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Heat Stress Impacts on Coral Reef Ecosystems and Communities: An Evaluation of Visitor Perceptions, Behaviors and Substitution Effects in the Florida Keys National Marine Sanctuary, USA

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Abstract: Evaluating the effects of environmental events across both biophysical and social dimensions is important in establishing a holistic view of such events. This study focuses on the impact of a devastating heat stress incident that occurred in many locations across the Caribbean region and South Atlantic during the 2023 summer season. The survey and focus of data collection was within Monroe County, a unique nature-based setting south of Miami, Florida, USA. The impact of the heat wave is still being calculated at the time of submission of this paper, but indications are that there was a major negative impact. The survey and data collection sought to understand recreationists' perceptions, knowledge, and behavior changes as result of the heat stress impact in the Florida Keys. Respondents were interviewed during community workshops in person and through an online sample of boating/angler license holders. The results indicated a change in behavior by some respondents, which may have a longer-term economic impact, along with trends of satisfaction with outdoor recreation over time. This rapid survey method can be applied to future scenarios where social and economic data are needed to fully contextualize environmental impacts in addition to biological endpoints.

Keywords: heat stress; socioeconomics; coral reef; human behavior; recreation visitation

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1. Introduction

The economic benefits of healthy ecosystems are vast with respect to tourism. In recent years, in the US, outdoor recreation has accounted for approximately 2% (over USD 450 billion) of the total gross domestic product according to the Bureau of Economic Analysis [1]. In the state of Florida, this percentage is higher, with outdoor recreation representing nearly 3.5% of the state GDP each year [1]. A critical component of recreation and tourism is the functionality of the ecosystem for users to interact within for activities. The perceptions associated with a "healthy" ecosystem may be significant drivers of tourism behaviors and use patterns [2]. Many potential users make decisions about where to visit and where to spend time and money based upon such perceptions and attitudes associated with the ecosystem and amenity status.

The Florida Keys coral reef ecosystems are experiencing unprecedented threats from multiple stressors, including disease, water quality changes, habitat disruption, and others [3,4]. One such stressor is the changing climate conditions, especially with respect to the temperature. With rising temperatures comes additional stress on coral reef ecosystems,

which may cause the degradation and even death of corals [5]. Extreme and prolonged heat is an example of a stressor that may lead to coral bleaching as the symbiotic relationships with helpful zooxanthellae algae are disrupted [6]. The algae help to provide food for the corals through photosynthesis, and heat stress causes the corals to expel the algae, resulting in starvation for the corals and the "bleached" appearance of just the coral skeleton. These events occur on occasion but have been increasing in frequency and intensity in recent years [7]. One such large bleaching event occurred in the summer of 2023, with huge amounts of coral bleaching occurring with the Florida Keys National Marine Sanctuary [8]. Some reef areas experienced up to 100% bleaching of corals, according to NOAA Sentinel site data. Significant levels of coral bleaching can lead to ecological disruptions but also socioeconomic disruptions if user activities are affected.

Previous research conducted by the project team in the Florida Keys in 2019 [9] indicated diver and snorkeler acceptability ratings on norm curves for coral bleaching of around 20% of the total visible area (Figure 1). This contrast in the user acceptability rating and the reality of heavily bleached reefs provides an incentive to study both sides of this issue and better inform and prepare for outcomes. User acceptability ratings for visible coral impacts may be quite low compared to the reality of the environmental conditions in some locations, especially during catastrophic events that damage ecosystems. Another component of prior research results indicates the level of interest and care that people place in resource conditions. Previous results [10] illustrate that the majority of respondents (>62%) believe that the health of coral reef ecosystems is declining in the Florida Keys. Over half (>55%) of the respondents find bleached coral to be strongly unacceptable as a resource condition, with a notable tipping point across acceptance levels at around 20% coral bleaching. In terms of importance, previous results indicate very high levels of importance (five-point scale) for seeing a healthy reef (4.3/5) and experiencing a clean reef free from debris (4.5/5). It is clear that people value resources and desire healthy conditions, but the importance can be measured more accurately when attributed to measures of the benefits and the vulnerabilities of these conditions and the associated benefits for climate change.

