

# Combining data sources to elucidate spatial patterns in recreational catch and effort: fisheries-dependent data and local ecological knowledge applied to the South Florida bonefish fishery

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**Abstract** Spatial data are key to fishery management; however, most often the spatial distribution of marine populations and fishing dynamics are poorly documented, especially for recreational fish species. The combination of fisheries-dependent data (FDD) obtained from logbooks, and local ecological knowledge (LEK) gathered from key stakeholders could be a powerful approach to inform data gaps in data-limited fisheries. In this study, we used both FDD from guides' catch reports and LEK using an online survey and key-informant interviews to reconstruct the spatial changes in bonefish (Albula vulpes) catch and fishing effort throughout South Florida over the past 35-40 years, and better understand the extent and spatial patterns of the bonefish decline described in previous studies. Although anglers perceived a decline of bonefish numbers across all fishing areas (26 to 53% drop across Biscayne Bay, the Florida Keys, and Florida Bay), the start of the bonefish decline in Florida Bay resulted in the highest drop in bonefish number (53%); thus, indicating both regional and localized decline events affecting bonefish abundance. Within Florida Bay, LEK and FDD concurred with an initial drop in bonefish at Inner Bay, followed by a greater magnitude of decline at Outer Bay. Metrics of effort derived from the survey and interviews depicted a shrinkage and aggregation in the spatial distribution of fishing and a shift of fishing activities toward the Lower Keys. In sum, the spatiotemporal patterns of catch and effort obtained from LEK and FDD allowed us to understand where, when and how this data-limited species declined in South Florida.

**Keywords** Recreational fisheries · Local ecological knowledge · Fisheries-dependent data · Spatial analysis

### Introduction

Spatial information is recognized as critical for marine population conservation and fishery management efforts, especially in recent years, as fisheries stock assessment and marine resource management moves toward a more integrated ecosystem approach (Link 2002; Babcock et al. 2005; Saul et al. 2013). For instance, data on the spatial distribution of marine fish populations are necessary for the identification and delineation of stocks and essential fish habitats, the design of marine protected areas, and the identification of vulnerable spawning aggregation areas (Grober-Dunsmore et al. 2009; Hazen et al. 2012; Harford et al. 2015; Nagelkerken et al. 2015). In addition, spatiotemporal information on fishing effort (i.e., when and where anglers are fishing) could facilitate the assessment on how fishing activities track marine populations and the identification of highly-targeted

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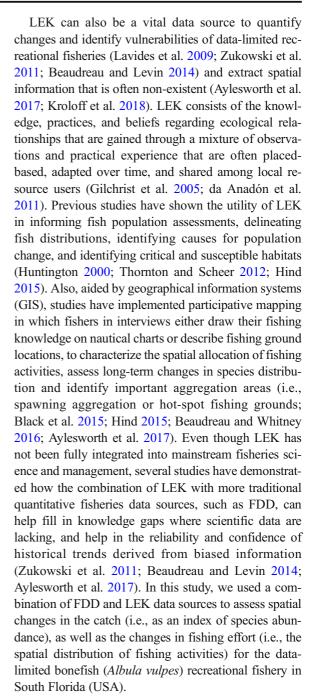
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areas susceptible to ecological impacts associated with fishing (Fonteneau and Richard 2003; Campbell 2004; Beaudreau and Whitney 2016; Aylesworth et al. 2017).

Despite recognition of the importance of spatial data for fishery management, most often the spatial distribution of marine populations, catch rates and fishing activities are poorly documented, especially for recreational fish species (Halpern et al. 2008; Yates and Schoeman 2013; Beaudreau and Whitney 2016). Recreational fisheries are a key economic activity in many coastal communities and primary users of many fish stocks (Coleman et al. 2004; Hughes 2015). Over the last decade, there has been a recognition that recreational fisheries, not unlike commercial and artisanal fisheries, can be subject to stock depletion due to harvest (or fishing mortality), habitat loss and other disturbances, and due to the interactive effects of climate and environmental disturbances and exploitation (Cooke and Cowx 2006; Armstrong and Falk-Petersen 2008; Planque et al. 2010; Post 2013). Thus, there is a need to assess spatiotemporal dynamics in abundance, catch rate, and effort allocation in order to achieve conservation and management outcomes and the long-term sustainability of recreational fisheries (Black et al. 2015; Beaudreau and Whitney 2016; Adams 2017).

Recreational fisheries, particularly catch-and-release, are often data-limited (i.e., lack of availability of stock assessments and biological studies), constraining our ability to conduct assessments from both a spatial and ecosystem perspective (Adams et al. 2014). Challenges remain about the best ways to generate spatial data to achieve conservation outcomes for recreational datalimited fish species (Post 2013; Aylesworth et al. 2017). Fisheries-dependent data (FDD) and local-ecological knowledge (LEK) are two sources of information that can be used to generate spatial assessments (Beaudreau and Levin 2014; Hind 2015; Aylesworth et al. 2017). FDD consist of the catch/landings reported by recreational anglers or commercial fisherman, that it is often used to derive quantitative information about stock status and trends (Maunder and Punt 2004; Cass-Calay and Schmidt 2009; Hind 2015). FDD from mandatory catch return cards, logbooks, sale slips or interviews often constitute the only available data source to inform long-term and spatiotemporal changes of fish abundance (Campbell 2004; Cass-Calay and Schmidt 2009; Winker et al. 2013), especially across varying spatial scales (Campbell 2004; Saul et al. 2013), but may be lacking for recreational fisheries, particularly catch and release.



Sport fishing is a multi-billion-dollar industry in South Florida (e.g., Edwards et al. 2016) where the bonefish fishery is exclusively catch-and-release and forms a key part of a popular flats fishery that focuses on sight fishing in shallow seagrass habitats. It is estimated that the bonefish fishery contributes approximately \$465 million/year to the local economy (Fedler 2013). Despite this high value both locally and



regionally, the availability of stock assessments and bioecological studies are limited, and key data on spawning and recruitment dynamics, habitat use patterns, and life history remain disjointed (i.e., datalimited fishery; Crabtree et al. 1996, 1998; Larkin 2011; Adams et al. 2014). In recent years there has been a pressing need to gather different data sources, reconstruct historical trends and investigate the sustainability of the bonefish fishery in South Florida due to reports pointing to a decline in catch over recent decades (Sosin 2008; Larkin et al. 2010; Frezza and Clem 2015; Santos et al. 2017). Both FDD (Larkin 2011; Santos et al. 2017) and LEK (Larkin et al. 2010; Frezza and Clem 2015; Rehage et al. in this issue) approaches have been used to describe and quantify the negative trend in bonefish catch, especially in Florida Bay, where the greatest decline appears to be happening (Frezza and Clem 2015). Nevertheless, the available LEK and FDD reports on the bonefish decline lack the spatial information needed to better assess whether the observed patterns have occurred regionally (differential trends across areas), localized (concentrated in a subset of areas) or both, which could help identify possible processes behind the decline. In addition, these reports lack a characterization of the spatial distribution of bonefishing activities, and how these may change over time, and a clear comparison between patterns in the bonefish abundance and fishing effort.

