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Seaweed Invasion! Temporal Changes in Beach Conditions Lead to Increasing Cenote Usage and Contamination in the Riviera Maya

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Abstract: Since 2011, tourism to Mexico's Yucatán Peninsula has been heavily impacted by large masses of sargassum seaweed washing up on the beaches, with the largest seaweed event occurring in 2019. Seaweed deters beach tourism, potentially shifting tourism inland towards other activities such as swimming in cenotes (sinkholes). Our mixed methods study combined data from surveys of visitors to the region, interviews with tourists and tour operators, thematic analysis of newspaper articles, laws and policies and analysis of water samples from a cenote to understand the environmental impact on cenotes of this shifting tourism industry. We identified intentional efforts by the tourism industry to encourage cenote tourism in response to the seaweed problem, and our survey and interview data confirmed that tourists are choosing to visit cenotes in lieu of beaches. Water samples from one tourist cenote in 2019 indicated increased pollution relative to previous years. Current regulations and management of tourist cenotes are weak, creating the potential for significant long term harm to the environment and to the water sovereignty of surrounding communities. Regulation of cenotes should be strengthened to protect these fragile karst ecosystems and to give local and indigenous residents a formal voice in the management process.

Keywords: Mexico; Cancun; tourism; water; seaweed; sargassum; climate change; adaptation; cenotes

1. Introduction

Since 2011, large masses of sargassum seaweed have washed up on the beaches of the Yucatán Peninsula in Mexico, wreaking havoc on the region's tourism intensive economy. The unexpected arrival of large masses of seaweed has occurred throughout the Caribbean, prompting investigations of the source of these new seaweed events. It was originally assumed that the source of these mass seaweed arrivals was the Sargasso Sea, an area of the Atlantic Ocean north of the Antilles that has historically had large masses of this seaweed [1,2]. However, drawing on remotely sensed imagery, and models of ocean temperatures and currents, Wang et al. (2019) [3] found that the increase in sargassum seaweed in the Caribbean was directly tied to a number of factors related to climate change

and globalization; the factors included changes in ocean temperatures and circulation patterns, the high volume of sargassum seaweed from the previous season which served as a "seed source", and increased nutrient runoff from the mouth of the Amazon River in Brazil, resulting from increased deforestation and the industrialization of their agricultural systems. The source of the current sargassum seaweed blooms has been identified as an area in the north of the mouth of the Amazon and Orinoco River, off the northern coast of Brazil, in the zone known as the North Equatorial Recirculation Region (NERR) [3–6]. Historically, this region has not typically been associated with the growth of Sargassum seaweed. Scientists believe this recent change is due to increased nutrient loads in the Amazon River caused by intensification of Brazil's agriculture systems, and the upwelling plumes off northwest Africa and the equator [7] combined with the impacts of global climate change, which has increased ocean water temperatures and changed ocean currents [6,8]. The models by Wang et al. (2019) also predict that under conditions of increasing nutrient inputs and deforestation in Brazil, along with the existing substantial seed masses of Sargassum seaweed in the tropics, these big seaweed events are likely to occur with more frequency and severity in the future [3].

Seaweed events of lesser magnitude were observed in the years following 2011 [8,9]. However, in 2014 and 2015, an intense and strong 'sargassum event' occurred again, which affected the Greater Antilles, as well as some countries bordering the Caribbean Sea, including Mexico [9,10]. An even larger sargassum event occurred again in 2019 [3]. The Riviera Maya of Mexico, a region which includes Cancun, is strongly dependent on tourism. The region's tourist industry generates $US8.6 billion of income annually, which represents 85% and 8.9% of the Gross Domestic Product (GDP) state and national, respectively [11]. These large sargassum events have generated significant aesthetic, health, economic and environmental concerns, and the potential continuation of this environmental phenomena has also created great uncertainty about the long term impact of these seaweed invasions on the tourist industry for the region.

The immediate impacts of the mass arrival of sargassum in the Riviera Maya have been varied. From the aesthetic point of view, sargassum alters the beauty of the region's pristine sandy beaches and the decomposition of the seaweed emits an unpleasant odor as it releases sulfuric acid upon decomposition [12]. Accumulation of sargassum seaweed results in a lack of tourist access to the beaches, high cleanup costs, and the inability to operate waterways and coastal activities. In severe cases, tourists cancel vacations, hotels close rooms, and beachfront restaurants close their doors, resulting in the dismissals of personnel and an economic hit to the coastal tourist economies [9]. From an ecological perspective, the most significant concerns, such as beach erosion and disturbance of marine species, are limited to the coastal regions of the Yucatán Peninsula.

A similar situation occurs with algal blooms and eutrophication, which are extreme environmental events that are often driven by complex factors (like climate change) beyond the control of the individual actors in the tourism dependent region. These extreme environmental events can create negative perceptions about tourist destinations, leading to displacement of tourists from or within the region [12]. Globally there have been numerous case studies documenting the impact of eutrophication and algal blooms on tourism in other regions of the world [13–15]. In 1989 there were severe algal blooms in the Italian Adriatic Sea, which resulted in a 25% decline in visitors and a significant impact on the region's image as a tourist destination [16]. From 1993 to 2013, major outbreaks of algal blooms in the North and Baltic Seas similarly affected tourist destinations, resulting in declines in tourism [17]. In their studies of the Baltic Sea, Nilsson and Gössling (2013) [11] likewise found that algal blooms in the Baltic Sea had a significant and negative impact on the summer tourist season in southern Sweden, which coincided with the time period when the risk of algal blooms is greatest. Given the complexities of global climate change, the impacts of these extreme environmental events on tourist destinations and the subsequent displacement of tourist populations warrants further exploration.

Since the first massive seaweed arrivals in Mexico in 2011, there have been a number of initiatives to investigate the impacts and management of sargassum in the region. However, management responses have been reactive rather than proactive, very costly, and not always sustainable. Most have

focused on mitigating the presence of seaweed on the beaches. The potential impacts of the sargassum seaweed on the inland tourism industry have been largely overlooked, despite the fact that there are many additional types of recreational activities, such as theme parks, *cenotes* (sinkholes), and cultural tours. If tourists are moving away from the beaches towards these inland activities, it may have a positive economic impact on these other tourist activities, but also poses potential new issues with environmental impacts as additional people visit other types of ecologically fragile areas

Open *cenotes* or sinkholes are geological structures that are common throughout the Yucatán Peninsula. They are formed by the dissolution of carbonated rocks; natural weathering processes form underground caves filled with water, and over time the roof of the cave may completely or partially collapse. These cenotes are part of a karst aquifer system which provides the only source of drinking water in the region [18,19]. Many of these cenotes are used as recreational features where tourists can swim or go cave diving [20]. However, intensive tourism and rapid population growth is putting the Yucatán's groundwater aquifer at risk due to water contamination from tourism and urban development [19,21–24]. The geological characteristics of karst systems allow the rapid flow of water into the aquifer and laterally throughout, thus transporting associated contaminants [24]. Disposal of untreated or improperly treated wastewater and inadequate septic systems makes these cenotes highly susceptible to fecal contamination [21,25], affecting the drinking water source for surrounding residents and the health of tourists visiting the region.