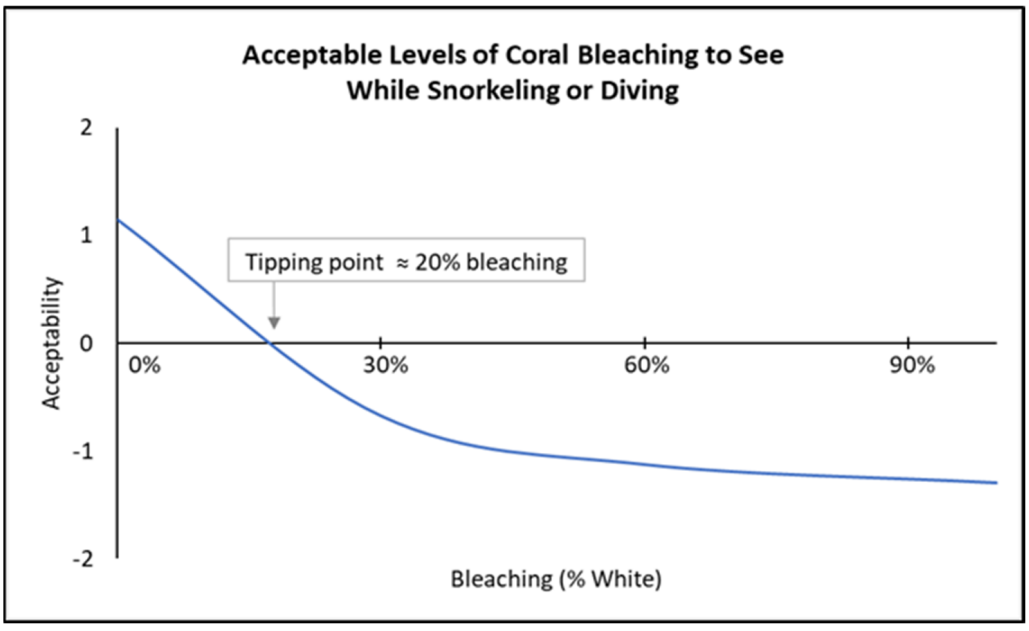

Figure 1. Norm curve of coral bleaching acceptability across pilot study survey of thousands of sanctuary users in the Florida Keys. Acceptability scale shows positive values as acceptable and negative values as unacceptable.

Coral reefs in Florida are also extremely valuable with respect to economic benefits. Benefit analyses complied by the NOAA estimate over USD 3 billion in economic benefits associated with coral reefs across the US [11], with over half of this associated with recreational diving and snorkeling. Changes due to heat stress threaten this economic activity, and there is a need to understand the user perceptions as they relate to attitudes and use behavior. Potential substitution effects could undermine the sustainability of tourism and community economies associated with healthy coral reef ecosystems, causing changes in livelihoods and reductions in tourism potential. Therefore, it is critical to evaluate perceptions now as they relate to tourism strengths and weaknesses and the potential for substitution effects. The coral reef ecosystems of Florida are receiving media attention, which helps bring the threats to light for the average person. This creates an opportune time to assess the public in a way that better positions the Florida Keys National Marine Sanctuary (Sanctuary) and the Marine Preservation Society (Society) for the coming years in terms of changing visitation and use associated with a changing coral ecosystem.

