CITIZEN SCIENCE:
THEORY AND PRACTICE

Using Citizen Science to Track Population Trends in the American Horseshoe Crab (*Limulus polyphemus*) in Florida

METHOD

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ABSTRACT

We used citizen science to improve understanding of population trends and behavior in the American horseshoe crab (*Limulus polyphemus*) along the entire coast of Florida. First, we used 18 years of public sightings data, beginning in 2002, on horseshoe crab mating to determine which spawning locations were used most. Then, a subset of those locations was more rigorously surveyed through the Florida Horseshoe Crab Watch program. Florida Horseshoe Crab Watch, implemented in 2015 by a collaboration between the Florida Fish and Wildlife Conservation Commission (FWC), University of Florida Institute of Food and Agricultural Science (UF/IFAS), University of Florida Department of Biology (UF), and Florida Sea Grant (FSG), uses trained citizen volunteers to survey beaches with high spawning activity. Volunteers count, weigh, measure, and tag horseshoe crabs that are nesting on the shoreline. These data contribute to a nationwide mark–recapture program managed by the United States Fish and Wildlife Service (USFWS) and are used in Florida to inform species management decisions and to increase general understanding of the species. We developed and adapted both phases of the research by implementing modern technology, improving survey design, and expanding geographic coverage. The quality and accuracy of public reports have improved with technological advancements. The quality of the morphological data collected by Florida Horseshoe Crab Watch volunteers was comparable to that of data collected by professional scientists. Our design can serve as a model for programs regardless of region or taxon of interest and when funding is limited but public interest is high.

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INTRODUCTION

Geographic distribution and population growth rate are two important metrics that fish and wildlife managers use in decision-making. Management institutions often give priority to species of economic value, whereas species that are ecologically valuable but difficult to monitor can be given a lower priority (Darwall et al. 2011). Setting harvest limits without sufficient data is sometimes required to maintain a fishery, but its effects can be unpredictable. For example, overharvesting can still occur, impacting ecosystem dynamics and possibly causing trophic cascades (Walsh et al. 2011). This has happened in the wide-ranged and once abundant American horseshoe crab (*Limulus polyphemus,* henceforth horseshoe crab), which is a vital ecosystem component as predator, prey, and host (Botton 2009; Heres, Kilcollins, and Crowley 2020). It is also important economically, primarily because it supports a bait fishery and is used in biomedical research and manufacturing.

American horseshoe crab populations have been declining throughout much of their range, which spans the North American coast from Maine to Alabama and parts of Mexico's Yucatan Peninsula (ASMFC 2020). Declines in horseshoe crab populations are due to bait harvest, shoreline hardening, sea-level rise, and biomedical harvest (Botton, Loveland, and Jacobsen 1988; Widener and Barlow 1999; Loveland and Botton 2015). Some eastern states have restricted harvests to reverse population decline. In 2008, Delaware mandated that only male horseshoe crabs could be collected for bait, and in New Jersey, the bait fishery was closed (ASMFC 2020). The Atlantic States Marine Fisheries Commission's Interstate Fishery Management Plan for Horseshoe Crab was created in 1998 to monitor horseshoe crab populations and to create and later enforce collection quotas on the Atlantic coast (ASMFC 1998). Horseshoe crab populations are declining in New England and New York, are stable in Delaware Bay, and are stable in the Southeast (ASMFC 2020). Although Florida is in the commission's southeast management unit, its most recent stock assessment does not reflect the status of Florida's horseshoe crab population because survey data were limited when the assessment was published (ASMFC 2020). Florida is under the jurisdiction of both the Atlantic States Marine Fisheries Commission (ASMFC) and the Gulf States Marine Fisheries Commission (GSMFC). Regulation is delineated by coast, with ASMFC regulating the Atlantic coast, and GSMFC advising the Gulf of Mexico's interstate species; however, there is no fishery management plan for horseshoe crab. Ultimately, horseshoe crab management on the west coast of Florida is under the purview of FWC.

The Atlantic States Marine Fisheries Commission (ASMFC) uses both spawning-beach surveys and targeted trawl surveys to monitor the horseshoe crab and assess its population status through the central part of its range (ASMFC 2020). Before 2015, the only horseshoe crab population data available for Florida had been obtained from fishery-independent trawls that targeted finfish and from commercial landings data (Brockmann, Black, and King 2015). Since the trawls do not target horseshoe crabs—as they do in the mid-Atlantic states—and since the commercial fishing data are scant, population estimates and biological data are limited. At present, little funding is dedicated to the study of horseshoe crabs, and with 2,170 km of Florida coastline to cover, it is virtually impossible to study Florida horseshoe crab populations without the help of volunteers.

In 2002, the Florida Fish and Wildlife Conservation Commission's Fish and Wildlife Research Institute (FWC-FWRI) requested the public's assistance in documenting horseshoe crab spawning behavior, with the goal of quantifying spawning populations and horseshoe crab habitat. This effort was undertaken in part to comply with the Interstate Fishery Management Plan for Horseshoe Crabs, which requires states with minor bait fisheries to define essential horseshoe crab habitat. This request for public reports gave FWC-FWRI biologists a tool for determining on which beaches horseshoe crabs spawned most often and gave members of the public an opportunity to participate in scientific research.