Another contamination risk factor associated with the increase of tourists in recreational cenotes is the intensive use and application of sunscreens. Sunscreens contain organic and inorganic compounds that have adverse effects on aquatic biota [26–28]. In oceans, sunscreen contamination has been shown to such reduce coral cover, reduce the density of aquatic herbivores and carnivores, as well cause as an increase in macroalgae coverage [29]. Less is known about the specific impacts of sunscreen contamination on aquatic biota in cenote systems. The components of sunscreens are highly toxic, and their effects on biota may cause endocrine disruption, bioaccumulation or they can be lethal [27,30,31]. The use of sunscreens by the more than 15 million tourists who visit the Riviera Maya each year poses a potential risk to the cenotes in the region, particularly if tourist activities shift inland and away from the seaweed covered beaches. However, despite these potential risks, there is a lack of knowledge about how many people are choosing to visit these sites and the potential impacts on these fragile groundwater dependent ecosystems.

The seaweed problem is complex in terms of both its origins and impacts on the Riviera Maya region, and thus solutions to this problem must also take an interdisciplinary approach, incorporating understandings of the economic, social, and environmental drivers and impacts. The objective of our research was to understand how the sargassum seaweed problem has impacted tourist perceptions and behaviors in the Riviera Maya region, including their awareness of the sargassum problem, and how the presence of seaweed on the beaches has driven changes in their behaviors as tourists. Understanding how tourist behaviors are affected by the sargassum seaweed is essential in order to establish improved public actions and policies that protect the local environment and the tourist-dependent local economy in relation to changing touristic activities.

2. Study Area

The Riviera Maya of Mexico is a located in the eastern Yucatan Peninsula of Mexico, surrounded by the waters of the Gulf of Mexico and Caribbean Sea, in the eastern state of Quintana Roo. The region begins just south of Cancun and extends towards the city of Tulum, although for the purposes of this paper we are including tourism to the city of Cancun in our discussion of tourism in the Riviera Maya (Figure 1). The Riviera Maya is famous for large all-inclusive resorts and luxury travel, as well as smaller boutique hotels and sleepy beach towns. In particular, tourists are drawn to the region because of the white sandy beaches and opportunities to visit the MesoAmerican Barrier reef which spans the length of the peninsula, and continues south towards Guatemala. Additional touristic activities include ecotourism, such as visits to the jungle or the cave systems (including cenotes), and cultural

tourism of Mayan ruins and indigenous Mayan communities (Figure 2). Many of these activities, such as swimming in cenotes, take place along *La Ruta de Cenotes*, a 35 km stretch of road that joins the towns of Leona Vicario and Puerto Morelos.

Figure 1. Reference map of the Yucatán Peninsula depicting the three states of Campeche, Yucatán, and Quintana Roo (**left**) and the state of Quintana (**right**), with the Riviera Maya extending from Puerto Morelos south to Tulum. The majority of tourist activity occurs in the north of Quintana Roo, with extensive tourism of cenotes happening along the Ruta de Cenotes.

Tourism is central to the economy of Quintana Roo and the Riviera Maya; as of 2018, the city of Cancun had a population of 88,600 but received approximately 17 million tourists [32,33]. Many of these tourists remain in Cancun, but others travel south to other cities and hotels within the Riviera Maya. Tourists arrive from all over the world, with the most popular source countries including the United States, Canada, various countries in South America, and less frequently from Europe. Peak tourism to the region occurs during the summer months (June and July) and winter months (December through March), with fewer tourists visiting during the low season months [34]. In the Mayan Rivera in 2017 economic benefits of around 8.8 billion dollars were generated, with an average occupancy of 79.7% [35].

Figure 2. Tourists swimming in a popular cenote in Quintana Roo, Mexico. (Photo by C. Gallaher, 2019).

3. Methods

In this study, we used a mixed methods approach to data collection in order to understand tourists' perspectives on the sargassum seaweed problem and how their perspective influences their behaviors. Field data for this study were collected over a period of two weeks in July 2019 and consisted of three distinct components: 1) surveys of tourists regarding the seaweed problem, 2) semi-structured qualitative key informant interviews with people affected by the seaweed problem, and 3) collection of water samples from one cenote in the region. Additional qualitative data was collected from news articles about the seaweed phenomena in the region, and legal documents pertaining to management and regulation of cenotes.

3.1. Surveys and Interviews

Surveys and interviews were conducted in the municipalities of Benito Juárez and Puerto Morelos in the state of Quintana Roo, Mexico, in five sites: two in the Municipality of Benito Juárez (Playa Forum and Playa Langosta in the hotel zone of the city from Cancun) and three in the Municipality of Puerto Morelos (One on the Coastal Walk in the town of Puerto Morelos, and two on the Route of the Cenotes of Puerto Morelos). Additional surveys were conducted at multiple cenotes along *La Ruta de los Cenotes*. We surveyed visitors to touristic areas (n = 253), including both foreign and national tourists and local residents, in beaches, downtown areas, and cenotes. Sampling of respondents was pseudo-random; most visitors passing through our study sites were asked to participate in the survey, but some declined. Survey questions focused on basic sociodemographic questions and concerns about environmental issues in the region. Additionally, visitors were asked about perspectives on the sargassum seaweed problem, and choices they made in response to the seaweed problem. Surveys were administered on iPads using the survey software Qualtrics. Questions used a combination of formats including multiple choice, multiple answer, Likert scale ratings, and open ended responses, and were designed using concepts from literature and personal experience in the field. When administering the

survey, questions were read to the respondents if they wished, or they were allowed to take the survey themselves. Surveys were pretested on a small number of tourists (n = 20) prior to beginning actual data collection, and questions were revised for clarity. Data from the surveys were analyzed using SPSS version 26 (IBM, USA) to test the relationships between sociodemographic variables, general environmental concerns, awareness about the sargassum seaweed problem, and the impact of the seaweed on the choices they made as tourists. Additionally, semi-structured, qualitative key informant interviews were conducted with local business owners, scientists, community activists and visitors to the region (n = 18). Interview participants were recruited using a snowball sampling approach. Interviews were audio-recorded, transcribed, translated, and thematically analyzed using a grounded theory approach [36] to understand the impact of the seaweed problem on the tourism industry, as well as the community and governmental response to addressing the seaweed problem.

3.2. News Articles and Policy Documents

Additional qualitative data was collected in the form of articles from newspapers or online travel websites related to the seaweed problem. We analyzed articles from international, national, regional, and local newspapers and international travel websites that discussed the seaweed problem and that encouraged alternative forms of tourism (Table 1). These newspapers and travel websites were chosen for two reasons; the range of target audiences, including international tourists, national tourists, and local residents, and because these sources contained articles about sargassum seaweed and alternative tourist activities. Given the relatively new nature of this phenomenon, articles on this topic were limited. To identify articles, we performed a general web search in Google, and then specific searches within each of the chosen news sites using the terms 'seaweed', 'sargassum', 'tourism', 'cenotes', 'Yucatán', and 'Riviera Maya' alone or in combination, in English or in Spanish. Because we were interested in the impact of the seaweed on changing tourist behaviors, we only included articles that discussed the seaweed problem in relation to alternative touristic activities.