Heat stress of coral, along with ocean acidification, caused by increased atmospheric carbon dioxide, remains a dire problem that impacts not only the ecosystem itself [12] but also people across many facets of associated lives and livelihoods [13,14]. Coral reefs are critical to areas such as the Florida Keys. Being able to survive a major hurricane with less economic loss, corals and associated plants and animals are needed for medicinal purposes and provide an extremely important economic benefit as a result of fisheries and touristic/outdoor recreation activities [13]. The economic contribution of the Florida Keys coral reefs is estimated at USD 3.8 billion annually and snorkelers/divers contributed USD 1.2 billion annually [10]. Environmental issues and the role of recreationist displacement have been studied often over the past four decades across myriad settings, including marine settings. One of the key concepts associated with displacement is the role that change plays. A change in the ecosystem, change in management, or change in human behavior may result [15,16]. Finally, a related concept is satisfaction with the trip experience, a concept oft studied in nearly all facets of our lives [17,18] and particularly in outdoor recreation and tourism [19,20].

The aims of this research were to (1) identify initial social perceptions, knowledge, and attitudes associated with heat stress events in the coral reef habitats of the Florida Keys and (2) evaluate behaviors and activities associated with heat stress events. The previous work by the authors in the Florida Keys in 2019 helped to define the basic levels of coral reef conditions and environmental concern but did not include the evaluation of acute heat stress events. Due to the acute summer heat stress event of 2023, this rapid assessment survey was designed and deployed to build upon the foundational social data from the previous work and to focus on the emergent issue of heat stress events for the coral reef ecosystems of the Florida Keys.

2. Materials and Methods

The rapid assessment described in this study is not designed to be representative of the entire population of Monroe County visitors but is a snapshot in time of a current critical environmental impact. The survey was developed by researchers at West Virginia University, building upon previous research in the region with respect to visitation and outdoor recreation [9,10,21]. This rapid assessment effort builds upon over three decades of previous experience in the project team and more recent research-associated surveys for coral reef restoration through the Mission: Iconic Reef (M:IR) program [22]. The M:IR program is a large, multi-dimensional effort that includes long-term (20 year) restoration efforts to collect biological and human use data. The M:IR's social science research focus is to develop a full suite of sampling surveys that capture all focal data related to the ecosystem changes and associated tourism fluctuations in the Keys.

Over a two-week period (7–21 September 2023), email survey invitations from West Virginia University and the National Marine Sanctuary Foundation using the Qualtrics survey software (Version 2023) were distributed to potential respondents. A reminder

email was sent at the midpoint of the rapid survey time window to encourage respondents to complete the survey. It is important to note that these data were collected with the intention of corresponding temporally with the excessive water heating and subsequent coral bleaching events of summer 2023 (Figure 2). The sample of respondents included recreationists who had responded to an earlier survey from WVU and the NMSF [10]. This purposeful method was used to ensure that the responses were relevant to the Florida Keys and the recreation situation associated with heat stress. Data reported are from survey summary statistics, along with a *t*-test comparison of the respondent satisfaction levels before (i.e., before June) and during (i.e., June–September) summer 2023. These tests were performed using the R statistical software version 4.4.1 and evaluated using standard assumptions for two-sample tests with unequal variance and an alpha level of 0.05 for significance.

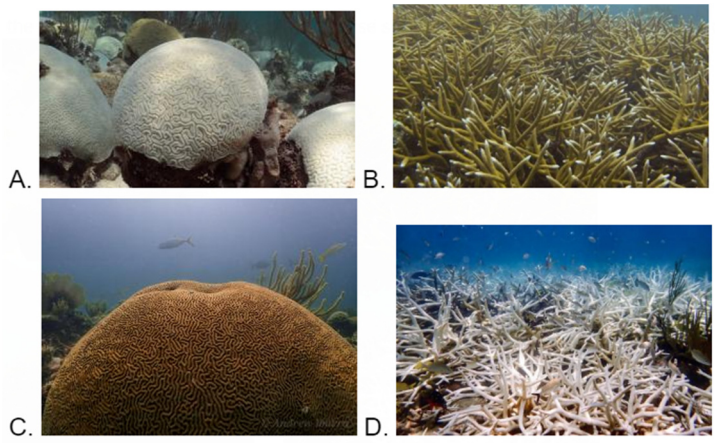

Figure 2. Photographs of coral reef (**A**–**D**).