In this study, we used both FDD and LEK to reconstruct spatial changes in both bonefish catch and fishing effort (i.e., distribution of fishing grounds) between 1975 and 2015 throughout South Florida. Specifically, we contrast FDD from fishing guide reports and LEK from two survey efforts targeting anglers and guides to assess spatial differences in bonefish catch and effort over time, and examine regional versus localized patterns, especially within Florida Bay. We added emphasis in Florida Bay since coastal environment in the bay, some of which constitute essential habitat for bonefish (i.e., foraging grounds, nursery habitats), have been subject to a series of anthropogenic disturbances that have provoked major state shifts largely associated with altered freshwater deliveries throughout the Everglades watershed (Fourqurean and Robblee 1999; Hall et al. 2016) and with altered circulation patterns due to coastal infrastructure (e.g., roads, bridges, railroad - Rudnick et al. 2005). In addition, we used LEK obtained from key-informant interviews to characterize the spatial details of bonefish effort distribution and how this changed over time (since <1975). We expected to find a greater decline in bonefish catch in Florida Bay in contrast to other bonefish fishing grounds (i.e., localized decline; Frezza and Clem 2015), followed by an overall reduction in the distribution of fishing effort and shift of this effort toward more 'profitable' fishing grounds.

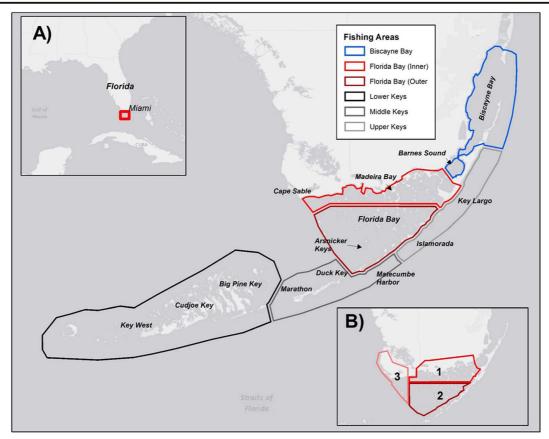
#### Materials and methods

Study domain

We examined the spatiotemporal trends in the bonefish flats recreational fishery in South Florida across two spatial domains, a regional domain that encompassed about 400 km from Biscayne Bay to the Marquesas (Fig. 1), and a finer localized spatial domain that concentrated in Florida Bay. The regional spatial extent focused on three main fishing areas/subregions in the South Florida bonefish fishery: Biscayne Bay, the Florida Keys and Florida Bay (Fig. 1b). Biscayne Bay is a shallow-water subtropical lagoon located adjacent to the city of Miami, with more than half of the bay contained within Biscayne National Park. The Florida Keys consist of a chain of islands, surrounded by extensive seagrass meadows and reef areas that are part of the Florida Keys National Marine Sanctuary and strongly dependent on tourism and associated activities, such as recreational fisheries (Fedler 2013). For the purposes of the survey, we delineated the region into three regions Upper Florida Keys (Key Largo to Lower Matecumbe Key), Middle Keys (Long Key to the Seven Mile Bridge), and Lower Keys (Seven Mile Bridget to the Marquesas). As elsewhere, areas on the bayside of the Upper and northern part of the Middle Keys were considered part of Florida Bay (Frezza and Clem 2015).

Florida Bay, considered in both the regional and localized spatial scale, is a shallow, subtropical estuarine lagoon located at the southern end of the Everglades National Park (ENP). ENP is an IUCN Category 2 protected area 2357 mile<sup>2</sup> in area (Heinen 2012) that has been designated as a World Heritage Site, a Wetland of International Importance and a Biosphere Reserve under several international agreements (Heinen 1995; Fig. 1b). The focal study area also included the 'bayside' of the upper Florida Keys, from Key Largo to Long Key. At the localized scale, three fishing areas within Florida Bay were considered: Inner Florida Bay (1), Outer Florida Bay (2) and Cape Sable Area (3) (Fig. 1a, b).





**Fig. 1** a Map of the study domain (South Florida bonefish spatial extent) and the focal fishing areas targeted in the angler survey: Biscayne Bay (blue), Florida Bay (red, shown as 2 sub-fishing areas – Inner and Outer Bay), and the Florida Keys (black/grey,

shown as 3 sub-fishing areas - the Upper, Middle and Lower Keys). Also, **b** an inset map showing the 3 fishing areas within Florida Bay used to report catch in the in Everglades National Park (1 – Inner Bay, 2 – Outer Bay, 3 – Cape Sable)

We used both spatial domains to evaluate bonefish catch in Florida Bay because of the availability of spatial data of various resolutions due to the existence of different monitoring efforts, including the monitoring of recreational catches, which are absent elsewhere in the region (Osborne et al. 2006; Briceño et al. 2013; Hall et al. 2016). In addition, even though the bay is an iconic ecosystem of high socio-ecological value, it has been subject to a series of anthropogenic disturbances associated with freshwater management upstream that have exacerbated natural droughts, causing hypersalinity events resulting in prolonged seagrass dieoffs events, affecting up to 30% of the bay (i.e., 1987 and 2015 seagrass die-off) (Fourqurean and Robblee 1999; Rudnick et al. 2005; Madden et al. 2009; Stabenau and Kotun 2012; Hall et al. 2016). Natural drought events have interacted with chronically-diminished, managed freshwater inflows to unleash a cascade of major ecological effects, including epibenthic community shifts due to

seagrass mortality, algal blooms, sponge mortality, and reductions in shrimp and spiny lobster landing (Fourqurean and Robblee 1999; Boyer et al. 2009; Hall et al. 2016). Thus, focusing in Florida Bay provided the opportunity to understand how the bay's ecosystem changes may affect bonefish fisheries.

## Data collection

To elucidate and assess spatiotemporal trends on bonefish catches and spatial distribution of bonefishing effort, we used: 1) fishery-dependent data (FDD) obtained from professional guide logbooks, and local ecological knowledge (LEK) gathered from 2) a representative population of anglers and guides that specialized in bonefishing via an online survey and 3) key informant interviews. All of these datasets have pros and cons, and are affected by their own biases (Davis and Wagner 2003; Maunder and Punt 2004); however, the combination of FDD and LEK



have been recognized as an efficient and insightful way to assess long-term changes in species abundance and distribution, especially among data-poor resources such as recreational and catch and release fisheries (Beaudreau and Levin 2014).