Public reports required little effort, but the data were not always precise and only provided presence information. To ensure consistent measures of spawning activity and density as well as both presence and absence data, in 2015 the Florida Horseshoe Crab Watch was created. The goal of the Florida Horseshoe Crab Watch is to collect mark–recapture and biological data that can be used to evaluate the spawning status of the horseshoe crab in Florida, which public reports cannot do, and that can contribute to a nationwide mark–recapture study conducted by the United States Fish and Wildlife Service (USFWS) and the ASMFC (ASMFC 2020). We created the horseshoe crab spawning public reports and the Florida Horseshoe Crab Watch program to learn where and at what densities horseshoe crabs spawn, and whether populations were changing through time. Here, we outline how both projects were implemented and maintained, how we tested the quality of the data, how technology and the iterative process aid in answering the questions raised, and how both projects work independently and in conjunction with each other.

METHODS

We describe the design and implementation of both the public reports and Florida Horseshoe Crab Watch.

While regulation is required only by the ASMFC, and thus encompasses only Florida's Atlantic coasts, surveys and reports were collected statewide at the direction of FWC. We used the data collected from both projects to investigate the accuracy of each method.

HORSESHOE CRAB SPAWNING: PUBLIC-REPORT DATA

In 2002, FWC requested, via press release, that members of the public report observations of horseshoe crab spawning activity; they could report activity by phone, e-mail, or in an online survey. In 2018, a smartphone app (FWC Reporter) was created for reporting these observations. Initially, FWC requested the following information: a general description of the spawning location, date, time, county, number of horseshoe crabs observed, spawning status, juvenile presence, and additional comments. In 2008, FWC added two parameters, the sex of the horseshoe crabs and presence of any dead horseshoe crabs. Data were hampered by vague information regarding location, so in 2018 FWC added the exact GPS location through the FWC Reporter smartphone application by capturing the phone's GPS coordinates at the observation location. In 2019, FWC launched an online survey (Survey123; Esri 2019) that collected GPS location even if observers were not at the spawning beach when submitting the survey by allowing them to select their location on a digital map. The data collected were compiled in a database. When GPS location was unavailable or not reported but a written description was provided, GPS coordinates were assigned to the location as closely as possible. We created an accuracy index to rank the quality of the estimated coordinates (***Table 1***). Reports outside Florida or with incomplete vital information (e.g., no date, no county), were excluded from analyses. We examined the level of accuracy by year and method of collection to understand trends in data quality.

FLORIDA HORSESHOE CRAB WATCH

Origin

Florida Horseshoe Crab Watch was developed through collaboration among FWC-FWRI, University of Florida's Institute of Food and Agricultural Science Nature Coast Biological Station (UF/IFAS), University of Florida's Department of Biology (UFDB), and Florida Sea Grant (FSG). The program was modeled on a long-term sampling project conducted on Seahorse Key, an island within the Cedar Keys National Wildlife Refuge (Brockmann and Johnson 2011), on the Delaware Horseshoe Crab Survey (Smith et al. 2002), and on Project Limulus (Mattei et al. 2015).

Survey design

The Florida Horseshoe Crab Watch program consisted of beach spawning surveys, measuring and tagging a sample of spawning horseshoe crabs, and re-sighting the previously tagged animals. To the extent possible, the protocol was designed to follow the procedures of the Delaware Bay surveys (Smith et al. 2002). But the biology of Florida horseshoe crabs differs from that of Delaware horseshoes, which required some changes to the survey protocol. Florida horseshoe crabs are seasonal and are found nesting from late February through May (varying from year to year) and again from late August through October (Rudloe 1980; Sasson et al. 2020), so we conducted surveys in both the spring and the fall (Delaware Bay has only one season, April–June). We knew that Florida horseshoe crabs were strongly influenced by inundation (tides and wind surge), so that more animals would be present when water levels were higher (Rudloe 1980; Barlow, Powers, and Kass 1988; Brockmann and Johnson 2011). Therefore, each round of sampling consisted of beach-transect surveys on three dates at the time of the highest predicted high tides, which are consecutive days, on or around the new or full moon. (In Delaware Bay surveys, sampling was done on the day of the new or full moon, two days before and two days after). We used only daytime high tides, as nighttime high tides occurred at too late an hour for volunteers. The surveys began at the time of the predicted high tide, and four rounds of surveys (two new moon and two full moon) were conducted each season. We chose not to sample using the quadrat method used in Delaware Bay because horseshoe crab populations in Florida are much sparser than those in Delaware, so all crabs in a designated area can be counted (Smith and Bennet 2004). Also, Florida horseshoe crabs are often patchily distributed, which violates assumptions of random encounters on which quadrat sampling is based.

INDEX NUMBER	DEFINITION
Highest	Coordinates provided by application or within the text of the location description
High	Location described at the beach level
Medium	Location described at the city/town level
Low	Location described at the county level

Table 1 Index of accuracy used to measure location data described in public reports.

Site selection

Survey locations were established after a season of scouting surveys to ensure that they represented viable spawning beaches. When possible, beaches deemed hot spots, based on high abundance of horseshoe crabs in the public-report data, were selected for Florida Horseshoe Crab Watch surveys, but some could not be used because they were not sufficiently accessible for volunteers. The survey distance for each beach transect was determined by beach size and physical landmarks or blockages.