3. Results

In the two-week survey sampling period, a total of 121 completed responses and 31 partial responses were recorded, creating an approximately 16% response rate. Over three-quarters of the respondents (78%) stated that they believed that the warmer water temperatures are having a negative or extremely negative impact on the Florida Keys waters. A notable proportion of respondents (16%) reported that there was no impact or a positive impact. Six percent of respondents responded that they were unsure about the impact of the warmer water (Table 1).

Table 1. Survey responses for perception of high water temperature event impact in Florida Keys National Marine Sanctuary.

Response	Frequency	Overall Percentage (%)
Extremely Negative Impact	40	34
Negative Impact	51	44
No Impact	18	15
Positive Impact	1	1
Extremely Positive Impact	0	0
Not Sure	7	6
Total	117	100

When asked about their primary recreation activity, just over one third (34%) referred to fishing and one quarter (25%) referred to snorkeling. Just under a fifth (17%) primarily participated in general boating and 13% participated in either diving or kayaking/paddle sports (Table 2).

Table 2. Survey responses for primary outdoor recreation activity in Florida Keys National Marine Sanctuary.

Response	Frequency	Overall Percentage (%)
Fishing	38	34
Snorkeling	28	25
General Boating	19	17
Diving	12	11
Kayaking/Paddle Sports	7	6
Other	8	7
Total	112	100

To understand how visitors responded to the change in the resource conditions, we inquired about any changes in behavior related to recreation (Table 3). For the greatest proportion of the respondents, their recreation locations stayed the same, and, for a minority, the activities stayed the same and/or the frequency stayed the same. However, a notable proportion of people decreased the amount of time for which they participated in Florida Keys recreation, and some people switched recreational locations or activities due to the warmer water temperatures. A small percentage of the respondents increased the amount of recreation that they participated in during the heat stress situation.

Table 3. Survey responses for behavior changes in recreation activities as a result of warm water temperature events in Florida Keys National Marine Sanctuary. Respondents could select more than one option so the total response percentages may add up to beyond 100 percent.

Response	Frequency	Overall Percentage (%)
My recreation locations have stayed the same	48	44
My recreation activities have stayed the same	38	35
My recreation frequency has stayed the same	34	31
I have decreased the amount of time I do recreation	32	29
I have switched locations for my primary recreation activity	13	12
I have switched my primary activity to another activity for recreation	5	5
I have increased the amount of time I do recreation	3	3
Other situation	3	3
Total	176	160

The respondents were asked about their knowledge and concern regarding the summer 2023 heat stress situation (Tables 4 and 5). The respondents reported the greatest knowledge of issues such as increasing water temperatures, coral bleaching process, water quality, and habitat loss from coastal development. The respondents had the highest concern for water quality, pollution, fish and marine animal health and disease. The respondents generally stated that they had the smallest amount of knowledge about ocean acidification and the smallest amount of concern about the sea level rise.

To understand how the respondents typically received information about recreation in the Florida Keys, we inquired about the most and least common sources of information (Table 6). The most used sources of information for the respondents were the internet, the Florida Fish and Wildlife Conservation Commission, and word of mouth. The least used information sources were the Atlantic States Marine Fisheries Commission, the National Marine Sanctuary Foundation, and the American Sportfishing Association. One third of the respondents sought information from the FKNMS website, while one fifth of the respondents reported FKNMS social media as an information source that they used.

Table 4. Survey responses for knowledge and concern level related to heat stress and environmental factors with responses on 5-point Likert scale [1] for each respective theme.

Factor	Mean Knowledge Score	Mean Concern Score
Increasing water temperatures	3.6	3.6
Coral bleaching process *	3.6	4.0
Water quality *	3.6	4.2
Habitat loss from coastal development *	3.6	4.0
Pollution (mercury, sewage, pesticides, etc.) *	3.5	4.1
Coral disease and health *	3.4	4.0
Sea level rise	3.4	3.3
Fish and marine animal health and disease *	3.3	4.1
Ocean acidification *	2.7	3.5

[1] Average knowledge and concern (scale 1 = not at all familiar to 5 = extremely familiar and 1 = not at all concerned to 5 = extremely concerned). * Indicates statistically significant difference overall ($p < 0.05$).

