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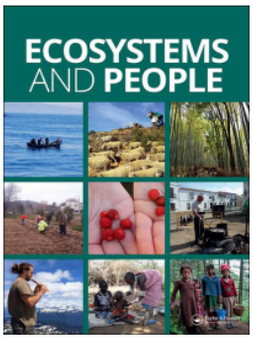

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RESEARCH

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Local ecological knowledge and perception of the causes, impacts and effects of *Sargassum* massive influxes: a binational approach

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ABSTRACT

Coastal communities of the Caribbean Sea and Gulf of Mexico have been affected by atypical influxes of pelagic macroalgae (*Sargassum* genus) since 2011, entailing ecological, economic and social impacts in need of characterization. We compiled and documented local ecological knowledge (LEK) and perceptions across diverse stakeholder groups from coastal communities in Mexico (Quintana Roo) (n=50 participants) and the United States (Florida) (n=36 participants) through on-site and online interviews and workshops undertaken from January to March of 2022, to understand how the knowledge of this phenomenon varies among communities and to characterize ecological and well-being impacts. Participants in Quintana Roo associated these influxes with both global phenomena (e.g., climate change) and local scale processes (e.g., currents/wind patterns) while Florida participants associated these events more with the latter. The communities in both regions perceived that the economy and the environment were the most impacted well-being categories. While influxes effects were mostly negative (80%) according to Quintana Roo participants (e.g., affected fisheries), Florida participants considered many positive effects of *Sargassum* (40%) on several well-being and ecological components (e.g., nursery habitat for marine species). In general, the perception of *Sargassum* as a problem was less pronounced in Florida, and these differences in perception are related to the magnitude of these influxes' effect on the daily life of these communities. Overall, macroalgae management is still mainly focused on beach cleanup. Documenting LEK is important to delineate scientific research priorities and to provide decision makers with resources to develop efficient public policies and coastal management decisions.

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1. Introduction

Pelagic *Sargassum* is a group of floating macroalgae species (*Sargassum natans* and *Sargassum fluitans*) that represents an important habitat for which the Sargasso Sea is named in the subtropical Atlantic. Since 2011, large amounts of *Sargassum* aggregate seasonally from April through August across the central tropical Atlantic Ocean (Wang et al. 2019). These aggregations (i.e. floating mats) occur under and along the Intertropical Convergence Zone and eventually reach the coasts of Caribbean nations including Mexico and the United States (US) during northern summer, causing multiple social and ecological problems as the algae accumulate and decompose on coastal waters and beaches (van Tussenbroek et al. 2017; Resiere et al. 2018; Rodríguez-Martínez et al. 2019; Saldarriaga-Hernández et al. 2021).

On beaches, massive amounts of decaying *Sargassum* release toxic gases such as ammonia, methane and hydrogen sulfide (Resiere et al. 2021). In coastal waters, *Sargassum* accumulation and decomposition increase turbidity and nutrients that can lead to eutrophication. These conditions may stress or smother marine organisms (van Tussenbroek et al. 2017; Rodríguez-Martínez et al. 2019). *Sargassum* strandings may also result in the contamination of aquifers via leaching of arsenic, heavy metals and other compounds (van Tussenbroek et al. 2017; Hernández-Terrones 2020).

In addition, impacts of *Sargassum* influxes on tourism are manyfold. These include the aesthetic appearance deterioration of beaches, unpleasant odors and hindrance of water activities such as swimming, diving and boating (Louime et al. 2017). The

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local economic impacts derive from loss of tourism and expensive harvest and containment efforts (CONACYT 2019). Artisanal, commercial and recreational fisheries are also affected (Ramlogan et al. 2017). For instance, during atypical influxes, fishing activity is affected as the algae becomes entangled in nets and boat motors become clogged and damaged (Ramlogan et al. 2017).