Survey protocol

For each survey, volunteers began walking the shoreline at the time of the predicted maximum high tide. Volunteers worked in pairs recording the number of horseshoe crabs observed nesting on the beach or just offshore or swimming near the beach (because of water turbidity, this was not more than 1 m offshore). A note was made distinguishing between paired horseshoe crabs (male attached to a female), unpaired males, unpaired males in physical contact with pairs (i.e., satellites), and unpaired females, and of the numbers of each (Brockmann 2003). After walking the survey area, volunteers picked up horseshoe crabs at random, tagged them, and held them in buckets until the spawning survey was completed. If any previously tagged horseshoe crabs were observed, the tag number and status of the horseshoe crab (alive or dead) were recorded. If dead, the tag was removed, the number recorded, and the tag discarded. If the horseshoe crab was alive, its tag number was recorded, and the animal was returned to the water at the shoreline. Any data collected from previously tagged horseshoe crabs during the surveys were submitted to the USFWS by the Florida Horseshoe Crab Watch statewide coordinator. These data are used as part of a range-wide program to establish horseshoe crab population size and movements. Tags include a website link so that members of the public who find a tagged crab can report it directly to the USFWS (ASMFC 2020).

Once the volunteers reached the end of the beach transect, the horseshoe crabs that had been captured were measured and tagged to identify the crabs again and gather biometric data for later analysis. Individuals were then sexed, the prosoma width (mm) measured, and the crab weighed (g) using a spring scale or digital scale (Shuster 2009). Finally, a tag with a unique number, provided by the USFWS, was inserted into the prosoma on the left side. This was done by creating a small hole in the shell using a sharpened awl and inserting the tag into the hole (Beekey and Mattei 2008). The tag is ribbed so it cannot fall out after it is pressed into the shell (***Figure 1***).

For each survey, data about volunteers' efforts were also recorded on the data sheet, including the number of miles traveled, the number of hours donated, and the number of interactions with the public. Interactions with the public included encounters with anyone in the area who asked the volunteers what they were doing; these events constitute part of the program's outreach.

Coordination structure and training

The Florida Horseshoe Crab Watch program was maintained by one statewide coordinator who oversaw site coordinators. Site coordinators were usually education coordinators at science-based organizations such as UF/IFAS and the Florida Department of Environmental

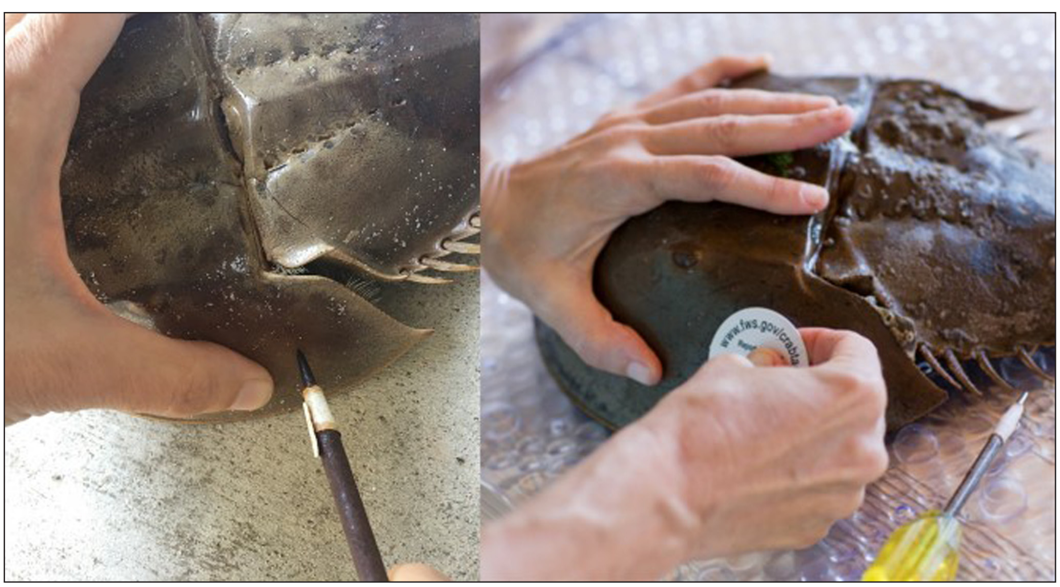

Figure 1 American horseshoe crab being tagged using an awl to create a small hole in the prosoma, and insertion of a U.S. Fish and Wildlife Service tag.

Protection, or environmental nonprofits such as the Marine Discovery Center in New Smyrna Beach. Some site coordinators were not affiliated with an organization. Site coordinators were trained individually or in small groups. This training included the basic volunteer training (described below) and coordinator specific training. The site coordinator managed the survey locations, local survey schedule, and recruitment of volunteers.