Table 5. Survey responses for identification of healthy versus unhealthy/bleached corals. Response selection frequency for each image is shown. Correct answer choices were image A and image D. Respondents could select more than one option so the total response percentages may add up to beyond 100 percent. Images A–D shown below.

Response	Frequency	Overall Percent (%)
Image A	71	66
Image B	12	11
Image C	6	6
Image D	91	85
Total	180	168

Table 6. Survey responses for sources of information utilized by respondents for information related to Florida Keys National Marine Sanctuary. Respondents could select more than one option so the total response percentages may add up to beyond 100 percent.

Source	Frequency	Overall Percentage (%)
Internet	73	70
FWC: Florida Fish and Wildlife Conservation Commission	62	59
Word of mouth	54	51
Fishing magazines/newsletters	53	50
NOAA's National Marine Fisheries Service	42	40
Florida Keys National Marine Sanctuary Website	35	33
Television	35	33
Newspapers	29	28
SCUBA diving magazines/newsletters	25	24
Florida Keys National Marine Sanctuary Social Media	21	20
Radio	20	19
International Game and Fish Association	14	13
Florida Keys National Marine Sanctuary Advisory Council and/or Staff	7	7
American Sportfishing Association	6	6
National Marine Sanctuary Foundation	5	
Atlantic States Marine Fisheries Commission	4	
Other social media	19	
Others	21	
Total	525	

The interviewees were asked to report the number of days for which they participated in recreation in the Florida Keys monthly (Table 7). The respondents reported a mean number of 5.9 days participating in recreation each month at the Florida Keys National Marine Sanctuary, while the median value for the number of days participating in primary recreation activities was 4 days per month.

Table 7. Survey responses for typical ocean recreation frequency (days per month) in Florida Keys National Marine Sanctuary.

	# of Days	Frequency
Average	5.9	
Range	0–31	
Total		103

Overall, the respondents provided a mean satisfaction level of 7.04/10.0, which corresponded to "moderately satisfied", with their most recent recreational experience in the Florida Keys National Marine Sanctuary (Table 8). The respondents' ratings of satisfaction linked with the date of their most recent recreational outing in the FKNMS were compared and found to show no statistical difference (t = 1.94, df = 48.9, p-value = 0.058) in the time periods representing pre-summer (before June 2023) and summer (June–September 2023). The mean satisfaction decreased between the pre-summer and summer periods (from mean value 7.6/10 to mean value 6.6/10, respectively) of 2023, which temporally corresponded with the increasing water temperatures and coral bleaching impacts (Figure 3).

Table 8. Survey responses for trip satisfaction [1] with respondents' most recent recreation experience in Florida Keys National Marine Sanctuary.

	Satisfaction Rating	Frequency
Average	7.04	
Range	1.1–10.0	
Total		105

[1] Average trip satisfaction (scale 1 = extremely dissatisfied to 10 = extremely satisfied).