The knowledge of ecosystem dynamics and resource management practices that reside among a specific group of people is defined as local ecological knowledge (LEK) and is pivotal to describe and understand complex socio-ecological issues and systems (Folke et al. 2004). This LEK is usually shared among local resource users but differs from Traditional Ecological Knowledge (TEK) which refers to a historical and cultural continuity of resource use (Olsson and Folke 2001). Although many authors (e.g. Davis and Wagner 2003; Begossi 2015) that describe LEK separates this form of knowledge from conventional scientific knowledge, other authors (e.g. Olsson and Folke 2001; Ballard 2005) acknowledge that some local people that have long-term anecdotal knowledge of their surrounding ecosystems, are also scientifically trained. Hence, several local people hold and use different forms of knowledge (Ballard 2005).

Whenever is necessary to advance the knowledge of a natural phenomenon, habitat or species, alternative forms of knowledge can provide data and may be helpful in management decisions (Gilchrist et al. 2005). For example, LEK has helped to (1) derive new information about marine and terrestrial biodiversity, (2) detect changes in population size and/or distribution, (3) identify potential mechanisms or drivers of population change over time and (4) understand species behavior, biology and ecology (Gilchrist et al. 2005; Schlacher et al. 2010; Silvano and Begossi 2010; Beaudreau and Levin 2014). Therefore, LEK is pivotal to highlight research needs and is required to achieve sustainable, effective and equitable coastal management decisions (Palacios-Agundez et al. 2013; Wadsworth et al. 2014).

Although several studies have been published on ecological impacts of *Sargassum* (e.g. van Tussenbroek et al. 2017; Rodríguez-Martínez et al. 2019; Casas-Beltrán et al. 2020; Rodríguez-Muñoz et al. 2021), the social and economic impacts, especially understood and characterized from the local communities' perspective, are poorly documented. Thus, it remains a research priority to describe the effect of *Sargassum* atypical influxes on the daily life and well-being on affected coastal communities.

The goal of this study was to gather knowledge on atypical influxes of *Sargassum* by documenting and analyzing LEK and collective perceptions of multiple stakeholders. We compiled LEK through one-on-one semi-structured interviews and on-site and online participatory workshops in local coastal communities of Quintana Roo (Mexico) and Florida (US). We analyzed this knowledge to understand the individual and combined perspectives of these communities on (1) the timing of *Sargassum* awareness, (2) the factors that have contributed to its massive growth and arrival to coasts and local beaches, (3) the impacts on well-being, (4) the environmental and the ecosystem effects, (5) the views of *Sargassum* as a resource, a problematic waste, or a natural occurrence and (6) the most common current management and use practices.

2. Materials and methods

2.1. Study site and local communities

2.1.1. Quintana Roo state

Quintana Roo is a state in southeast Mexico with a population of 1,857,985 (INEGI 2021). The state is composed of 11 municipalities allocated in three regions: the Northern area (that includes important touristic destinations such as Cancun), the Central area (Mayan area) and the Southern area. These regions differ in terms of geographical characteristics, territorial integration, productive activities, economy, cultural and social activities (INEGI 2021). Tourism and fishing are among the six economic pillars of Quintana Roo, along with agriculture, forestry, manufacturing and business support (Secretaría de Economía 2016). The main fishery products of the state include spiny lobster, queen conch, rock shrimp, red shrimp and finfish from various families, with a predominance of groupers and snappers (Enríquez-Hernández 2017).

The Mexican Caribbean coast of the state of Quintana Roo extends for ~900 km (Figure 1) (INEGI 1991). The continental shelf is narrow from 20 km wide around Cancun to 1–3 km width in the Sian Ka'an region (Wilkinson et al. 2009). The Caribbean Surface Water and the North Atlantic Subtropical Underwater are the continental shelf water masses of the region (Carrillo et al. 2016). The northward-flowing Yucatan Current connects the circulation of the Caribbean Sea with that of the Gulf of Mexico and serves as the primary conduit of *Sargassum* to the Gulf of Mexico (Doyle and Franks 2015). Oceanographic dynamics influencing *Sargassum* beaching also includes near-shore eddies at a scale of tens of kilometers, and the influence of the Trade Winds (Chávez et al. 2020).