Once a site coordinator had been trained, a volunteer training event was held. These training events were designed to be systematic and thorough. They began with an overview of horseshoe crab biology, life history and anatomy, management, and an introduction to citizen science. Volunteers were encouraged to ask questions throughout the presentation as a means encouraging their interest and engagement. After the presentation, a series of YouTube videos, developed by FWRI, UF/IFAS, and FSG, were shown to introduce and demonstrate the survey process. The *YouTube (Florida Horseshoe Crab Watch)* training videos were available to view at any time by volunteers, coordinators, and the general public. Finally, the volunteers cycled through five stations designed to mimic survey data collection. Each volunteer practiced determining the sex of horseshoe crabs; measuring, weighing, and tagging crabs; and recording data. If the training was held near the first survey date of the season, volunteers joined the coordinators for an on-site practice survey. This allowed for further hands-on experience and for the opportunity for volunteers to ask questions before surveys. If an on-site practice survey was not possible before the first survey of the season, a mock beach transect was created to demonstrate a typical survey. Once volunteers had attended the training event and signed safety waivers, they were eligible to sign up to formally participate in Florida Horseshoe Crab Watch surveys.

Data entry and quality control and assurance

For the first three years, data were submitted to the statewide coordinator and entered into Excel. As the program grew, site coordinators were asked to submit all volunteer-collected data after each survey season using a Microsoft SharePoint page with levels of access based on levels of training (Microsoft Corporation 2019). Using SharePoint, site coordinators could input data, but they could not delete it; only the statewide coordinator could delete data, which limited accidental data loss. The SharePoint input forms had drop-down columns with selection options designed to reduce data-entry errors. These features increased data accuracy so the statewide coordinator did not have to do much to ensure quality control (Wiggins et al. 2011). The SharePoint page also housed training materials, state and federal permits, and other useful guides so site coordinators could easily access Florida Horseshoe Crab Watch materials without needing to request them from the statewide coordinator. The statewide coordinator checked all physical copies of the data sheets against the digital submissions made on the Microsoft SharePoint page and discussed any discrepancies with the site coordinator. Data found to be inaccurate were removed.

Quality analysis

To determine whether data collected by volunteers during Florida Horseshoe Crab Watch surveys were comparable to data collected in more traditional, agency-specific data collection efforts (i.e., "trained or professional scientist"), a Welch's t-test was used to compare mean prosoma width and mean mass between crabs collected by volunteers and those collected by professionals. We used data from Levy County where Cedar Key is located, because that site had the most data available.

RESULTS

Results were compiled comparing the public-report data over time, and Florida Horseshoe Crab Watch data between different levels of experience.

HORSESHOE CRAB SPAWNING: PUBLIC-REPORT DATA

From April 2002 to June 2020, 5,286 reports were submitted by the public excluding those without viable date or county data (***Figure 2***). Most submissions were through the online survey (3,580, 67%), followed by Survey123 (644, 12%), e-mail (437, 8%), telephone calls (416, 8%), FWC Reporter (159, 3%), and personal communication (50, 1%). Horseshoe crabs were documented in all 35 coastal counties in Florida. The accuracy of reports, as evaluated by the index of accuracy, increased (***Figure 3***) as technology and recording capabilities improved (***Figure 4***).

FLORIDA HORSESHOE CRAB WATCH

The Florida Horseshoe Crab Watch program was active in 16 counties (***Figure 2***) with 28 actively surveyed beaches. As of June 2020, volunteers had conducted 1,356 surveys, counted 45,259 crabs, and tagged 4,995 crabs. We found no significant difference between professionals and volunteers in their estimates of the mean size and mass of male and female horseshoe crabs measured during spawning surveys performed in Cedar Key, Florida between March 2016 and June 2020. (***Table 2***; ***Figure 5***).

