indicates the 50 % mark, for reference

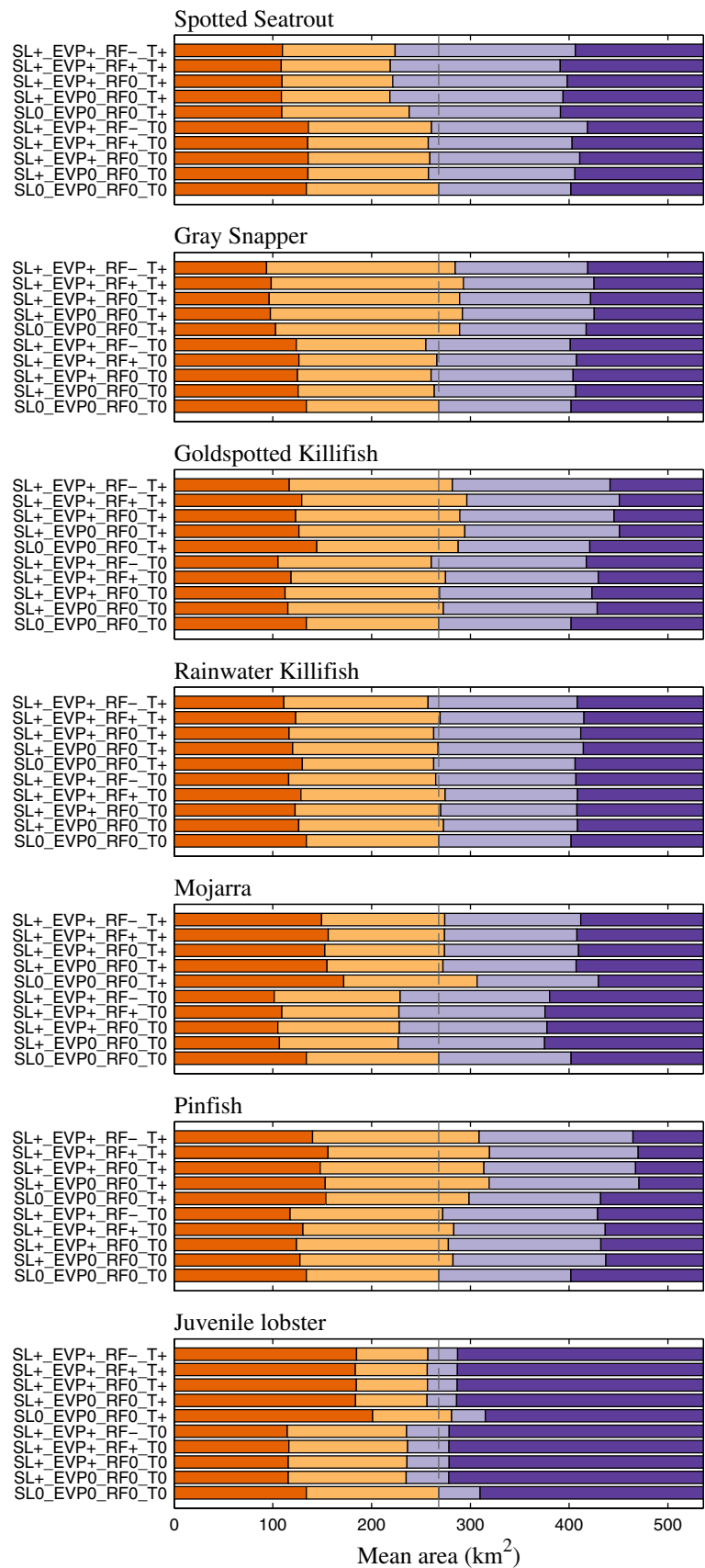


Table 11 Change in optimal habitat area, in km²

	Spotted Seatrout (134.17)	Gray Snapper (133.98)	Goldspotted Killifish (133.98)	Rainwater Killifish (133.98)	Mojarra (133.97)	Pinfish (134.17)	Juvenile lobster (226.13)
SL+_EVP0_RF0_T0	−4.21	−4.83	−26.58	−6.50	26.82	−35.54	31.59
SL+_EVP+_RF0_T0	−8.92	−2.07	−21.28	−5.98	24.29	−30.31	31.29
SL+_EVP+_RF+_T0	−1.37	−5.60	−27.54	−6.67	26.44	−34.91	31.36
SL+_EVP+_RF−_T0	−16.96	0.71	−15.48	−5.02	21.78	−27.01	31.16
SLO_EVP0_RF0_T+	10.58	−15.40	−19.03	−4.13	−27.70	−30.14	−5.38
SL+_EVP0_RF0_T+	7.82	−23.36	−49.13	−12.49	−5.04	−69.05	23.79
SL+_EVP+_RF0_T+	3.68	−19.85	−43.55	−9.85	−7.54	−65.60	23.06
SL+_EVP+_RF+_T+	10.80	−23.18	−48.95	−13.03	−5.91	−68.09	22.96
SL+_EVP+_RF−_T+	−4.58	−16.98	−39.50	−6.38	−9.86	−62.87	22.60

The number following each species name indicates the yearly-averaged optimal habitat under baseline conditions (SLO_EVP0_RF0_T0), and each table entry indicates the change relative to that value

larval exchange into locations that are currently inaccessible.

The HSI models presented in this paper look at impacts of physical drivers on a single species, and as such do not account for species interactions. For example, fishery species are highly dependent on other organisms, such as seagrass and macroalgae, for habitat, and thus will be affected significantly by how climate change alters those species. Scenarios that alter the density and composition of seagrass beds will likely alter most finfish distributions; likewise, juvenile lobster depend on macroalgae and sponges for habitat (Butler et al. 1997; Butler and Herrkind 1997). Our HSI models also fail to take into consideration predator/prey interactions, either in the initial presence/absence patterns (opposite trends in the predator and prey species with respect to temperature and salinity may arise due to competitive and predatory influences on populations rather than due to the physical environment) or in the predicted change in habitat quality. For example, conditions improve for spotted seatrout under all scenarios that include temperature increase, except one; however, their prey species all show significant decreases under these scenarios. Thus, even as habitat suitability conditions may improve for spotted seatrout in these scenarios, their populations may become limited by prey availability.