The LEK data were gathered using a targeted approach (i.e., non-random survey design) to maximize the sampling of anglers that have heavily invested in bonefishing and acquire a more precise description of spatiotemporal patterns of bonefish catch and bonefishing effort. The online survey was administered using Qualtrics (www.cast.fiu.edu/projectbaybones.com; see Rehage et al. in this issue for additional details). Respondents were asked to evaluate the quality of bonefish across time steps and areas. The five focal fishing areas included: Biscayne Bay, Florida Bay, Uppers Keys, Middle Keys, and Lower Keys. Then within each selected fishing area, respondents were asked to score the quality of bonefishing in terms of the number of shots. Number of shots refers to how many times an angler had an opportunity to cast at a bonefish. Number of shots was scored using a 5-point Likert scale (1 = 0 shots, 2 = 1-3 shots, 3 = 4-10 shots, $4 \ge 10$  shots, 5 = unlimited shots) at present, and relative to the past (in 5 to 10 y periods), corresponding to a total of seven time steps: 2015, 2010, 2005, 2000, 1995, 1985 and 1975. This spatiotemporal matrix format of the questionnaire was an adaptation of the life history calendar (LHC, Freedman et al. 1988) approach usually use in demographic social science. A LHC approach allows for the collection of reliable and detailed retrospective data, focusing on the timing and sequence of life events (Freedman et al. 1988; Axinn et al. 1999). By using a matrix of time periods (horizontal) and events (vertical), the approach visually cues the survey respondent, enhancing autobiographical recall and accuracy in the timing of events (Belli et al. 2001; Glasner et al. 2015; Morselli et al. 2016).

Since bonefishing is most often done by sight fishing (i.e., visual confirmation before casting; Fernandez and Adams 2004), number of shots was used as an index of abundance, thus refer to bonefish number hereafter. This may be a relatively more reliable index of abundance since it reflects the encounter rate with a bonefish school and the size of such a school, removing angler skill at landing the bonefish (Frezza and Clem 2015; Rehage et al. in this issue). The number of shots metric was accompanied by reference points for what to consider high vs. low quality. These reference points provided

common metrics by which to standardized respondent perceptions, and were developed in consultation with a subset of experienced South Florida anglers and guides. A total of 219 respondents answered the survey completely (approximately 48%), of which 149 identified themselves as anglers (68%), and 32 as fishing guides (15%; 38 provided no information; 17%).

In addition to the online survey, LEK data were obtained using key informant interviews to gain a deeper knowledge of the fishery and get a retrospective understanding of the distribution of bonefishing effort. Key informant interviews are a series of open-ended questions that can spur meaningful discussion on a specific topic (Shrestha-Acharya and Heinen 2006; Hind 2015; Kroloff et al. 2018). The interviews targeted the most experienced and valuable members of the fishery community that have a long history and/or extensive expertise bonefishing in South Florida to get reliable decadal and spatial data on where bonefish were fished. A total of 20 guides and anglers were interviewed. Each interview was recorded and lasted anywhere from 30 min to 2 h and was then transcribed to extract general locations of bonefishing and to track changes in bonefishing spatial distribution and core fishing activity in South Florida. Using key informant interviews, though a more qualitative method of data collection, can produce important quantifiable results and has been used in many contexts throughout the socio-ecological literature (Heinen and Shrivastava 2009; García Lozano and Heinen 2016). For example, key informant interviews have been used to identify gaps in the implementation of international regulations on the trade of endangered species (Dongol and Heinen 2012), elucidate factor that influence collective action among small-scale fishers in Costa Rica (García Lozano and Heinen 2016), and delineate fishing grounds and inform catch estimates in data-limited fisheries (Hind 2015; Léopold et al. 2014).

Third, we used FDD to assess the spatiotemporal pattern in bonefish catches in Florida Bay. Specifically, the FDD used in this study were derived from professional fishing guides operating within ENP and submitting monthly logbooks (see Santos et al. 2017 for additional details). In their logbooks, guides reported the number of fish kept and released per species, effort (number of anglers, hours fished), and main species targeted (i.e., the primary species that was targeted in the trip) within 6 fishing areas (Tilmant et al. 1986; Schmidt et al. 2002; Osborne et al. 2006). For this study,



we used the data reported in fishing areas in Florida Bay where bonefish occur (Fishing Area 1–3, Fig. 1b). We used guide reports for the period 1980 to 2014 (n = 34 years), totaling 5039 guide reports that reported on bonefish and averaging 144 bonefish reports per year. For all analyses, catch data were aggregated to monthly totals to smooth daily variation due to weather, differences in fishing activity between weekends and weekdays, and other temporal factors (e.g., variability on reporting, seasonal effects, Santos et al. 2017). Reporting compliance may influence the precision of our abundance interpretation from catch data (Maunder et al. 2006; Osborne et al. 2006); however, we could not control for reporting compliance biases in our FDD analysis due to the lack of information on compliance.

# Data processing and statistical analyses

We used linear spline models (LSM) to assess the temporal trends in bonefish catches (i.e., number of shots from an online survey and total mean catch from FDD), and detect distinct trends among the fishing areas (Biscayne Bay vs. the Florida Keys vs. Florida Bay) from 1975 to 2015. Previous modelling approaches applied to the LEK and FDD data accounted for potential biases that influence catch, other than the abundance of fish (i.e., angler experience and type-angler vs. guide, fishing behavior and tactics, and species composition; see Rehage et al. in this issue, and Santos et al. 2017 for details), but showed a minor role of these factors. Based on the outcome of these models (i.e., lack of influence of bias from factors tested), the LSMs considered in this study only included Year as a continuous variable and were performed separately for each fishing area. The Year effect within the LSMs was structured as a sequential comparison of the seven time-steps considered in the online survey (1975– 1985, 1985–1995, 1995–2000, 2000–2005, 2005– 2010, 2010-2015). Then, significant estimated coefficients within each LSM (t-statistic, p value <0.05) were used to contrast the temporal trends in catch among fishing areas.