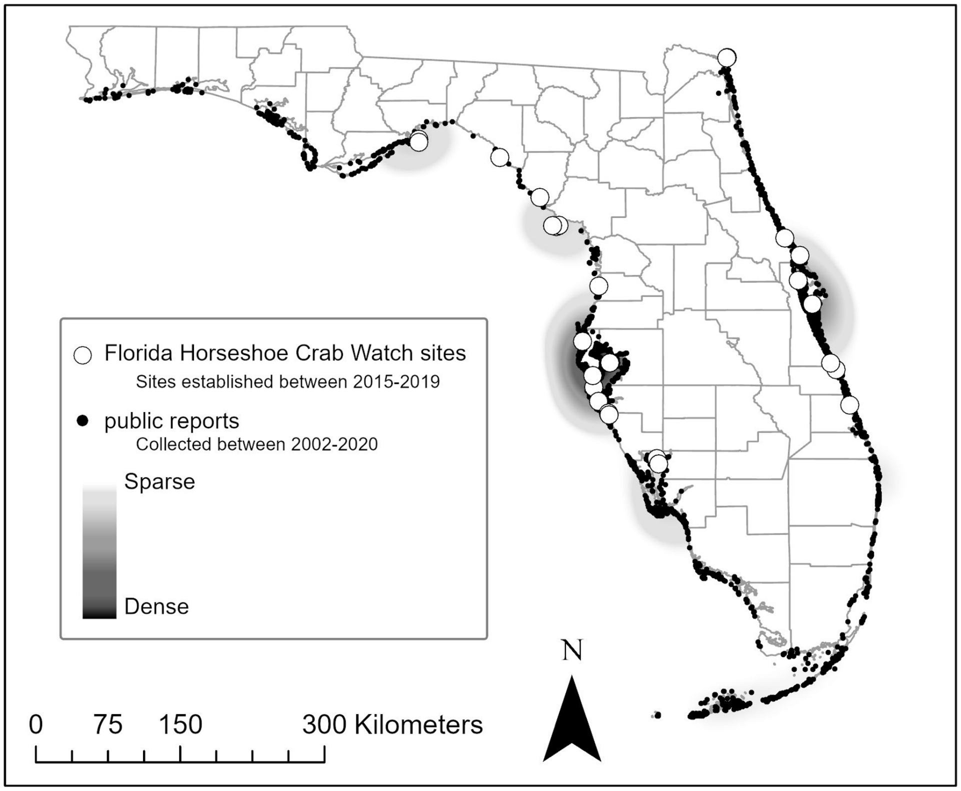

Figure 2 Florida Horseshoe Crab Watch sites (open circles) and public reports (closed circles). Shading shows relative density of public reports. Atlantic States Marine Fisheries Commission has Atlantic coast jurisdiction, Gulf States Marine Fisheries Commission has Gulf coast jurisdiction.

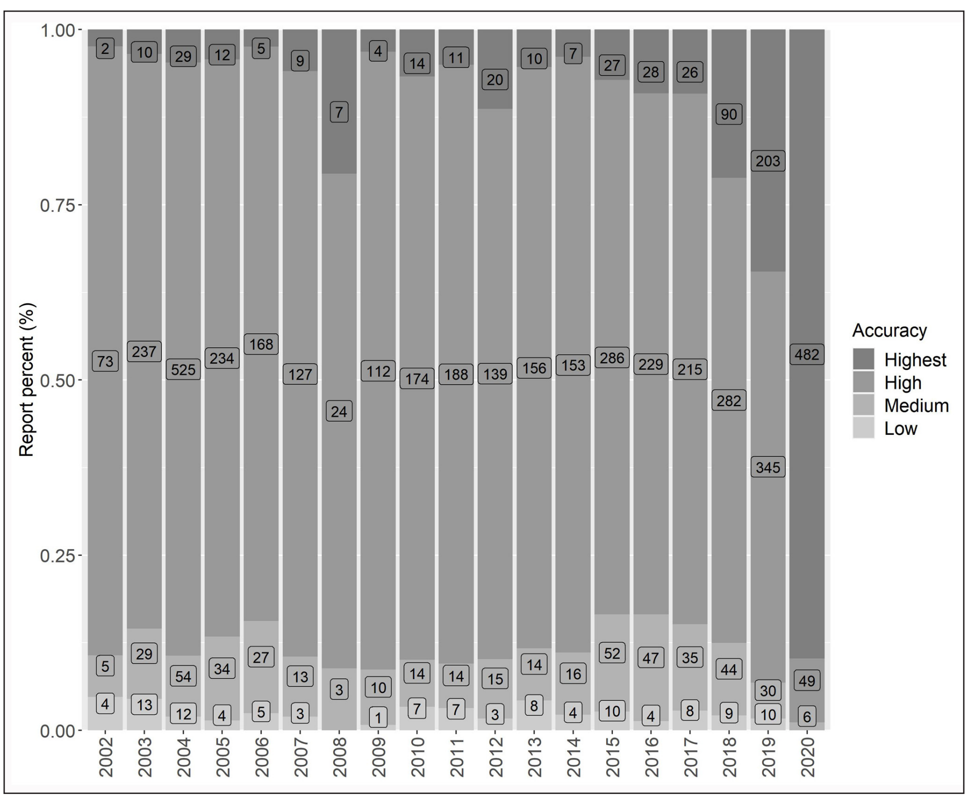

Figure 3 Ranking of the accuracy of public reports sighting locations over time. Highest accuracy requires GPS coordinates; high accuracy requires specifying the beach on which an observation was made; medium accuracy requires specifying the name of a nearby town; low accuracy requires specifying only the county in which an observation was made. Number of reports for each accuracy index is reported in bars by year.