Table 1. Articles from international, national, regional, and local newspapers and international travel websites were included in our content analysis of the ways in which the tourism industry was encouraging alternative forms of tourism in response to the sargassum seaweed problem.

	Source	Target Audience
International		
Travel website	Travel Weekly www.travelweekly.com	International tourists
Travel website	Trip Advisor www.tripadvisor.com	International tourists
Newspaper	The Daily Mail www.thedailymail.co.uk	International tourists
National		
Newspaper	Mexico News Daily www.mexicodailynews.com	English speaking Mexican nationals or international tourists
Newspaper	El Universal www.eluniversal.co.mx	Spanish speaking Mexican nationals or international tourists
Regional		
Newspaper	Novedades Quintana Roo https://sipse.com/novedades	Local residents and Spanish speaking tourists
Newspaper	Riviera Maya News https://www.riviera-maya-news.com/	English speaking local residents and tourists
Travel company website	Selvatica www.selvatica.com.mx	Tourists
Travel company website	Absolute Adventure www.absolute-adventure-mexico.com	Tourists

We also analyzed laws and policies relevant to the environmental regulation of cenotes based on the regulatory framework proposed by Cortés and Campo (2018) [37]. We identified 15 federal, state and municipal laws and policies that govern karst groundwater systems in the states of Campeche, Yucatán, and Quintana Roo, and analyzed each of these policies and laws to understand whether or not the regulations were specific to cenotes or more general to groundwater in the Yucatán Peninsula. Additionally, we categorized the regulations based on whether or not they specified management in relation to four additional criteria: water quality, appropriate uses of the cenotes, touristic activities, and general ecological conservation.

3.3. Water Chemistry from a Cenote

Water samples from the cenote were collected using a Beta Van Dorm Wildco water sampler (Yulee, FL) at the surface near the south edge. Samples were collected in the same two week time period during the summers of 2017–2019. All samples, with the exception of the alkalinity samples, were immediately filtered using 0.2 µm syringe filter, placed in a cooler and stored at 4 °C until analysis. A HACH HQ 40d multi-probe (Loveland, Colorado) was used to measure physio-chemical properties of unfiltered samples in the field for pH, temperature (°C), electrical conductivity (µS/cm), dissolved oxygen (mg/L), and oxidation-reduction potential (mV). A plastic beaker was rinsed three times with sample water prior to measurements. Probes were calibrated regularly according to instructions of the manufacturer. A HACH DR2800 Spectrophotometer (Loveland, Colorado) was used to measure nitrate, nitrite, ammonia, and phosphate within 24–48 h of sample collection. Alkalinity was measured with digital titrations using a HACH digital titrator.

Water samples for major ion analysis were transported and stored in sterile, polypropylene 50 mL centrifuge tubes rinsed 3x with sample water. Major ion analyses were tested on a Dionex Ion Chromatography System (IC; Waltham, Massachusetts) at Northern Illinois University (NIU). Samples were analyzed for major cations including sodium, potassium, calcium, magnesium, and ammonium, as well as major anions including fluoride, chloride, nitrate, phosphate, and sulfate.

3.4. Limitations

This was a preliminary study based on a rapidly evolving natural and social phenomena, so there are limitations to our methodology that are worth acknowledging. First, the number of cenotes that we were able to collect survey and interview data from was somewhat limited relative to the total number of touristic cenotes in the region, although we chose three prominent cenotes along the Ruta de Cenotes. Second, water samples were collected from a single cenote over a period of three years. In the future, we plan to conduct a more comprehensive study that will include more regular sampling of multiple cenotes over the course of the tourist season. Finally, content analysis of news articles was limited by the lack of published articles on the topic of seaweed and cenote tourism, so these findings should also be considered as preliminary. However, the messaging was consistent across the articles we identified.

4. Results

In our sample (n = 253), 66% of participants were considered to be local residents of the state of Quintana Roo, and the other 34% were tourists visiting the Riviera Maya from other parts of Mexico or abroad. Of non-residents, approximately half (48%) were Mexican nationals and the remainder were visiting from all over the world, including the United States, Canada, Europe, and various parts of South America (Table 2). This composition of nationalities is fairly typical for the summer tourist season, which tends to see more tourists from other regions of Mexico and South America when it is winter in the southern hemisphere, whereas during the winter months of the northern hemisphere, the tourist population in the Riviera Maya is predominately from North America and Europe. There were some differences between survey participants who were local residents versus tourists in terms of both gender and level of education, with the participants who were tourists to the region being, on average,

somewhat more educated (college versus high school), and with more tourists than locals identifying as female (60% compared to 47%).

Table 2. Characteristics of the sample. Our survey sample of visitors to the region was diverse in terms of gender, age and place of residence.

	Locals	Tourist	All Participants
Gender			
Female	47.2% (n =77)	59.7% (n =52)	51.6% (n = 129)
Male	52.1% (n =85)	40.2% (n =35)	48% (n = 120)
Nonbinary	0.6 (n =1)	0%	0.4% (n = 1)
Mean Age	32.8 ± 10.9	37.8 ± 13.6	34.5 ± 12.1
Average level of education	High school	College graduate	Some college
Place of Residence			
Mexico	100% (n = 163)	47.6% (n = 41)	
USA		24.4% (n = 20)	
Canada		4.6% (n = 4)	
Colombia		5.8% (n = 5)	
Europe		6.9% (n = 6)	
Central America		3.4% (n = 3)	
South America		3.4% (n = 3)	
The Caribbean		3.4% (n = 3)	
Australia		1.1% (n = 1)	

4.1. Seaweed Decreased Beach Tourism

Given the importance of tourism to the local economy of the Riviera Maya, we were first interested in understanding whether or not tourists were made aware of the seaweed problem prior to traveling. The majority (60%) of tourists we surveyed reported receiving information about the seaweed problem prior to traveling to the Riviera Maya, while a smaller number (20%) were given information about the problem after arriving in Cancun. During qualitative interviews, participants shared that most information prior to traveling came from reading the news, Facebook group pages, and travel blogs.

However, key informant interviews with local business owners revealed concerns that the seaweed problem was being exaggerated on social platforms and negatively impacting local businesses. As an owner of a local bed and breakfast explained:

> The problem with sargassum and tourism is that people get online and start sharing all the pictures and people say "Oh my God." We have a Facebook page for the town called Friends of Puerto Morelos, and some people would go and take pictures . . . well, thank you very much for telling the world that they shouldn't come to Puerto Morelos for tourism. Because it (sargassum) comes and goes. But they would take horrible pictures of how it was here, so people were canceling reservations . . .