The climate change scenarios representing alternative potential futures for Florida Bay resulted in a variety of changes in habitat suitability for the species covered in this study; however, few of these responses were large. In fact, only pinfish showed a greater than 50 % change in optimal habitat under any of the scenarios. This

suggests that the effects of climate change on Florida Bay's estuarine fauna may not be as great as what might be experienced by other components of the ecosystem, particularly the stenohaline and stenothermic taxa that inhabit the freshwater and marine ecotones along the northern and southern boundaries of Florida Bay, respectively. However, this analysis should be considered a first-order approximation of potential species-specific responses to climate change as it is based on a simple correlative model rather than specific mechanisms, and these correlations may well change as species potentially adjust and adapt to previously unseen climate conditions. In addition, this model does not incorporate species interactions and other ecosystem-related factors that will likely influence the response of specific species to climate change.

This exercise is a step toward evaluating potential relative changes in system carrying capacity as mediated by climate-driven changes in habitat quality. As noted above, there are numerous interactions among biotic and abiotic system components that have not been captured here, but that clearly deserve consideration and integration as more data become available and as complementary models (e.g., hydrodynamic, trophic, demographic, human behavioral) become more comprehensive and spatiotemporally resolved. Realistic predictions of how the gamut of climate-related changes in and around Florida Bay will ultimately affect regional patterns of human distribution, freshwater consumption/diversion, watershed development, coastal pollution, and fishing pressure will depend on close collaboration and coordination among a diversity of technical experts.