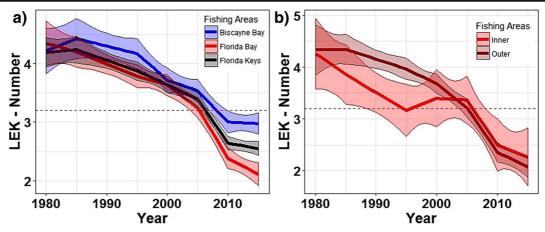
In addition to the catch data, we derived three different metrics from the online survey and the key informant interviews to quantify the spatial distribution of fishing effort. Using how the online respondents scored the number of shots across the time-space survey matrix (i.e., when and where each respondent scored), we determined the *percent of inclusion* for each fishing area

within each time-step. This metric can be considered as the likelihood of selecting an area for fishing since the process of selection is a binomial process: a binary choice process in which an angler either scored an area (1) or not (0) based on his/her fishing preference/selection. Generalized linear models (GLM) using a logit link function and quasi-binomial error distribution were used to examine and test for a difference in the percent of inclusion among the fishing areas as a function of time (Year). In this analysis, fishing areas for the Florida Keys were split into Upper, Middle and Lower Keys for a total of five fishing areas.

Two other metrics of spatial effort distribution were derived from the fishing locations detailed by key informants in interviews in order to obtain more detail on the changes of bonefishing effort distribution over timing. First, we used the transcribed interviews to extract names of fishing locations (e.g., specific flats, keys, channel markers) mentioned by the interviewees at a decadal scale (<1975, 1976-1985, 1986-1995, 1996-2005, 2006–2015). Each location was located on a map and georeferenced with a general set of coordinates (centroid latitude and longitude), and categorized to a focal fishing area (e.g., Florida Bay, Biscayne Bay, Upper, Mid or Lower Keys). After this data processing, 1) the unique number of locations mentioned by interviewees (location number) and 2) the frequency of any one location being mentioned (location frequency) were estimated across each fishing area and time-period combination. Location number was used as a proxy for spatial fishing distribution (i.e., effort spread), whereas location frequency was used as a proxy for spatial effort concentration. GLMs using a log link function and quasi-Poisson error distribution were used to test for a temporal effect on location number and frequency by considering these two metrics as response variables and the time-periods as an explanatory factor. Tukey Post hoc tests were performed to assess pairwise differences among the five time-periods.

Last, to characterize the changes in the spatial extent of bonefishing across all key informants (e.g., expansion vs. contraction over time), we quantified the core fishing area from both all and individual anglers for each time-period using a kernel estimation of utilization distribution (KUD; Calenge 2015). The KUD was estimated using a bivariate Gaussian (normal) kernel with a bandwidth parameter (smoothing parameter), h, calculated with an ad-hoc method that considers both the variance





**Fig. 2** Mean fitted scores for bonefish numbers (number of shots) across the seven time-steps between 1975 and 2015 (a) within the general fishing areas (regional extent) and (b) within the Florida Bay local fishing areas (local extent). Shading shows 95%

confidence levels and dotted horizontal lines global means. Values estimated from the online survey as part of the local ecological knowledge (LEK) data

in x (longitude) and y (latitude). A 50% KUD was used to define the core fishing areas, as done in other spatially-explicit studies (Laver and Kelly 2008). The

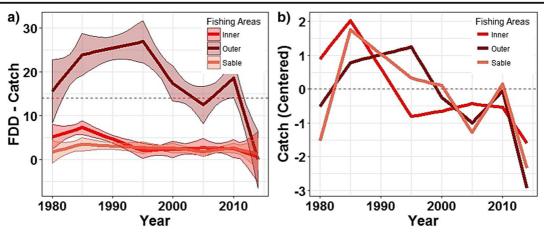
50% KUD estimated core fishing areas, interpreted as the areas in which there is a specified probability that fishing occurred during a given period (Beaudreau and

**Table 1** List of coefficients (Coef) associated with each term included in the bonefish number (number of shots) linear spline models performed for each general fishing area (Biscayne Bay, Florida Bay, Florida Keys). Shown are coefficients, standard errors

(SE), p values for the coefficient estimates (C.pval) for the null hypothesis of no difference with the reference point, and the adjusted  $R^2$  (adj.r) and associated p value for each linear spline model. Significant coefficients are bolded

Fishing areas	Term	Coef	Std.Error	C.pval	adj.r	R.pval
Biscayne bay	Intercept 1980–1985	-80.64 0.04	79.58 0.04	3.12E-01 2.86E-01	0.25	1.82E-19
	1985–1995	-0.03	0.02	2.38E-01		
	1995–2000	-0.09	0.03	9.05E-03		
	2000-2005	-0.04	0.03	2.21E-01		
	2005-2010	-0.11	0.03	1.02E-04		
	2010–2014	-0.01	0.03	8.43E-01		
Florida bay	Intercept 1980–1985	64.61 -0.03	76.90 0.04	4.01E-01 4.33E-01	0.39	2.91E-50
	1985-1995	-0.04	0.02	1.31E-02		
	1995–2000	-0.03	0.03	2.82E-01		
	2000-2005	-0.08	0.03	2.78E-03		
	2005–2010	-0.17	0.03	4.28E-11		
	2010-2014	-0.05	0.03	4.74E-02		
Florida keys	Intercept 1980–1985	-14.32 0.01	51.32 0.03	7.80E-01 7.18E-01	0.30	1.90E-69
	1985–1995	-0.04	0.01	1.09E-02		
	1995–2000	-0.05	0.02	3.56E-02		
	2000-2005	-0.05	0.02	1.05E-02		
	2005–2010	-0.15	0.02	2.69E-17		
	2010-2014	-0.02	0.02	3.02E-01		





**Fig. 3** Mean fitted values for bonefish catch in Florida Bay fishing areas (bold lines, Inner Bay – red, Outer Bay – dark red, Cape Sable – coral) from 1980 to 2014. Fitted values are represented in **a** absolute scale and **b** centered scale to aid the comparison between the fishing areas. Shading shows 95% confidence

levels and dotted horizontal lines global means. Values estimated from the fisheries-dependent data (FDD). Centered scale refer to values standardized to the distance from the mean (0 = mean, positive and negative values greater and less than the mean, respectively)

Whitney 2016), were overlaid in a satellite image using ArcGIS 10.3 to visualize the spatial change of the core fishing areas across the time-periods. KUD was also estimated for each key informant separately to examine temporal shifts in the size of fishing areas used by individual anglers and quantify variation in fishing core areas. The temporal difference among anglers' mean KUD was tested using a one-way ANOVA.

All statistical analyses were performed in R v3.2.5 (R Core Team 2017). The LSM, GLM and the Tukey Post hoc test were performed respectively with the Ispline (Bojanowski 2017), stats (R Core Team 2017) and multcomp (Hothorn et al. 2008) R packages.