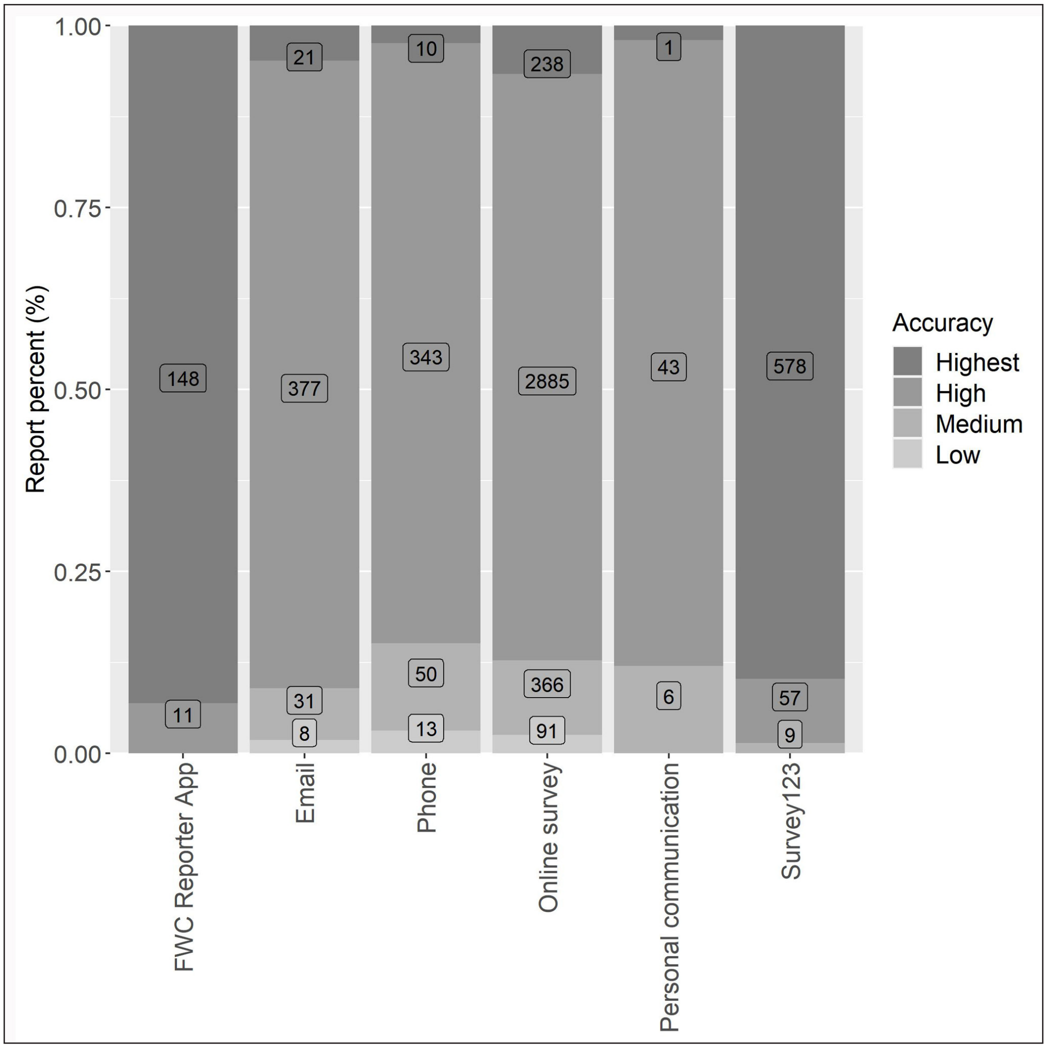

Figure 4 Percent ranking of accuracy index of public report sighting locations, by report type. Number of reports for each accuracy index rank is represented in bars for each report type.

METRIC EXAMINED	PROFESSIONAL TOTAL N = 676	VOLUNTEER TOTAL N = 2,333	T-VALUE	DF	P-VALUE
Mean prosoma width (mm), males	158.10 n = 420	157.75 n = 1,315	0.55	750.16	0.58
Mean prosoma width (mm), females	216.69 n = 256	215.00 n = 1,018	1.45	402.93	0.15
Mean mass (g), males	436.28 n = 420	436.74 n = 1,315	−0.06	735.79	0.96
Mean mass (g), females	1,402.46 n = 256	1,375.57 n = 1,018	1.21	415.74	0.23

Table 2 Results of Welch's t-test for unequal variance used to compare means of prosoma width and mass of horseshoe crabs by sex, as recorded by a professional or by a volunteer.

DISCUSSION

Both the public reports and Florida Horseshoe Crab Watch have been shown to be complementary, valuable methods of data collection. It is logistically and economically impossible to monitor horseshoe crabs on every Florida beach. By using public monitoring in conjunction with data collected by trained citizen volunteers at established