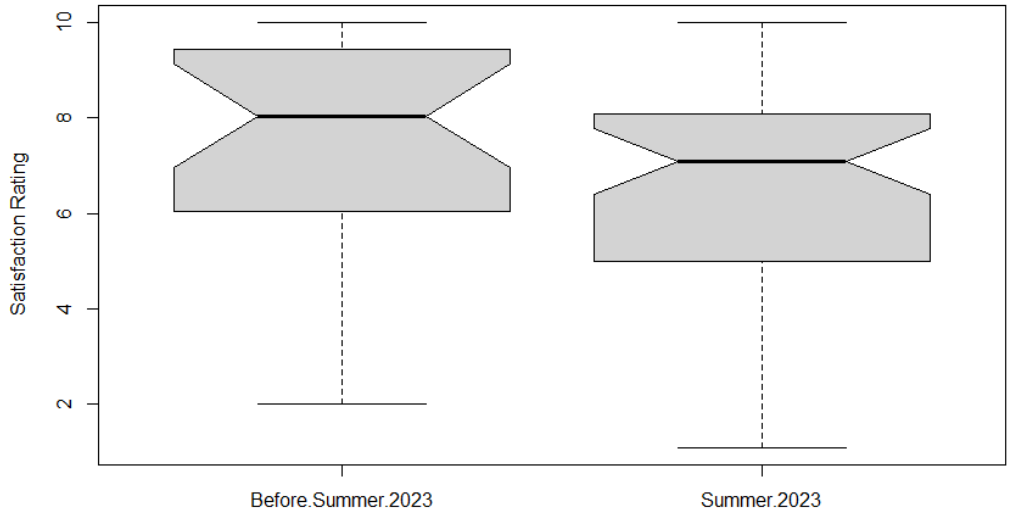

Figure 3. Survey respondent satisfaction ratings for most recent recreational outing in the Florida Keys National Marine Sanctuary plotted over two time periods. Two time periods are shown, representing pre-summer (before June) and summer (June–September) timeframes in 2023. Mean satisfaction values were higher (7.6/10) before summer 2023 than during summer 2023 (6.6/10), although the difference was non-significant (p = 0.058).

4. Discussion

The evaluation of heat stress on coral ecosystems has been conducted for numerous years, with efforts to understand the mechanisms of impact and improve their tolerance and survival [23]. Some research suggests and predicts an increasing frequency and severity of heat stress events and a lack of time for coral acclimation and/or adaptation [24]. Others demonstrate the potential for ecological resilience to climate change effects and the

reduction of bleaching damage [25]. Advances in understanding, from heat shock proteins' presence to the mechanisms of transcriptome expression, have helped to establish the biophysical relevance of thermal stress events [23]. Concurrently, the further understanding and awareness of the economic benefits of functional coral reef systems and their value to society has created a need for holistic research that considers the effects of heat stress events on human perceptions and behaviors.

In the Florida Keys, coral reef systems have experienced both positive and negative production dynamics over previous decades [26]. The potential for positive accretion may be species- or location-dependent, while erosion in some areas may be unavoidable due to thermal stress and disease occurrence [26,27]. However, some models suggest a reef accretion capacity at focal M:IR reefs following restoration activities over future decades [26]. Moreover, the model projections often include the steady-state effects of human disturbance and emission scenarios in the future. Therefore, the importance of incorporating human socioeconomic data into the evaluation of such impacts as thermal stress events is critical. Restoration efforts can be more effective with support from people at various levels of involvement [28]. Understanding the effects on ecosystems of such events as thermal stress and restoration is paramount, but this should also include social and economic dimensions.

This rapid survey assessment represents a systematic data collection effort designed to allow the sanctuary and other interested people and organizations to better understand the visitors to the Florida Keys as they related to changing coral reef ecosystems and heat stress impacts. The effort employed data collection methodologies to understand visitor use patterns, as well as their expectations/preferences, motivations, trip experience, and substitution effect levels. The results of this effort will serve as a baseline for heat stress impact assessment regarding the communities and people associated with reef ecosystem visitation and use. The database generated will allow resource managers and officials to better understand the projected immediate impacts on tourism and associated outdoor recreation and aquatic activities. This will allow more informed planning, marketing, and amenity services, designed to be resilient to changes in the ecosystem and adjusting for potential visitor and client needs and preferences. The results will also allow natural resource leadership to best position itself in alignment with the changing management and conservation plans in the Florida Keys, driven by science. The incorporation of such social dimension data that correspond to ongoing biophysical phenomena can be informative in understanding the perceptions of the users of these resources and can provide further evidence and justification for management and conservation plans and actions.

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