### Results

Spatial changes in catch

Survey respondents perceived a decline in bonefish numbers (i.e., the number of shots at catching a bonefish) across all fishing areas (Fig. 2a); thus, pointing to a regional decline in bonefish. The mean score for shots at bonefish dropped between 26 and 53%, with the drop ordered as Florida Bay (-53%) > Florida Keys (-38%) > Biscayne Bay (-26%). However, the pattern of decline varied between the fishing areas as indicated by the linear spline models for bonefish number performed by fishing area (Table 1). In Biscayne Bay, only

two significant negative coefficients were observed in the time steps 1995–2000 and 2005–2010. In Florida Bay and the Florida Keys, four of the seven time-steps had a significant negative coefficient, suggesting a long-term declining trend (Table 1). The long-term declining trend in Florida Bay started from 2000, and was anteceded by a significant decline in 1985–1995 time step. In contrast to the Florida Keys, the significant declining slopes were detected between the time steps 1985–1995, and 2005–2015 (Table 1). In addition, the greatest deviation among the fishing areas occurred after 2010, where Florida Bay received the lowest score for bone-fish number.

In Florida Bay, both the FDD and LEK showed an overall decline in catch and distinct patterns of decline between the fishing areas within the Bay (Figs. 2b and 3). The catch proxy obtained from FDD indicated that the highest bonefish catches concentrated in the Outer Bay until 2010, and that both Inner and Sable fishing areas have consistently been suboptimal for bonefish catches (i.e., lower than the global mean, Fig. 3a). The spline linear models indicated a significant catch decline in Outer and Inner Florida Bay, and a consistent low catch in Cape Sable fishing area since 1980 (Fig. 3 and Table 2a). A decline was detected first in the Inner Florida Bay, as indicated by the significant negative coefficient of the time step 1985–1995, which was followed by consistent lower than average catches (Fig. 3b and Table 2a). For the Outer Florida Bay, a negative trend was detected later at the 1995-2000 and 2010–2014 time steps, and in a greater magnitude than



**Table 2** List of coefficients (Coef) associated with each term included in the Florida Bay A) bonefish catch and B) bonefish number (number of shots) linear spline models performed for Florida Bay fishing areas. Shown are coefficients, standard errors

(SE), p-values for the coefficient estimates (C.pval) for the null hypothesis of no difference with the reference point, and the adjusted  $R^2$  (adj.r) and associated p value for each linear spline model. Significant coefficients are bolded

Florida bay	Term	Coeff	Std.Error	C.pval	adj.r	R.pval
A) Bonefish cate	h					
Inner	Intercept 1980–1985	-827.17 0.42	748.31 0.38	0.271 0.267	0.17	1.45E-05
	1985-1995	-0.53	0.14	0.000		
	1995-2000	0.06	0.28	0.836		
	2000-2005	0.08	0.32	0.798		
	2005-2010	-0.04	0.36	0.910		
	2010-2014	-0.49	0.84	0.564		
Outer	Intercept 1980–1985	-3311.68 1.68	1959.75 0.99	0.092 0.090	0.10	1.88E-12
	1985-1995	0.29	0.41	0.480		
	1995-2000	-1.91	0.71	0.007		
	2000-2005	-0.97	0.67	0.148		
	2005-2010	1.22	0.71	0.086		
	2010-2014	-4.63	1.12	0.000		
Sable	Intercept 1980–1985	-692.61 0.35	655.17 0.33	0.293 0.291	-0.02	6.29E-01
	1985–1995	-0.08	0.12	0.524		
	1995–2000	-0.02	0.20	0.907		
	2000-2005	-0.15	0.17	0.401		
	2005-2010	0.15	0.19	0.423		
	2010-2014	-0.33	0.53	0.534		
B) Bonefish Nun	nber					
Inner	Intercept 1980–1985	164.55 <b>-0.08</b>	137.87 <b>0.07</b>	2.36E-01 <b>2.47E-01</b>	0.18	2.01E-04
	1985–1995	-0.07	0.04	7.93E-02		
	1995–2000	0.05	0.08	5.43E-01		
	2000-2005	-0.01	0.07	9.21E-01		
	2005-2010	-0.17	0.07	1.46E-02		
	2010-2014	-0.05	0.08	5.43E-01		
Outer	Intercept	2.28	98.50	9.82E-01	0.46	2.47E-50
	1980–1985	0.00	0.05	9.83E-01		
	1985–1995	-0.04	0.02	3.68E-02		
	1995–2000	-0.06	0.03	4.48E-02		
	2000–2005	-0.09	0.03	4.56E-04		
	2005–2010	-0.17	0.03	2.16E-10		
	2010–2014	-0.06	0.03	4.71E-02		

in Inner Florida Bay (Fig. 3b and Table 2a). The LEK survey respondents perceived a similar earlier decline in the quality of bonefishing in the Inner Bay from 1980 to 1995 (Fig. 2b and Table 2b). Here over the later years, the LEK survey differed from the FDD (i.e., asymptote

from 1995 to 2010 in Inner Bay, and decline after 1995 in Outer Bay), with the survey indicating a significant decline between 2005 and 2010 in Inner Florida Bay, and a continuous decline in Outer Florida Bay after the 1985–1995 time step (Table 2b).

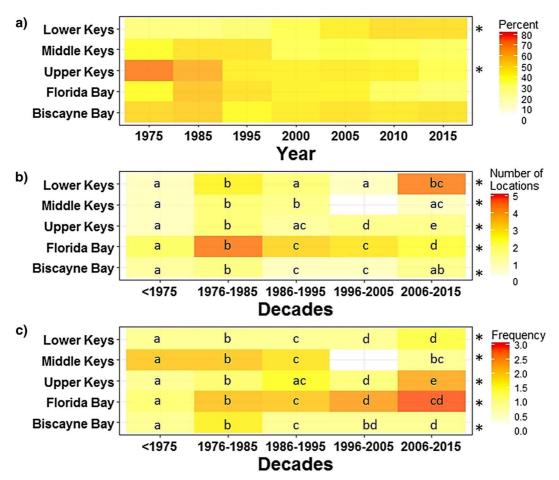


# Spatial changes in effort

Similarly to the catch, there were significant changes in the distribution of bonefishing effort, as reported by both survey respondents and key informants (Fig. 4). According to the LEK survey, high values of the percent of inclusion (i.e., the proportion of respondents that scored a fishing location within each fishing area) dispersed across all fishing areas during 1975 and 1985, except in the Lower Keys (Fig. 4a, Table 3). A negative trend on the percent of inclusion was observed in the Upper and Middle Keys and in Florida Bay; however, this reduction in the percent of inclusion over time was only significant for the Upper Keys (GLM<sub>quasibinomial</sub> z=-5.77, p value = 0.0022). In contrast, the percent of

inclusion significantly increased over the years in the Lower Keys ( $GLM_{quasibinomial}$  z = 6.01, p value 0.0018, Fig. 4a). In Biscayne Bay, values of a percent of inclusion fluctuated around intermediate values.