In Mexico, *Sargassum* can be harvested both in coastal waters and once it has beached. The 'Lineamientos Técnicos y de Gestión para la Atención de la Contingencia ocasionada por sargazo

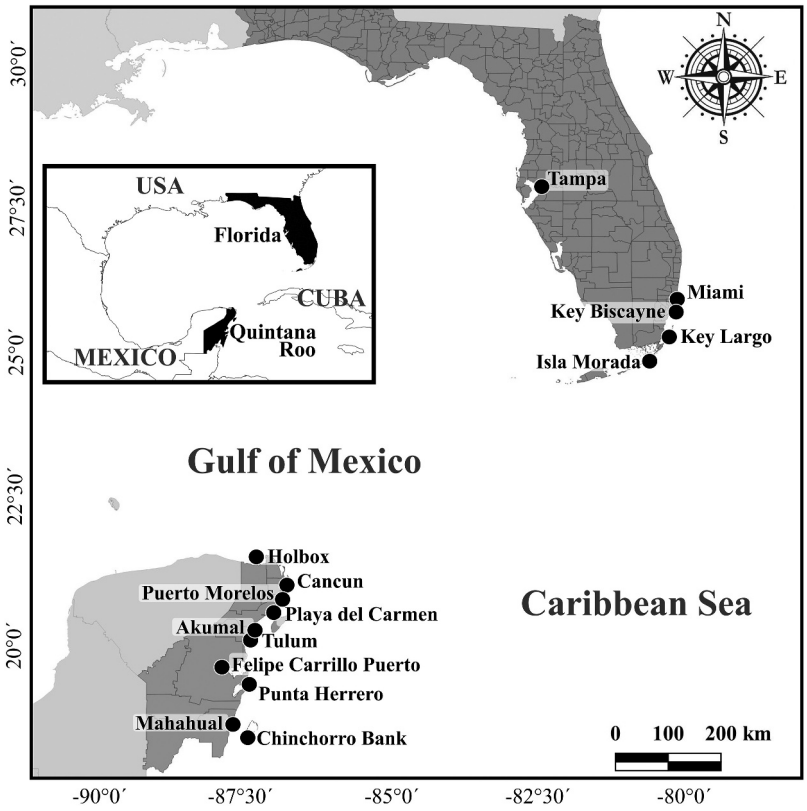

Figure 1. Study site map with location of local communities in Quintana Roo, Mexico and Florida, US that participated in this study via online, on-site workshops or one-on-one interviews.

en el Caribe Mexicano y el Golfo de México' are non-compulsory guidelines that establish the technical specifications for harvest, containment by barriers, removal on beaches, treatment prior to disposal, final disposal and quantification of the macroalgae for monitoring purposes (SEMARNAT 2021). Lack of information about the macroalgae is one of the main reasons why strategic policy development and management decisions are few and difficult (van der Plank et al. 2022).

2.1.2. Florida state

Florida is a state in the Southeastern region of the United States with a population of 21,974,310 (IBISWorld 2022). The six biggest industries that drive Florida's economy are tourism, international trade, life sciences, financial services, aerospace and agriculture (including seafood production) (Morris Southeast Group 2022; Florida Department of Agriculture and Consumer Services 2022). Florida is also considered the most important state for sports and recreational fishing in the US (Florida Fish and Wildlife Conservation Commission 2022). Among Florida's most valuable fishing commercial species are shrimp, spiny lobster and stone crab. Red snapper, grouper, king mackerel, swordfish and dolphin fish (Mahi Mahi) are also important species in terms of dockside value (Florida Fish and Wildlife Conservation Commission 2022).