Tour operators we interviewed in the region similarly expressed frustration with the situation because they regularly had to explain to visitors that seaweed did not affect certain aquatic activities such as snorkeling or boat tours. Both local business owners and tour operators felt the media exaggerated the overall impact of sargassum, particularly given that the arrivals in various beach towns differed significantly by geography. According to the Sargasso Monitoring Network of Cancun [38], sargassum arrivals in May 2019 were concentrated in the south of Quintana Roo (including the towns of Tulum, East Coast of Cozumel Island, Mahahual and Xcalak), and the impact on the northern towns (including Holbox, Cancun, Isla Mujeres, Playa del Carmen and Puerto Morelos) was significantly smaller (Figure 1).

Because of the seaweed problem, both local residents and tourists reported spending less time than expected at the beach, although local residents appeared to be disproportionately affected with

59% of local residents saying they were spending less time at the beach compared to 47% of tourists. This was true regardless of whether or not they had received information about the seaweed problem prior to traveling. Interviews with tourists and local residents suggested that while tourists may make the best of a short visit to the area and continue to visit the beaches, local residents were more put off by the duration of the seaweed event. Additionally, health concerns may also play a role, as several local residents reported developing skin rashes from coming in contact with the sargassum seaweed. Decomposition of seaweed releases hydrogen sulfide gas and ammonia, which can cause respiratory, skin and neurocognitive symptoms, and sargassum toxicity is now a syndrome that doctors are beginning to recognize amongst tourists who have visited Caribbean beaches that were covered in seaweed [39].

This overall decrease in tourism in beach towns as a result of the sargassum problems has significantly impacted local businesses near the beach. Hotel owners reported their occupancies were down as much as fifty percent in 2019, and a tour operator for a snorkeling business said that he had received approximately the same number of tourists that month as he previously could have expected in a single day at the same time of year [40–45]. A tour operator for a snorkeling company captured the tension of the situation well when he said, "We live on tourism. People come to the beach, see the seaweed and are not interested in asking if the reef is equally full of sargassum, so they leave." Local tour operators have adapted to the drastic decrease in income in a variety of ways. Some now work by collecting sargassum on the beaches as part of government programs to address this contingency (with a daily salary of $15 USD), which they also complement with other activities such as construction and gardening that allows them to cover their basic needs.

4.2. Tourism Shifted Inland towards Cenotes

Given that visitors to the Riviera Maya were spending less time at the beach because of the seaweed problem, we then sought to understand the extent to which tourists were participating in other touristic activities in the Riviera Maya. Participants who spent less time at the beach than expected because of the seaweed problem reported visiting a variety of other local attractions instead (Figure 3). The most popular alternative attraction was cenotes (visited by 56% and 47% of tourists and locals, respectively), followed by theme parks, archaeological sites, aquatic parks, trips to the jungle, or opting to swim in the hotel pool. We found no significant differences in terms of which touristic sites were visited based on gender, age, or nationality. This increase in tourism was confirmed by the cenote owners we interviewed who reported an increase in visitors this year, which they attributed to the sargassum problem at the beaches. As the manager of one cenote explained, "Many people say that they don't go to the beach because it smells bad there, so instead they decide to come here." This sentiment was also shared by business owners we interviewed near the beach, who indicated they felt their clients were moving inland towards the cenotes.

The shift in tourism away from the seaweed covered beaches towards inland cenotes may be a reflection of a deliberate marketing strategy by tourism operators in the region. In our review of international travel websites and local and national Mexican newspapers, we found a number of references to cenotes as a positive alternative to beach tourism in the context of the seaweed crisis. For example, in an article published in "Travel Weekly" in June 2019, the author writes

> *"If sargassum has your clients worried about an upcoming trip or hesitant to book in the future, there are still ways to maximize their time in this diverse part of Mexico, which has so much more than beaches. Here are a variety of ways to enjoy a vacation in Quintana Roo beyond the coastline."*

The first recommendation on the list of options that follows is that tourists can go visit the cenotes in the region [46].

Similarly, in a press release published on 8 June 2019 by the Tourism Promotion Council of Quintana Roo (CPTQ), they state that

> *"Due to the massive arrival of sargasso to the coasts of the Mexican Caribbean, the Tourism Promotion Council of Quintana Roo (CPTQ) has opted to modify its promotion strategy abroad, eliminating images of beaches and promoting alternative recreational activities, [such as] . . . .Maya archeological zones, cenotes, theme parks, Mexican cuisine and shopping malls, among others".* [47]

CPTQ then explain how they are revamping their promotional materials to reduce the number of beach images, instead focus on images of inland touristic activities. They planned to use these alternative promotional strategies at least through the end of the rainy season, when there would likely be a decrease in seaweed arrivals [47]. We identified similar strategies and advice for tourists in a number of other local, regional, and national newspapers.

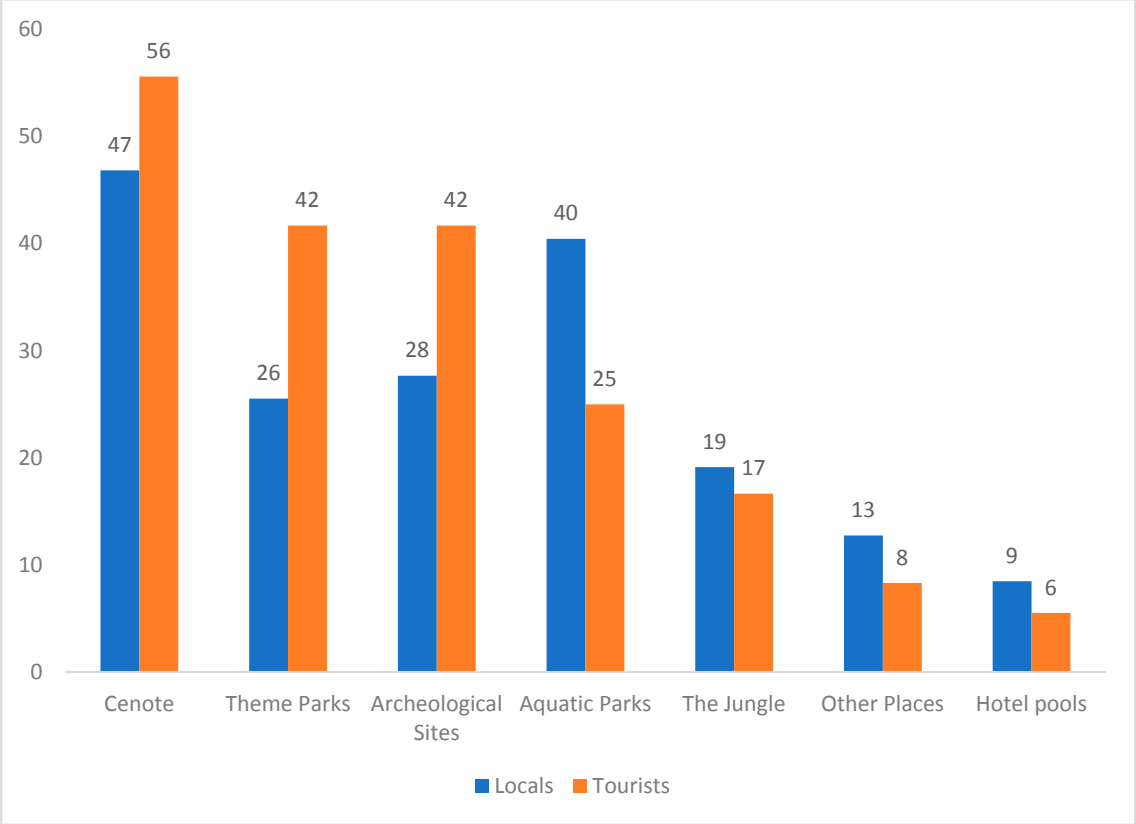

Figure 3. Participants who spent less time at the beach than expected because of the seaweed problem reported visiting a variety of other local attractions instead. Amongst both locals and tourists, cenotes were the most popular alternative destination followed by theme parks and archaeological sites for tourists, and aquatic parks and archaeological sites for local residents.