The metrics of anglers' spatial use derived from the key informant interviews, the unique number of locations mentioned (*location number*, Fig. 4b) and the frequency of location mentioned among interviewees (*location frequency*, Fig. 4c), also significantly varied among time steps and fishing areas (Table 4). All GLMs (GLM<sub>quasi-Poisson</sub>) for each fishing area showed that the factor "decades" was a significant term as pointed by a significant reduction in the residual deviance when added to a null model (ANOVA Chisq test, p < 0.05, Fig. 4b, c). Post-hoc Tukey tests showed that the



**Fig. 4** Heatmap plots illustrating the spatiotemporal patterns in bonefishing effort: **a** percent of inclusion, **b** unique number of locations mentioned and **c** the mentioning frequency of the locations. Percent of inclusion was obtained from the online survey responses, and the number of locations and mentioning frequency

were obtained from the key-informant interviews. Darker colors represent higher values per each legend. Asterisks in the side illustrate the fishing areas where the time effect was significant. The letters mark significant time-step groupings within the fishing areas



location number in all the fishing areas was the lowest in the first time period (<1975). The location number tended to be the highest during the 1976–1985 time period and gradually declined toward the last period (2006–2015), especially in Florida Bay (Fig. 4b). The highest location number in the Lower Keys was observed during the 2006–2015 time period. The Lower Keys also had the highest location frequency in this last time period. However, contrary to the low values of location number recorded in Florida Bay and Upper Keys during the last period, the highest values for location frequency in these two areas were prevalent in the last two periods (1996–2005 and 2006–2015), indicative of effort aggregation.

The combined core fishing grounds used by all interviewees showed a u-shaped pattern in the core area, with the core fishing area approximately three times smaller in the 1996–2005 time period than the core fishing areas in the <1975 (first time period), and 2006–2015 (most recent time period) (Fig. 5a). The core fishing area concentrated in Florida Bay, Middle and Lower Keys (Fig. 5a Lower Panel). The core of fishing re-expanded in 2006-2015 by including the Lower Keys (Fig. 5a Lower Panel). The mean core area fished per angler also showed a u-shaped pattern (Fig. 5b), however, there were no significant differences between the time periods (One-way ANOVA, p value >0.05). Generally, interviewees demonstrated a wider range in the core fishing area in >1975 and 2006-2015, reflecting higher individual variation in the extent of fishing areas during these two periods (Fig. 5b).

**Table 3** Generalized linear models (GLM) for percent of inclusion of the fishing areas included in the angler survey. Models based on a logit link function and quasi-binomial error distribution. Shown are model terms (Term), coefficient estimates (Coeff),

### Discussion

Fisheries, as components of ecosystems, tend to exhibit spatial patterns across multiple scales (Babcock et al. 2005; Post 2013; Saul et al. 2013). Thus, gaining a full understanding of the spatiotemporal patterns of both catch and effort is a priority to assess how and when fisheries change, and to provide management strategies that respond adequately to fishery dynamics (Fonteneau and Richard 2003; Campbell 2004; Post 2013). A combination of various types of data and methods are required to accurately reconstruct spatiotemporal changes in both catch and effort, especially for data-limited species (Ainsworth 2011; Carruthers and Hordyk 2016; Aylesworth et al. 2017). In our study, we used both FDD (traditional fishery data) and LEK (nontraditional fishery data) to assess spatial changes in bonefish catch and bonefishing effort in South Florida and help determine the extent of the decline (regional vs. localized) and to understand how anglers fishing distribution responded to the decline. Our proxies of bonefish abundance, bonefish catch from guides reports (FDD) and bonefish number from the online survey (LEK), suggested both a regional and localized decline in bonefish. Although the online survey respondents perceived a decline of bonefish number across all fishing areas, the decline in Florida Bay resulted in the highest drop in bonefish number perceived by anglers. Within Florida Bay, the observations from both FDD and LEK concurred with an initial drop in bonefish at Inner Bay (a suboptimal bonefishing ground), followed by a greater

standard errors (SE), *p*-values for the coefficient estimates (C.pval) for the null hypothesis of no difference. Significant temporal coefficients (*Year*) are bolded

Fishing areas	Term	Coeff	Std.Error	Z.values	C.pval
Biscayne bay	Intercept	9.08	8.56	1.06	3.37E-01
	Year	0.00	0.00	-1.08	3.31E-01
Florida bay	Intercept	23.58	15.42	1.53	1.87E-01
	Year	-0.01	0.01	-1.55	1.82E-01
Upper keys	Intercept	61.84	10.72	5.77	2.20E-03
	Year	-0.03	0.01	-5.77	2.19E-03
Middle keys	Intercept	16.07	10.12	1.59	1.73E-01
	Year	-0.01	0.01	-1.63	1.65E-01
Lower keys	Intercept	-47.92	7.90	-6.06	1.76E-03
	Year	0.02	0.00	6.01	1.83E-03



**Table 4** Generalized linear models (GLM) for the a) unique number of locations mentioned by interviewees (*location number*) and b) the frequency of any one location being mentioned (*location frequency*) within each of the fishing areas. Models based on a

log link function and quasi-Poisson error distribution. Shown coefficient estimates (Coeff), deviance of model and residuals (Deviance and Resid.Dev), *p*-values for the coefficient estimates (C.pval) for the null hypothesis of no difference

Variable	Term	Fishing areas	Deviance	Resid.Dev	C.pval
a) Location number	Decade	Biscayne bay	30.88	2.29	1.96E-60
		Florida bay	95.85	40.91	6.07E-22
		Lower keys	18.83	1.53	1.58E-46
		Middle keys	21.83	2.58	1.41E-13
		Upper keys	28.51	10.95	2.95E-09
b) Location frequency	Decade	Biscayne bay	45.99	8.80	9.14E-15
		Florida bay	799.65	41.68	7.54E-117
		Lower keys	45.82	10.46	1.24E-04
		Middle keys	14.90	5.35	8.70E-05
		Upper keys	51.90	9.82	6.03E-18

and later decline in the Outer Bay. The spatial metrics of bonefishing effort derived from the online survey and the key-informant interviews depicted a shrinkage of the bonefishing spatial distribution and a shift of fishing activities from the Upper to the Lower Keys.