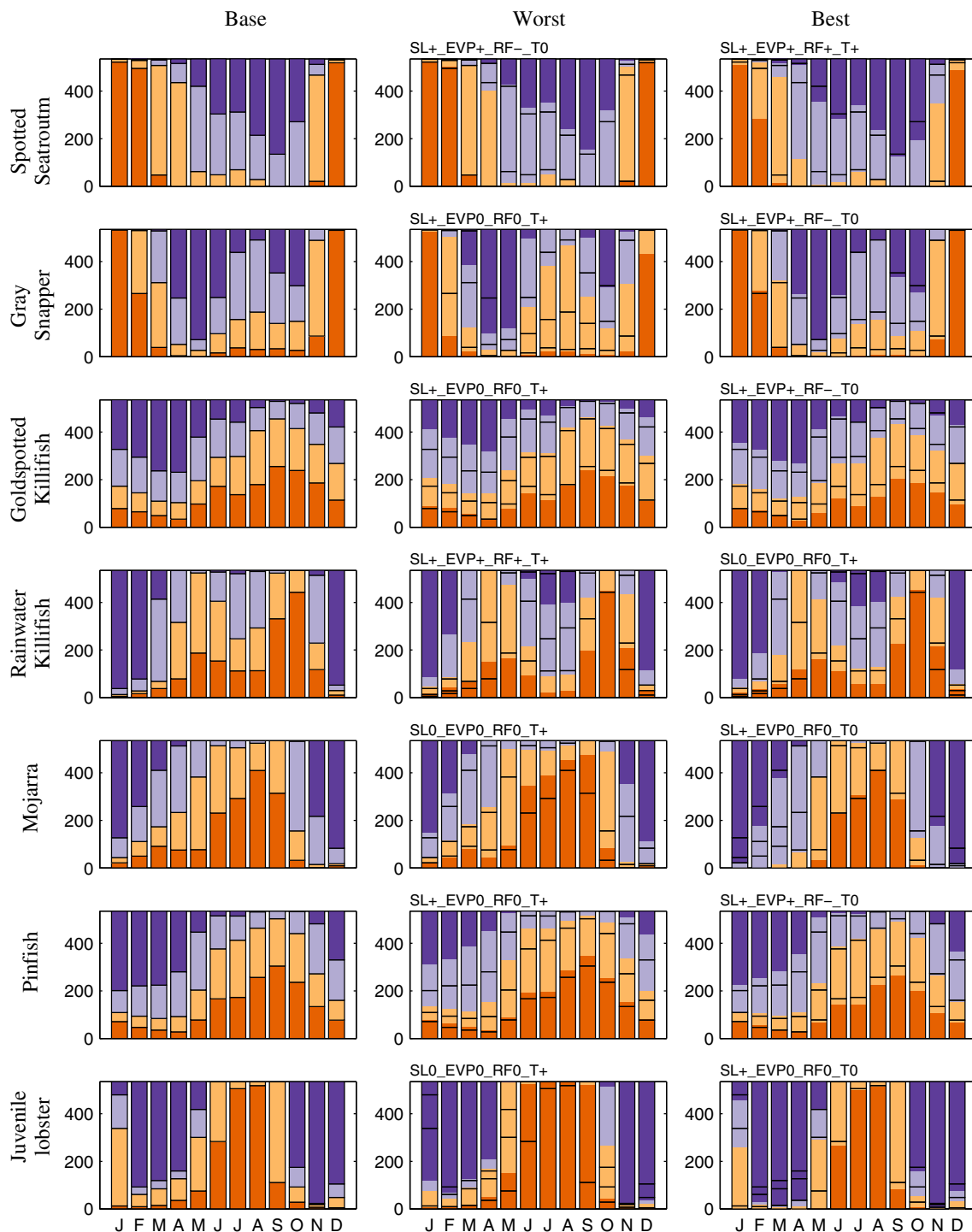


Fig. 7 Seasonal pattern in sampling region area distribution among quartiles under the baseline scenario, the scenario that results in the most habitat lost (or least gained) for each species, and the scenario that results in the most habitat gained for each species. Colors are the

same as Fig. 6, with dark orange, light orange, light purple, and dark purple representing poor, fair, good, and optimal habitat, respectively. The vertical axis represents sampling region area in km²

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