The strategy to shift tourism away from beaches to inland cenotes has potential social and ecological consequences which much be considered, particularly if this becomes a long term change in tourist behaviors. The tourist cenotes are part of a larger karst aquifer system in the Yucatán. In these karst systems, there is the potential for the rapid flow of contaminants into the cenotes and laterally into other parts of the aquifer. This karst aquifer is also the only source of drinking water for the region. If the presence of large quantities of seaweed on the beaches continues to drive tourism inland to cenote systems, this could have increasingly negative impacts on the water quality in the cenotes and the larger karst groundwater aquifer system. Even tourists reported concern about the impacts of tourism on the cenotes. Overall we found that about 92% of participants reported that they were concerned or very concerned about environmental issues in general, and the more concerned they reported themselves to be, the greater their level of concern regarding groundwater quality in the Yucatán and in the cenotes.

4.3. Changes in Water Chemistry at the Cenotes Over the Past 6 Years

Water quality was evaluated at one cenote along the touristic area of *La Ruta de Cenotes*. Samples were collected from a cenote where our survey and interview data confirm that there was an increase in tourism in 2019 relative to previous years. Various measures of water quality were collected at same cenote site during June of 2017, 2018, and 2019. In 2018, a single evaluation was conducted while in 2017 and 2019, multiple measures were made from the start to the end of daily tourist visits.

Accordingly with Reference [48], high levels of nitrite and nitrate are common indicators of the presence of human activities, related to the excretion of nitrogenous wastes (e.g., through urine and feces). At our sample location, the expressions of nitrate and nitrite rose during the three year period from 2017 to 2019, with the highest values detected at 2019 (Table 3). There was no increased human development in the area surrounding the cenote during this time period, thus we suggest that the increases in these values are indicative of increased tourist activities in the cenote, as a result of more tourists choosing to visit cenotes as an alternative to the beaches as a result of the sargassum seaweed. These preliminary findings confirm that increased tourist activities are impacting water quality in at least one cenote in the region.

Table 3. Results of selected water quality measurements of the cenote for 2017–2019. Results for nitrite and nitrate indicate a range of measurements for samples taken within the same 2-week time period during the summer.

Parameter/Year	2017	2018	2019
Temperature °C	27.2	27.7	28
pH	7.2	7.5	7.2
Conductivity (µS/cm)	1430	1086	1092
Nitrite NO_2 (mg/l)	0.45–0.077	0.055	0.067–0.69
Nitrate NO_3 (mg/l)	3.3–4.2	5.04	4.03–7.158

4.4. Water Policies and Laws in the Yucatán Peninsula

Given the shift in touristic activities towards inland cenotes, we analyzed applicable national, regional and local laws regulating the protection of groundwater and cenotes in the region. Mexico's National Water Law does not specifically regulate karst groundwater systems, nor cenotes and activities related to their use, because the legal definition of groundwater does not correspond directly with the characteristics of the *cenotes*. Under Mexican national law, groundwater is defined as "those national waters existing below the earth's surface", and does not consider natural surface outcrops of the water, although artificial outcrops by wells are included [36]. Cenotes are protected in a general sense by various other federal laws in Mexico, including the Agrarian Law, the General Law of Sustainable Rural Development, General Law of Ecological Balance and Environmental Protection, Expropriation Law, and Climate Change Law [36]. However, these laws focus broadly on conservation, protection and quality of natural resources, sustainability, and economic uses for natural resources. Absent from these laws are protections guaranteeing access to water, and they also do not contain specific provisions for different water sources such as karst groundwater systems.

An examination of regional and local water laws in the Yucatán Peninsula reveals broad variability in the types of protections afforded to cenotes (Table 4). Across the three states in this region (Campeche, Yucatán, and Quintana Roo), we examined the extent to which the existing laws and regulations protect cenotes in relation to four categories: water quality, water use, touristic activities, and general environmental conservation. The state of Campeche currently does not regulate *cenotes*, the state of Yucatán has the strongest protections, and the state of Quintana Roo has limited regulation of *cenotes* in only some of its municipalities (Figure 4). Within the five municipalities of Quintana Roo, only Solidaridad, Tulum, and Benito Juarez specifically regulate cenotes, while the municipality of Puerto Morelos lacks formal protection of its cenotes, yet receives a high concentration cenote tourism along the Ruta de Cenotes. Although a large number of tourists visit the city of Cancun, located in Benito

Juarez, there are no touristic cenotes in this municipality, so regulation of their use for tourism is less critical. Instead, tourists to Cancun head south towards cenotes in other municipalities, such as Puerto Morelos, which currently lack formal regulation.