These results contribute to the increasing research showing the importance of utilizing FDD and LEK to better describe the different components that affect the stability of fisheries, and to check for agreement between data sources to ascertain the reliability of observed patterns (Zukowski et al. 2011; Hind 2015; Aylesworth et al. 2017). However, despite their utility to assess long-term trends in different fisheries, both FDD and LEK suffer from biases and limitations worth

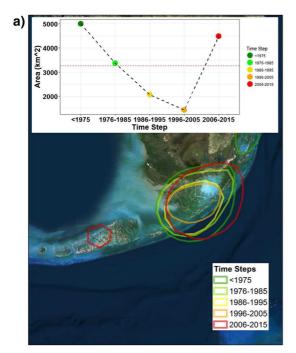
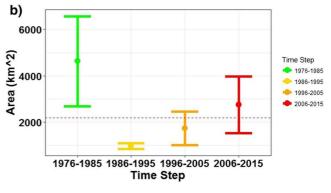


Fig. 5 The 50% KUD (kernel estimation of utilization distribution) for (a) the combined fishing area used by all interviewees overlaid over a South Florida satellite image, and (b) the mean



core area fished per angler averaged across all key informants ( $\pm$  standard errors) for each time-step from 1975 to 2015



noting. FDD are subject to potential biases since they are inherently affected by fishing dynamics and angler behavior, which may cause CPUE to deviate from abundance, resulting in at times in spurious inferences (Maunder and Punt 2004; Erisman et al. 2011). The catch data used in this study were previously standardized to account for variation in temporal (e.g., month, season), spatial (e.g., fishing areas), catch structure associated with shifting tactics, and effort dynamics (e.g., hours fished, number of fishermen; see Santos et al. 2017 for details). One common criticism of LEK is that human perception and memory are subject to the shifting baseline syndrome (SBS). SBS refers to a shift in perception of a biological system as a result of the lack of experience with appropriate historical reference conditions (Pauly 1995; Papworth et al. 2009), and in LEK datasets it can lead to highly variable resource assessments (Beaudreau and Levin 2014). In our study, we determined that the SBS were minimal since factors such as years of experience and angler type did not significantly influence the perceived trend in bonefish number (see Rehage et al. in this issue). Nevertheless, the concordance between the FDD indices of catch and the LEK perception of bonefish number in Florida Bay, and the agreement with the overall declining pattern described by previous FDD and LEK studies (Larkin 2011; Frezza and Clem 2015; Santos et al. 2017) provided confidence in the spatial declining patterns detected in this study. Also, the independence of the bonefishing effort metrics from the anglers' catch perception, as well as, the concordance of the effort metrics and the catch trends captured by FDD and LEK attest for a true response in bonefish abundance rather than a bias effect associated with the methodology.

The regional decline perceived across the fishing areas and the major decline in the core fishing area of anglers support in part the notion of a problem with recruitment and population dynamics operating at spatial scales extending outside of South Florida. Other comprehensive studies have hypothesized the lack of recruitment from regional larval supplies as a driver behind the decline of bonefish throughout South Florida (Larkin 2011; Frezza and Clem 2015; Santos et al. 2017; Brownscombe et al. 2018). Stocks are known to become susceptible to collapse due to lack of regional connectivity strength (i.e., depletion of a regional stock; Cowen et al. 2006; Jensen et al. 2012). The high level of genetic connectivity for bonefish across the Caribbean Basin (Wallace 2014), and the

extended pelagic larval stage of bonefish (Mojica et al. 1995) suggest that the link between the regional larval supply sources and later recruitment into South Florida could be highly vulnerable to unmanaged harvesting practices throughout the Caribbean basin (Adams et al. 2014). A preliminary surface trajectory larval model for bonefish suggests a high connectivity between Florida Bay recruits and larval sources from, among others, South Cuba (Zeng et al. 2018), a region of the Caribbean where bonefish populations are susceptible to unmanaged harvesting practices (Adams et al. 2014; Angulo-Valdes et al. 2017; Adams 2017). Similarly, a connectivity research work on Caribbean spiny lobster (Panulirus argus), a species also with a long pelagic larval duration, has demonstrated a high relationship of South Florida spiny lobster recruitment to larval sources from the Western Caribbean Basin (source from Mexico, Honduras, Nicaragua, Cuba, Kough et al. 2013). However, a recent hydrodynamic model of larval permit (Trachinotus falcatus) connectivity demonstrated high local retention and low connectivity with other Caribbean regions (e.g., Cuba and Belize) (Bryan et al. 2015); thus, highlighting the importance of local stocks as recruitment sources.

Stocks can also become susceptible to collapse due to the reduction of local self-recruitment (Swearer et al. 2002; Cowen et al. 2006; Jensen et al. 2012). Connectivity models for multiple species have demonstrated that South Florida has high level of domestic connectivity (i.e., self-recruitment; Cowen et al. 2006; Kough et al. 2013; Holstein et al. 2014); thus, highlighting the vulnerability of South Florida bonefish population to collapse due to local recruitment overfishing (i.e., where harvest exceeds the ability of a population to replace itself; Coggins et al. 2007), or due to other disturbances altering local recruitment through community and ecosystem dynamics (i.e., habitat degradation, altered cues and environmental conditions, competition, altered trophic dynamics). Besides fishing pressure, pharmaceuticals and heavy metals can potentially influence bonefish sub-populations near urban centers and freshwater man-made canals (Beck 2016), by influencing behavior and physiological conditions that lead to sub-lethal or chronic effects (Cooke et al. 2013; Horodysky et al. 2015).

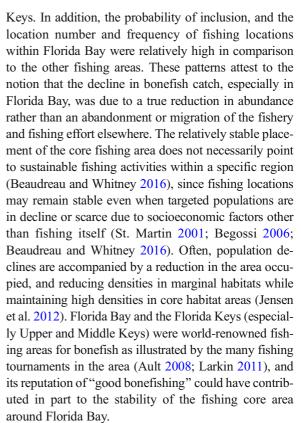
The distinct decline in Florida Bay (i.e., occurring earlier and showing a larger magnitude of decline) observed in both FDD and LEK, suggests the possibility of localized events of bonefish decline. Changes in the



environment and habitat quality can influence the productivity of fisheries in coastal environments and create localized changes in fish abundance (Armstrong and Falk-Petersen 2008; Planque et al. 2010; Post 2013). The first changes of bonefish catch in Florida Bay were observed in the Inner Bay fishing area, an area of the bay that suffered the harshest impact of the 1987-1992 seagrass dieoff and subsequent state shift (Fourqurean and Robblee 1999; Zieman et al. 1999; Briceño et al. 2013). This drastic alteration to the system may have induced a total collapse of the Inner Bay as a productive and attractive bonefish fishing ground, especially after the early 90s due to the persistence of algae blooms and low visibility conditions (Fourgurean and Robblee 1999; Zieman et al. 1999; Briceño et al. 2013). Inner Bay's nearshore habitats have been identified as possible nursery habitats for bonefish (Roessler 1970; Rehage and Santos unpubl. data). Thus, major environmental changes in Inner Bay nearshore environments during and after the seagrass die-off could have influenced the bonefish population across Florida Bay since the quality of and the connectivity to nursery habitats are important factors to sustain abundant adult fish populations (Mumby et al. 2004; Meynecke et al. 2008; Olds et al. 2012; Pittman et al. 2014; Nagelkerken et al. 2015).