The Florida coastline extends about 2000 km (Figure 1) (Snyder and Burgess 2016). The continental shelf off Florida's Gulf of Mexico coast is narrow to the north and broad off central and south Florida, where it can reach 250 km in width (Read 1985). The Loop Current stays off the west Florida shelf, and the circulation over the shelf itself is complex and affected by tidal motions, wind and freshwater discharge (Snyder and Burgess 2016). In contrast, Florida's east coast has a narrow shelf where the Gulf Stream comes close to the coast and there is substantial upwelling (Yeung and Lee 2002). Episodic strong wind events serve to modulate the onshore transport of *Sargassum* to the coasts of Florida, from the Gulf of Mexico on the west side of Florida, and from the Gulf Stream on the east coast (Dierssen et al. 2015; Doyle and Franks 2015). *Sargassum* arriving along the coasts of Quintana Roo and Florida has varied over time, area and quantity (Iporac et al. 2022; Zhang et al. 2022). Peaks in beached biomass were registered in 2015, 2018 and most recently in 2022 (CONACYT 2019; Rockport Analytics 2020; Infobae 2022; Zhang et al. 2022).

In terms of *Sargassum* management, the South Atlantic Fishery Management Council (SAFMC) of the US NOAA, has banned harvesting this macroalgae due to its role as essential fish habitat (SAFMC 2020). Policy on coastal harvest in Florida remains to leave *Sargassum* as undisturbed as possible (SAFMC 2002).

2.2. Participatory workshops and interviews

2.2.1. Quintana Roo on-site interviews

We conducted on-site one-on-one semi-structured interviews with stakeholders of Quintana Roo in Banco Chinchorro, Mahahual, Punta Herrero, Playa del Carmen, Tulum, Akumal, Puerto Morelos, Cancún and Holbox communities (Figure 1), during February 2022. These communities were selected to have a geographical representation of the three large areas that comprise the Quintana Roo state. Except for Holbox, which was treated as a control community for both Quintana Roo and Florida because *Sargassum* does not arrive there, these communities were also chosen based on the high level of stranded *Sargassum* that is experienced in these areas. The structure and questions of these interviews can be consulted in Appendix 1.

To select stakeholders we consulted local universities, science centers, government dependencies and NGOs and constructed a pool of potential participants with an in-depth and specialized knowledge of the community's interaction with the *Sargassum* phenomenon. We contacted participants to provide an overview of the project and, if they expressed interest and availability, we scheduled an interview. We sought local participants (i.e. have been living and participating in the structure of these communities for many years, as determined during the questionnaire) from diverse groups including researchers, educators, private industry, hoteliers, municipal government, tourism promoters, NGOs, fishery cooperatives and Mayan community members, since we intended to obtain local perspectives of different sectors that may have been affected by *Sargassum*. For the purposes of this paper, LEK is based on the definition coined by Olsson and Folke (2001) where LEK may be a mix of site-specific scientific and practical knowledge. Therefore, we considered that scientific knowledge and LEK of participants may be intertwined and gained through extensive empirical observations and interactions with the phenomenon (Berkes et al. 2000; Olsson and Folke 2001; Charnley et al. 2007). Most interviews were voice-recorded with previous informed consent from participants, and these recordings were only used to verify quotes or to corroborate there was no misinterpretation of the participant's perspective. The duration of each interview varied from 30 minutes to 2 hours, depending on how much the participant was willing to expand on a specific question. We interviewed 42 participants during 10 days of fieldwork.

2.2.2. Florida on-site interviews

We conducted on-site one-on-one semi-structured interviews with stakeholders from the Upper to Middle Florida Keys (Figure 1) during January of 2022. This region was selected due to the frequent influx of *Sargassum* to this region relative to the rest of the state (Burrowes et al. 2019; Iporac et al. 2022), the economic importance of marine-oriented tourism in the area (generating ~2 billion USD annually (Gazal et al. 2022) and logistical constraints (i.e. ability to travel within a central area). Given these constraints, we followed a snowball approach to select participants (Parker et al. 2019), starting with a small number of initial contacts in the fishery sector. Each interview lasted between 20 minutes and 1 hour. The structure of the interview mirrored the one conducted with Quintana Roo communities (Appendix 1).