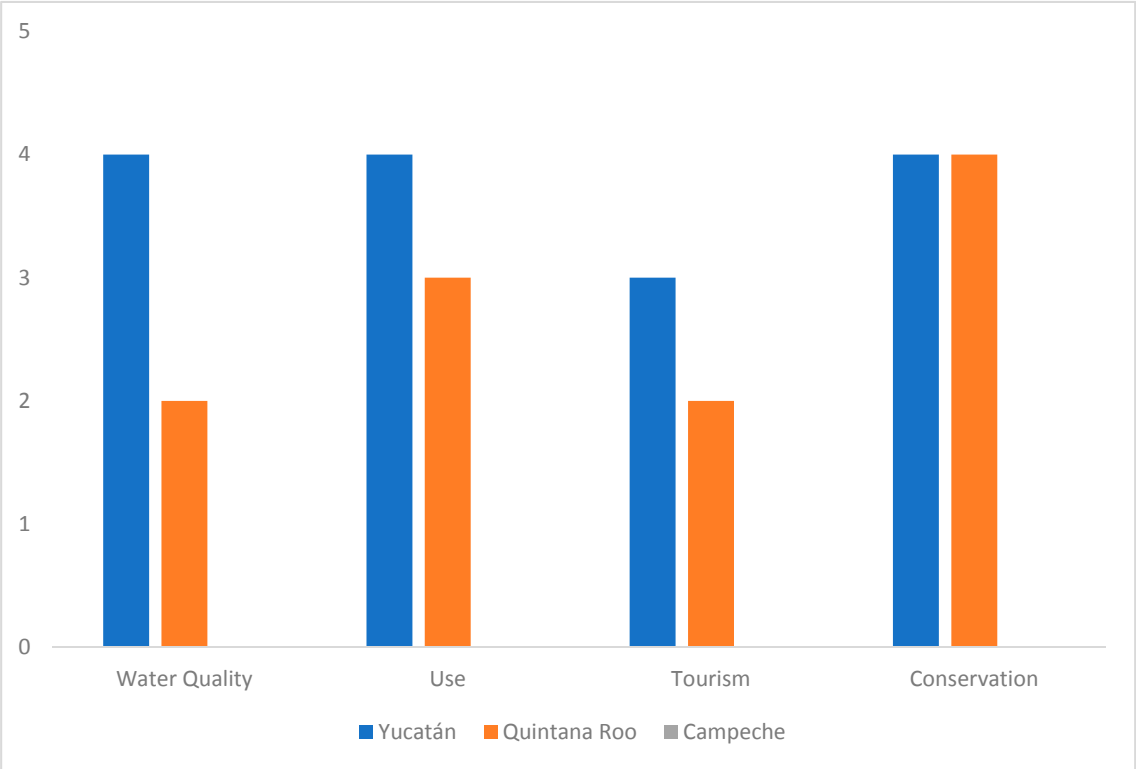

Figure 4. Laws and regulations in the state of Quintana Roo vary widely for cenotes in relation to the issues of protection of water quality, regulation of how cenotes can be used, tourist activities within cenotes, and general conservation of cenotes. Across these four issues, the state of Campeche has no laws or regulations concerning cenotes, the state of Yucatán has the strongest protections, and the state of Quintana Roo has limited regulation in some of its municipalities.

The municipality of Tulum regulates the use and conservation of cenotes and caverns, and requires the implementation of a Geographic Information System (GIS) to identify the locations of cenotes and to catalog baseline characteristics, such as water quality, associated natural resources such as flora, fauna, soils and geological traits, and various socioeconomic characteristics. This regulation also prohibits specific activities such as dumping organic or inorganic solid waste or liquids, dumping of dead animals, and use of cenotes as septic tanks. Additionally, it prohibits the use of fertilizers, pesticides, insecticides, soaps, detergents, shampoos and all other materials that endanger aquatic, terrestrial life, and the environment.

Finally, the regulation in Tulum requires that cenote users hold a concession permit from the National Water Commission.

Table 4. A summary of laws and regulations at the state and municipal level in Quintana Roo that are relevant to management of cenotes. In Yucatán, statewide laws govern the management of cenotes, while in Quintana Roo there is wide variability as only three municipalities have relevant laws. The state of Campeche lacks any formal regulation of cenotes.

Regulations of Cenotes	Number	Type	Level	State	Year	Regulation of Water Quality	Regulation of Use	Regulation of Tourism	Conservation
Law of Human Settlements of the State of Yucatán [49]	0	Law	State	Yucatan	1995	0	0	0	0
Law for the integral management of waste in the State of Yucatán [50]	0	Law	State	Yucatan	2016	0	0	0	0
Environmental Protection Law of the State of Yucatán [51]	1	Law	State	Yucatan	2010	1	1	1	1
Regulation of cenotes, caves and community wells of the municipality of Mérida [52]	1	Regulation	Municipal	Yucatan	2012	1	1	1	1
Regulation of the Law of Protection of the Environment of the State of Yucatan in Matters of Cenotes, Caves and Grottoes [53]	1	Regulation	State	Yucatan	2017	1	1	1	1
Decree number 117 - The protected natural area called the state geohydrological reserve of the Ring of Cenotes is established [54]	1	Regulation	State	Yucatan	2013	1	1	0	1
Total	**4**					**4**	**4**	**3**	**4**
Law for the Prevention and Integral Management of Waste of the State of Quintana Roo [55]	0	Law	State	Quintana Roo	2015	0	0	0	0
Law of ecological balance and environmental protection of the state of Quintana Roo [56]	1	Law	State	Quintana Roo	2001	0	0	0	1
Law of Human Settlements, Territorial Planning and Urban Development of the State of Quintana Roo [57]	1	Law	State	Quintana Roo	2018	0	1	0	1
Regulation of Ecology and Environmental Management of the Municipality of Benito Juárez, Quintana Roo [58]	1	Regulation	Municipal	Quintana Roo	2008	1	0	0	1
Regulation of activities in cenotes, caverns and caves of the municipality of Solidaridad, Quintana Roo [59]	1	Regulation	Municipal	Quintana Roo	2017	1	1	1	1
Regulation of activities in cenotes, caverns and caves of the municipality of Tulum, Quintana Roo [60]	1	Regulation	Municipal	Quintana Roo	2015	1	1	1	1
Total	**5**					**3**	**3**	**2**	**5**
Law for the prevention and integral management of urban solid waste and special management for the State of Campeche [61]	0	Law	State	Campeche	2014	0	0	0	0
Law of Ecological Balance and Environmental Protection of the State of Campeche [62]	0	Law	State	Campeche	2012	0	0	0	0
Law of Human Settlements, Territorial Planning and Urban Development of the State of Campeche [63]	0	Law	State	Campeche	2012	0	0	0	0
Total	**0**					**0**	**0**	**0**	**0**

Solidaridad, the municipality directly north of Tulum, also regulates activities related to cenotes. This regulation requires the owners of cenotes to have water samples from the cenotes analyzed twice a year (during the dry and rainy seasons) by a certified laboratory, and to deliver the results semiannually to the Environment Directorate. Additionally, the law requires owners and operators to conduct studies of the load capacity of reach cenote, cavern or grotto and to adhere to it for the execution of commercial activities. Owners who fail to carry out studies of carry capacity, or whose commercial touristic activities exceed the allowable load will be sanctioned. The law is not specific regarding who or how these carrying capacity studies should be done, but does suggest that capacity is a function of physical and chemical parameters, and not due to a perceived load capacity as stated by Blanco et al. 2019 [64]. The ambiguity in regulating cenotes in Solidaridad leaves the law open to interpretation or potential corruption to avoid penalties for noncompliance.

5. Discussion

5.1. Adapting to Future Seaweed Invasions

The seaweed invasion in the Riviera Maya of Mexico is representative of the complex ways that global environmental problems can play out with unforeseeable consequences on local communities. The Riviera Maya, much like the rest of the Caribbean, will need to find new ways to adapt to the likelihood that seaweed invasions, such as the one seen in 2019, will plausibly become more frequent events. In this context, it is important to consider the long term environmental and sociopolitical implications if the tourism industry does shift inland towards *cenotes*.

Although the seaweed events are not solely the result of a changing climate, the climate adaptation literature provides a useful framework for thinking about how best to adapt to the long-term impacts of major seaweed events in the Riviera Maya. Most of the literature on climate adaptation is framed using an adjustment approach, which tends to focus on technological adaptations to climate change, such as breeding more drought resistant crops or improving flood barriers [65]. This technological approach typically describes climate change as primarily an environmental problem, which requires consideration of the proximate factors of climate change and their technological solutions. The adjustment approach to adaptations is also similar to how the natural hazards literature has generally viewed environmental hazards as negative outcomes of the interaction between separate biophysical and social systems [66,67]. Limiting vulnerability and adapting to these hazards is achieved by strengthening the capacity of the existing system to increase resilience.