It is important to concomitantly assess the catch patterns observed from the FDD and LEK with measurements of fishing effort, especially the spatial distribution of fishing activities. This combination can help discern whether the changes in catch were associated with shifts in angler behavior (e.g., giving-up density, spatial migration of effort, shift in targeted species), determine the possibility of hyper-stability in the data, and identify areas of importance to anglers or areas with potential accumulation of fishing effects (Erisman et al. 2011; Post 2013; Beaudreau and Whitney 2016). Most of the spatial metrics of effort distribution in this study demonstrated a shrinkage in the bonefishing spatial distribution. Fishing effort can shift spatially due to changes in fish abundance (Fonteneau and Richard 2003; Campbell 2004; Beaudreau and Whitney 2016), and shrink with respect to the decline of targeted populations (Jensen et al. 2012). For example, the drastic decline in the abundance of northern cod was accompanied by equally dramatic changes in the distribution of the stock and fishing effort (Atkinson et al. 1997).

Even though the overall fishing area shrank, the core remained over Florida Bay and the Upper and Middle



The relatively stable placement of the core fishing area, the overall reduction of fishing locations, and the increase in the frequency of locations being mentioned (e.g., concentration) indicate that the bonefish population in South Florida likely faced localized fishing effects. There are numerous examples of how fishing pressure can directly influence the abundance and diversity of exploited species (Roughgarden and Smith 1996; Pauly 1998; Worm et al. 2006), including among recreational fisheries (Schroeder and Love 2002; Coleman et al. 2004; Cooke and Cowx 2006). Concentrated fishing effort (i.e., aggregated only in good fishing grounds) can lead to the collapse of populations by reducing directly or indirectly abundance down to ecologically unviable densities (Post et al. 2008; Jensen et al. 2012; Post 2013). However, it is a challenge to determine long-term fishing effects on populations in catch-and-release fisheries, such as the bonefish fishery, due to the inherent assumption that most released fish survive and to the difficulty in measuring stress chronic effects (Cooke and Cowx 2006; Cooke et al. 2013; Horodysky et al. 2015).

Bonefish is a long-lived species (Crabtree et al. 1996; Larkin 2011), which makes it more susceptible to small



increments in mortality as consequence of the accumulation of sub-lethal and lethal effects over many years (Schroeder and Love 2002; Coggins et al. 2007). Based on two stock assessment models (i.e., a stochastic ageindependent continuous population model and a catchfree assessment model), Larkin (2011) estimated an increasing trend in fishing mortality after the mid-1980s in Florida Bay and in the Florida Keys that coincides with the period of fishing effort aggregation observed in our study. Larkin (2011) also suggested that even relatively low mortality could substantially reduce the local bonefish stock abundance if effort and releases were high, as expected in areas of high fishing pressure. Also, it would be expected the fishing pressure to increase due to the high population growth rate in South Florida. For instance, anglers have perceived a higher bonefish abandonment of flats (i.e., bonefish redistribution due an increase of boat activity (Kroloff et al. 2018; Rehage et al. in this issue). The high site fidelity (Humston et al. 2005; Larkin 2011; Murchie et al. 2013) and long lifespan of bonefish (Larkin 2011), as well as the observed aggregation of effort observed in this study, raise the following queries: What are the long-term implications to the population when constantly catching and releasing the same individuals? Could this concentration of effort cause displacement to "refuge habitats"? Is the concentration of effort hindering spawning activities or the fecundity of the population? Is catch-andrelease fishing increasing the susceptibility to predation? These are relevant questions that have not been examined yet in South Florida (Brownscombe et al. 2018), but necessary to address some of the pitfalls of using catch data from FDD and LEK.

A partial migration of fishing effort towards the Lower Keys was suggested by the increase in the number of fishing locations mentioned over the years and the inclusion of the Lower Keys within the 50% fishing core area during the most recent study period (2006–2015). Similar to Beaudreau and Whitney (2016), it is still unclear in our study whether this pattern indicates a southerly migration of the bonefish range, changes in fishing behavior or community, or a shift in the residency geography of the respondents. The pattern in the effort is likely related to the proximity of "profitable" fishing sites, rather than shifts in abundance and distribution of bonefish in South Florida. However, this needs to be tested with a series of interviews combined with a further spatial assessment of bonefish abundance.

In sum, our study shows that by combining LEK and FDD, we were able to reconstruct both spatiotemporal patterns of bonefish catch and fishing effort allowing for an increased understanding of where and how this datalimited species declined in South Florida. Similarly, previous studies have emphasized the importance of using multiple lines of evidence to support the inference of occurrence and abundance patterns (Hall and Giddings 2000; Diefenderfer et al. 2016; Bland et al. 2017). The data-limited nature of most recreational fisheries and the increase in the use of catch-and-release as fisheries management strategy highlight the need to further develop data integration approaches and tools that help assess fish population trends and the sustainability of fishery resources. The agreement of the catch description in both the LEK and FDD adds to mounting evidence that LEK can successfully complement scientific data to produce better assessments of fish populations and offer management outputs (Zukowski et al. 2011; Aylesworth et al. 2017). The production of both catch and fishing effort estimates across space using LEK also highlighted the versatility of this approach to generate information to assess different components that may influence the stability of recreational fisheries (e.g., population dynamics, fishing culture and behavior, socio-economics) (Hind 2015; Beaudreau and Whitney 2016; Aylesworth et al. 2017). The managers of recreational fisheries should consider the combination and integration of both approaches as a toolbox to not only determine the distribution and abundance of targeted species with confidence but also to identify essential areas, assess cumulative impacts of fishing and prioritize areas that are vulnerable or worth of protection.

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### Compliance with ethical standards

**Ethical approval** Our survey was approved by the Human Subjects Board at Florida International University and was performed in accordance with the ethical standards as laid down in the



1964 Declaration of Helsinki and its later amendments or comparable ethical standards. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. For this type of study formal consent is not required.

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