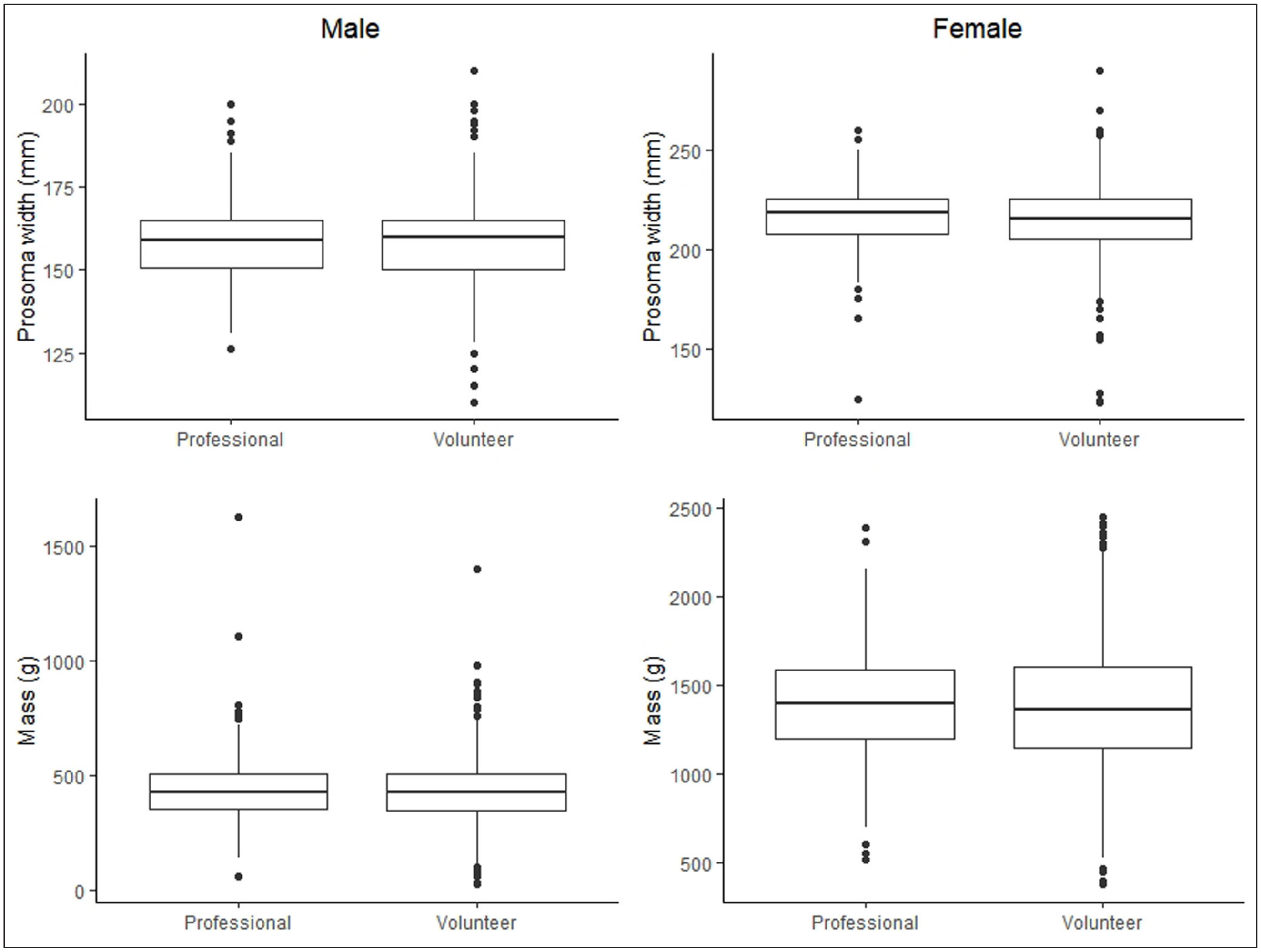

Figure 5 Box plot depicting mean prosoma width and mass for males and females, as collected by Florida Horseshoe Crab Watch professionals and volunteers. Median represented by center line; *25% quartiles* within box; lines represent upper and lower *25% quartiles,* and points represent outliers. Note that outliers are present in both professional- and volunteer-collected data.

horseshoe crab spawning locations, we have, with limited resources, collected data throughout the state.

DATA FROM PUBLIC REPORTS

Public-report data have proved valuable for documenting the presence of horseshoe crab spawning without the need for extensive surveying or scientific expertise. The public reports disproportionately covered commonly visited locations, such as public beaches and causeways, compared with, for example, remote spoil islands, keys, and mangrove islands, also common on Florida's coast. Nevertheless, during the 18-year period of this study, more than 5,000 reports were made, allowing us to delineate spatial and temporal trends in spawning activity. If horseshoe crab habitat changes, so may horseshoe crab behavior. Changes like increased public traffic, shoreline development, red tides, or hurricanes can also affect spawning behavior. By observing the number of reports and the number of crabs before and after such events, we can identify if a change has occurred. This is one of the most sought-after metrics in ecology, and while simple public reports are not robust enough to pinpoint a cause, they can better prepare managers for outcomes when such events happen again. This can lead to better decision-making during times of crisis in the horseshoe crab fishery. These data can also be used in conjunction with other data, such as data from the FWC Fisheries Independent Monitoring program, to better characterize the ecological status of the species throughout the state.

FLORIDA HORSESHOE CRAB WATCH

The public-report data have been valuable and have greatly enhanced horseshoe crab data collection. Following reports of potential spawning sites, Florida Horseshoe Crab Watch used such information to find and select sites and implement a program in which citizen scientists use a standard protocol to collect biometric data on horseshoe crabs. There were no significant differences between data collected by volunteers and data collected by trained scientists. Therefore, data collected by volunteers should be used in state and national management decisions pertaining to Florida's horseshoe crab populations. More generally, Florida Horseshoe Crab Watch also highlights the value of skilled volunteers who are willing and able to learn to record complex scientific data. The results also show that the training regimen results in a strong understanding of the methods. Our results indicate that data collected in the present study are of merit, so it is worthwhile to continue surveys at the same sites and to expand the project to areas for which data are insufficient, such as Monroe County in southern Florida and Escambia County in western Florida.

Citizen science and the iterative process

The public-reporting program and Florida Horseshoe Crab Watch were both managed using a process of continual assessment and development, open to technological advancements and creative thinking. When the collection of public-report data began in 2002, it was done primarily through phone reporting, but as the technology developed, e-mail and online surveys were used as reporting tools. When cell phone GPS technology became more reliable, the FWC Reporter application enabled collection of precise coordinates. Most recently, the map built into Survey123 has allowed the public to report precise spawning locations even after they have left the observation location. At the end of 2020, nearly 100% of reports are being collected though Survey123. The flexibility in how the public-report data are collected has seen improvements in accuracy, in ease of reporting, and in data compilation.