However, political economists and ecologists have historically argued that the focus within the adaptation literature on physical environmental problems misses the broader context in which these problems occur. Power and politics deeply influence human adaptation and ignoring the social and political context has the potential to exacerbate social vulnerabilities [68]. They argue for a reformist or transformative approach to adaptation, which places vulnerability and resilience in broader political, economic, and environmental contexts [65]. Rather than tweaking the status quo, these approaches advocate for changing the underlying system. Jennings (2011) [61] illustrated the risks of ignoring the social and political contexts in developing a climate adaptation plan in her study of a tourist village in Cornwall, England. Following a particularly intense flood, the town underwent extensive structural improvements to prevent damage from future flooding events, and their efforts have been held up by the UK government and major environmental organizations as an example of Britain's highly successful climate adaptation measures. However, Jennings' ethnographic study found that native villagers felt the adaptive measures put in place largely prioritized the needs and perspectives of the tourism industry, business interests, and government officials over the needs or desires of local residents [69].

The economy of the Riviera Maya is highly dependent on tourism, and the impacts of these large seaweed events are significant. The first major sargassum seaweed event occurred in 2011, followed by major and minor sargassum events every year thereafter. The initial responses to dealing with the

seaweed have primarily been focused on technological approaches to preventing the seaweed from washing ashore, or for removing the seaweed from the beaches. In 2015, more than 4400 workers were used to remove the sargassum from beaches that were considered to be most important for tourism; however, about 90% of the coast was not deemed essential for the tourism industry, and no seaweed was removed [70]. The Mexican federal government allocated $US 3.2 million to sargassum extraction in 2015, but the amount of seaweed exceeded the extraction capacity [70]. By late summer in 2019, Mexico had spent $US 17 million in seaweed removal efforts. Seaweed was removed from beaches in Cancun and some other cities of Quintana Roo using tractors with sweepers that combed the beaches, off loaded the seaweed into dump trucks, and disposed of the seaweed in formal or makeshift landfills (Figure 5). However, removing seaweed from the beach inevitably also removes large quantities of sand from the beaches, and disposal of the seaweed is complicated by the fact that the decomposition process releases large quantities of hydrogen sulfide gas, and some seaweed is high in heavy metals [9]. Another approach, such as the one used by the town of Puerto Morelos, is instead to use a series of floating seaweed booms to try to prevent the seaweed from being washed ashore. In 2019 the municipal government of Puerto Morelos placed 2200 linear meters of marine barriers in front of public beaches in the municipality [71].

Figure 5. Seaweed is removed from beaches in the Riviera Maya using a variety of techniques, such as the blue floating booms used by the city of Puerto Morelos (left) and tractors with sweepers used on the beaches of Cancun (right). (Photos by C. Gallaher, 2019).

Given the extent of this problem, the Mexican government has released guidelines for the management of sargassum in the Mexican Caribbean and the Gulf of Mexico. They provide specific technical recommendations and policies for the removal of the sargassum for capture and removal of seaweed from the ocean and beaches to agencies of the federal, state, and municipal government, the permit holders of the Federal Terrestrial Maritime Zone, maritime beaches, and those responsible for the turtle camps in which there is a problem generated by the sargassum [72]. Following the massive upheavals of sargassum along the Mexican Caribbean coast in 2015, the National Council of Science and Technology (CONACYT) created a multi-agency working group which released official recommendations for mitigation of and adaptation to sargassum seaweed in the Riviera Maya [71]. In the short term, the primary focus of their recommendations was on mitigation strategies to prevent

seaweed from reaching the beach by using new technologies for monitoring and capture of the sargassum seaweed, as they felt that the environmental impacts of cleaning up seaweed once it washed ashore were too significant to be viable in the long term. There was also minor discussion of socioeconomic responses that are needed in the short term, such as quantifying the economic impact of these large seaweed events on the tourism and fishing industries, and on understanding the potential human health impacts. At present, the Mexican government is using public resources for the removal of sargassum, which is expensive and becomes an environmental liability. Therefore, in the medium to long term, the working group also recommended regulated and sustainable use of sargassum as an industrial raw material for various economic sectors, and encouraging technological development associated with the sustainable use of sargassum. This could include commercial uses of sargassum in pharmaceutical and neutraceutical products, since Sargassum species analgesic, anti-inflammatory, antioxidant, neuroprotective, anti-microbial, anti-tumor, fibrinolytic, immune-modulatory, anti-coagulant, hepatoprotective, and anti-viral activity compounds [73].

Additional policy responses have been passed by various local governments in response to the seaweed problem. At the federal level, a proposal was made to categorize sargassum seaweed as a special residue, which would mandate its management under the General Law for the Prevention and Integral Management of Waste (section XI of Article 19) [74]. On 13 May 2019, the city council of Puerto Morelos approved a municipal regulation that regulates the management of sargassum waste, including the collection, transfer, storage, and final disposal of bio-waste, and fostering the intervention of the private productive sector to implement technology, which allows the use and final destination of these, for economic use [75]. Finally, on 7 June 2019, the State Government of Quintana Roo issued an emergency declaration for all coastal municipalities of the State of Quintana Roo, in the face of the "imminent natural disaster" as a result of the ecological damage caused by the sargassum seaweed. This emergency declaration provides access to federal emergency relief funds, and the government of Quintana Roo expects to gather 600 million pesos (approximately 30 million US dollars) to meet the contingency, which will come from the three levels of government and revenue from the Federal Terrestrial Maritime Zone [76].

Overall the responses by the national and local governments and research institutions emphasize an adjustment approach to mitigating and adapting to these seaweed events through the use of technological innovation. However, ocean barrier and beach removal technologies are costly and often insufficient, and many beaches are continue to be plagued by large quantities of sargassum. Thus, as explained previously, another major adaptive response has been the tourism industry's attempt to shift the focus inland towards other types of attractions, such as theme parks and cenotes. This shift is part of a deliberate strategy by tour operators and the Tourism Promotion Council of Quintana Roo to adapt to the detrimental impacts these large seaweed events have had on the beach tourist economy. Similar to the technological solutions to cleaning up the seaweed from the beaches, this again represents an adjustment approach to adapting to this problem, wherein one tourist activity is simply substituted for another. However, given the vulnerability of the cenotes within a karst groundwater dependent ecosystem, and the importance of the karst groundwater to surrounding residents who relying on this for drinking water, we argue that conversations about how to adapt to seaweed invasions need to use a much more transformative approach to adaptation that considers the broader sociopolitical context of a shifting tourism industry.

The Riviera Maya is still in the early stages of a new environmental reality. While the residents of this region have little control over the complex global factors driving these large seaweed events, the government, local business, and local residents can strategically choose how they approach adapting to the sargassum problem. Moving forward, there is an opportunity to improve the region's adaptive response to these seaweed events in a way that creates a more socially and ecologically resilient system. However, this will require more than just minor adjustments to the status quo. If tourism of inland cenotes intensifies, environmental policies in the region should be transformed and strengthened to better protect these ecologically fragile karst groundwater systems and the local residents who rely on

the groundwater for their livelihoods. In the next section, we will discuss the current shortcomings of the existing environmental regulations in the region that govern cenotes and discuss ways in which these regulations could be strengthened to accommodate a more comprehensive and resilient adaptive response that is inclusive of broader socioeconomic and political issues.

5.2. Regulation of Cenotes in the Yucatán

The majority of tourists to the Yucatán Peninsula visit the state of Quintana Roo, and it is this region that is also most impacted by the recent large seaweed events. As discussed previously, currently only three of the eleven municipalities of Quintana Roo have environmental regulations specific to cenotes: Solidaridad, Tulum, and Benito Juarez. Solidaridad and Tulum, located in the south of Quintana Roo, have the most comprehensive policies regarding management of cenotes, but receive far fewer visitors than Benito Juarez, which has less comprehensive policies and includes the city of Cancun, which receives the majority of tourists to the region. The municipality of Puerto Morelos, which receives many visitors to cenotes and includes our study sites, currently has no environmental regulations pertaining to cenotes (Figure 1). Importantly, the existing laws in Solidaridad, Tulum, and Benito Juarez do not regulate the maximum number of visitors or carrying capacities of the touristic cenotes. As the tourism industry in the Riviera Maya strategically shifts tourist activities inland towards cenotes, these deficits in environmental protections may have serious implications for this fragile groundwater dependent ecosystem.

There is a high risk of environmental contamination if tourism of cenotes. One potential source of contamination is sunscreen, which is commonly worn by tourists visiting the region. Most cenote operators require tourists to shower prior to entering the cenote, and specifically advise tourists against wearing sunscreen. However, in interviews with several tourists to cenotes, we found that many tourists applied sunscreen just before arriving at the cenotes to avoid scrutiny, and that showers were quick and unlikely to wash away the sunscreen they had applied. The adverse effects of sunscreen components can be devastating to aquatic communities; the negative impact of sunscreen on coral reefs has been well documented, but even freshwater systems can be adversely affected by sunscreen residues that can cause an increase in macroalgae and a decreases in carnivores and herbivores [28]. In 2018, the state of Quintana Roo received 21 million tourists who used 229.76 tons of sunscreen overall, which entered both marine and inland aquatic environments causing potential harm to these ecosystems [77]. The lack of existing laws or regulations to protect cenotes in Quintana Roo, particularly in the highly visited municipalities of Puerto Morelos and Benito Juárez, means that the health of these ecosystems is at risk. It also puts the rural populations near these cenotes at risk, as they must deal with the problems associated with groundwater contamination including fecal contamination and other types of pollutants such as sunscreens, medications, cosmetics, and hormones, introduced by tourists swimming in the cenotes.

Another key concern related to conservation and access to groundwater in the Yucatán is that cenotes are considered to be economically valuable water resources due to their competing uses as sources of drinking water for local households, use in irrigation systems, depositories for industrial wastes, and in some cases as popular tourist attractions due to the their beautiful cavernous formations and relationships to historical archaeological sites. This diversity of uses has caused many cenotes in the Yucatán Peninsula to be subject to buying and selling. Although the Mexican Constitution prohibits the sale of water resources, in practice these resources are commercialized through the sale of the lands where they are located [36]. An increased interest in tourism of cenotes may result in tourism companies looking to buy cenotes and land for their businesses, without considering the economic involvement of local communities. This process jeopardizes the water sovereignty of local residents, and can be considered as a violation of their fundamental human rights to water and a healthy environment.

The sargassum seaweed problem is likely to persist in the near future given the complex global drivers, such as changing ocean currents related to global climate change and increased nutrient

influxes from the Amazon. A more transformative approach is needed to protect the local residents and the groundwater dependent ecosystems that cenotes are part of. In Quintana Roo, regulation of groundwater and the tourism industry needs to be strengthened in the municipalities of Solidaridad and Tulum, and new regulations must be created for the municipalities of Puerto Morelos and Benito Juárez, which are most commonly visited by tourists. These new regulations should include inventories of all cenotes that are used for touristic activities and regulation of the maximum carrying capacity of each cenote that is grounded in the ecological resilience of the cenotes. Most importantly, a transformative approach to this problem must formally involve local and indigenous communities in decision making about tourism to cenotes in a way that provides maintains their rights and access to cenotes and to clean drinking water. Without explicitly involving local and indigenous communities in the creation of regulations and decisions about management of cenotes and the groundwater, it is likely that adaptation to the seaweed problem will prioritize the monetary needs of the tourism industry, rather than the water sovereignty of the local community members and the ecological health of the karst groundwater system.

6. Conclusions

Countries and communities throughout the Caribbean have been directly impacted by large sargassum events since 2011, with the problem being particularly intense in the Yucatán Peninsula. Our research investigated how the sargassum seaweed problem has impacted tourist perceptions and behaviors in the Riviera Maya region and how the presence of seaweed on the beaches was driving changes in their behavior. We demonstrate a clear change in tourist behaviors, away from beach tourism towards inland tourist activities such as swimming in cenotes, and the potential negative impacts if the tourist industry shifts inland without careful consideration of the ecological impacts of tourist activities or concern of local and indigenous communities. Because of the importance of tourism to the economy of the Riviera Maya, the government's adaptive response thus far has been largely focused on short term technological improvements to track and remove seaweed or prevent its arrival, as well as promotion of alternate tourist activities. However, current regulations and management of tourist cenotes is weak, creating the potential for significant long term harm to the ecology and water quality in cenotes, and to the water sovereignty of surrounding communities. These regulations should be strengthened to protect these fragile karst groundwater dependent ecosystems and to give local and indigenous residents a formal voice in the management and regulatory process.

Although our research focused on the impact of sargassum seaweed on tourism in the Yucatán Peninsula of Mexico, many tourist communities throughout the Caribbean have been impacted by these major seaweed events. Because this is a relatively novel problem, it is not well understood, nor is there scientific consensus about how intense or widespread these events are likely to be in the future. However, there is general agreement that these large sargassum seaweed events are likely to continue in the near term [3,5,68], and communities throughout the Caribbean will need to adapt in ways that will likely result in permanent changes to the tourism industry in some regions. The immediate adaptive responses in many countries have been primarily focused on prevention and cleanup of the sargassum from touristic beach zones. Many of the technological approaches described above, such as beach removal efforts and ocean barriers, are also being employed in other countries throughout the Caribbean [9]. Additionally, monitoring efforts have been implemented throughout the Caribbean to better understand the scale of the problem and their impacts on tourist beaches [34]. As Caribbean communities adapt to these large sargassum events in the longer term, it is extremely important that more transformational approaches to adaptation are implemented that consider the complex implications for local populations and the environment. Local laws and regulations may need to be strengthened or new laws created, and local communities must be involved in the decision making process. Without doing so, the long term impacts of the sargassum problem are likely to be inequitable and harmful to both local communities and environmental sustainability.

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