Florida Horseshoe Crab Watch data collection has undergone a similar process. Florida's coastline is vast and diverse, and each survey location is unique. There are up to five genetically distinct subpopulations of horseshoe crabs in Florida (Brockmann, Black, and King 2015), which differ in average body size and other traits (Brockmann and Johnson 2011). This diversity has sometimes required modifications to the sampling protocol. For example, in most locations, the horseshoe crabs are carried to the tagging location in a plastic five-gallon bucket, but in northeast Florida, in Nassau County, horseshoe crabs are larger than elsewhere in the state, and rather than force large crabs into buckets, we use large reusable bags to carry and weigh the crabs. More substantial changes to protocol require data analyses and input from volunteers, coordinators, and scientists. For example, sampling procedures were modified in the Indian River Lagoon in Brevard County to include surveys outside of the time of the predicted maximum high tide. The Indian River Lagoon is microtidal (Weaver, Johnson, and Ridler 2016) and tide-based surveys do not capture peak spawning activity there (Ehlinger and Tankersley 2009), so procedures were modified for this area, and volunteers surveyed every day during the spawning season. They also recorded additional environmental variables (wind speed, wind direction, air temperature, and water temperature) to elucidate what does trigger horseshoe crab spawning in this area, where tides do not. Using these data, we developed a protocol for surveys performed during wind-driven water rise that mirrored conditions observed during high spawning activity, tailored to be specific to the microtidal locations. We also recognize that mating behavior varies throughout the state. In the more northern parts of its range, the horseshoe crab spawns during the spring (Smith et al. 2002), but in Florida the pattern is more complex. In south Florida, they are active through most of the year except the hottest summer months (June–August). On the central and northern Gulf coast of Florida, they do not spawn in winter (November–January), with peaks in spring and fall (Rudloe 1980; Brockmann and Johnson 2011; Sasson et al. 2020). The northern Atlantic coast of Florida appears to follow the pattern of the more northern sites, i.e., spring spawning.

Using two citizen-science projects in conjunction

We found that both citizen science projects had strengths and weaknesses and were most successful when used together. The public-report data served as the first step in facilitating the collection of more scientifically rigorous data. For example, a public report of 5,000 spawning pairs usually occurs in only two areas of the state, which are monitored by Florida Horseshoe Crab Watch. A report of more than 1,000 horseshoe crabs in an area, such as the panhandle, would require investigation and corroborating reports around that time to be worth possible adoption as a site within the Florida Horseshoe Crab Watch, since it has not had a report of that number in the 18 years of reporting. Similar methodology has been used to monitor horseshoe crabs before, using public reports and following up with more in-depth review (Liao et al. 2019). Maintaining a process of review and adaptation has enhanced both programs. Horseshoe crab spawning-report data entry is now largely automated, with built-in quality assessments that reduce the need for visual checks. Florida Horseshoe Crab Watch is on track to estimate population size at sites within the next 10 years, which is standard for mark–recapture studies of this taxon (David Smith, personal communication). Additionally, the methodical nature of the program has allowed us to examine new questions as they arise, as was the case for horseshoe crabs spawning in the Indian River Lagoon. We intend to examine these trends in coming publications. Both programs described here have provided and will continue to provide valuable information to managers, researchers, and the public.

CONCLUSIONS

Although these programs cost less than other similar surveys run strictly by trained scientists, a considerable amount of resources is required by both the statewide coordinator and individual site coordinators to cover training and coordination of volunteers and compilation and quality assessment of data. Although public reports are less intensive to maintain, their drawback is a higher risk of inaccurate data or poorly described or missing data. Estimating locations of public reports based on descriptions was particularly time consuming. Additionally, moving from past reporting platforms to Survey123 required planning, but offered built-in quality checks that ultimately reduced effort (Wiggins et al. 2011, 2013). We advise future researchers implementing citizen science projects to use technology to improve data quality whenever possible. We also suggest that managers remain open to the questions and improvements that volunteers suggest. The citizen scientist, trained or untrained, is an invaluable resource to managers. Involving them provides a different type and quality of data collected, but with forethought and adaptability, scientists, managers, and public participants can gain a better understanding of their resource. Our programs are an example of two levels of public participation that can provide data for answering questions that would not be possible if attempted by scientists alone. Furthermore, these two projects work in conjunction with and complement each other, one by providing preliminary data, and the other by using more rigorous methods to gather more complex data. This framework can be applied to many other taxa and research questions. We hope that readers will use these methods in their citizen science projects and in future research.

DATA ACCESSIBILITY STATEMENT

All raw data and analyses are available upon request. Identifying information from public reports and volunteers are removed before sharing to protect their privacy.

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

Florida Horseshoe Crab Watch design and implementation and general manuscript edits by J. Brockmann and S. Barry. Public-report oversight, manuscript design, general manuscript edits by C. Crowley. Public-report consolidation, data analysis, graphs, and manuscript composition by B. Heres.

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