Initial interviews were centered around marinas where fishers and members of the dive industry were likely to frequent. This focus continued for the first 3 days, with the final set of interviews focusing on members of the hospitality industry that were not sampled well at the initial locations, given the initial focus on marinas. Most interviews were documented in writing due to logistic difficulty in using a recording device (i.e. safe distance between interviewee and researcher due to COVID-19 safety requirements, wind noise, movement of interviewees doing other tasks while discussing topics, refusal from participant to be recorded, etc.). We interviewed 15 participants during 4 days of fieldwork.

2.2.3. Quintana Roo on-site workshop

We conducted an on-site workshop in March 2022 with members of the Mayan community of Felipe Carrillo Puerto with a sample size of eight participants. Although this community is not coastal, it was chosen because it encompasses most of the indigenous population in the state, with 67% of its total population being Mayan (Carrillo Puerto Municipality 2018). Furthermore, this municipality is located within the Sian Ka'an Biosphere Reserve, which has been severely affected by *Sargassum* atypical influxes (Chávez et al. 2020). Additionally, fishing is one of the main pillars of the town's economy (Carrillo Puerto Municipality 2018) with many fishing villages found within the Sian Ka'an area (e.g. Punta Herrero). The workshop was conducted for a period of 4 hours. It was divided into six sections, and for each section there was a moderator and one rapporteur. We provided handouts for participants to respond to specific topics and write general notes. Major topics were summarized on flip charts to keep track of participant feedback and avoid repetition. All sections were recorded with previous informed consent from participants. Although we had written notes from all the sections, recordings were used to verify quotes or to corroborate there was no misinterpretation of the participant's perspective. The sections of the workshop are summarized in Figure 2.

2.2.4. Florida online workshop

With the help of local universities, science centers, government dependencies and NGOs, we identified key Florida stakeholders for an online workshop held in January 2022. There were 21 local participants during this online participatory workshop, which included Tampa, Miami and Florida Keys communities (Figure 1). This workshop followed the same structure as the Quintana Roo workshop with minor logistic differences due to the online modality: Tools such as Miro™ and Mentieter were used instead of handouts and flip charts (Figure 2).

2.3. Data analysis

Gender, age and stakeholder group were analyzed by country and binationally. To test for statistical differences in these variables among regions, we used a chi-square test, while a Fisher's exact test was used to confirm the chi-square test results (Yates et al. 1999). Each participant from the workshops and the interviews was assigned with an ID number so all subsequent analysis of the provided information did not jeopardize any sensitive information, nor a specific answer could be tracked down to a specific participant. Since a participant's answer was usually multi-layered within a specific topic, each perspective was considered as a separate mention. We used notes, audio recordings and video extracts to synthesize the information into six major themes, as summarized as follows:

a. *Sargassum* awareness timeline: We registered and counted participants' accounts regarding the year when they remembered being aware of the presence of *Sargassum* and also seeing *Sargassum* in massive quantities for the first time. With this information, we constructed timelines spanning from 2011 (beginning of atypical influxes) to 2021 (last year mentioned by participants). Whenever a participant mentioned a year previous to 2011, we counted the mention and classified it under a 'before 2011' category.
b. Causes of atypical *Sargassum* influxes: We registered, listed and counted participants' mentions of various factors that they associate with macroalgal influxes in recent years. We determined which factors were mentioned most frequently by standardizing the mention counts and selecting those that were above one standard deviation from the mean. Sample quotes from participants were summarized to illustrate all the nuances and complexities of participants' responses (Appendix 2).
c. *Sargassum* well-being effects: We registered, listed and counted participants' mentions regarding how *Sargassum* is affecting their daily life. These mentions were assigned to a well-being category previously described by Breslow et al. (2016). The well-being categories were divided into well-being components, also defined by these authors, but we modified these

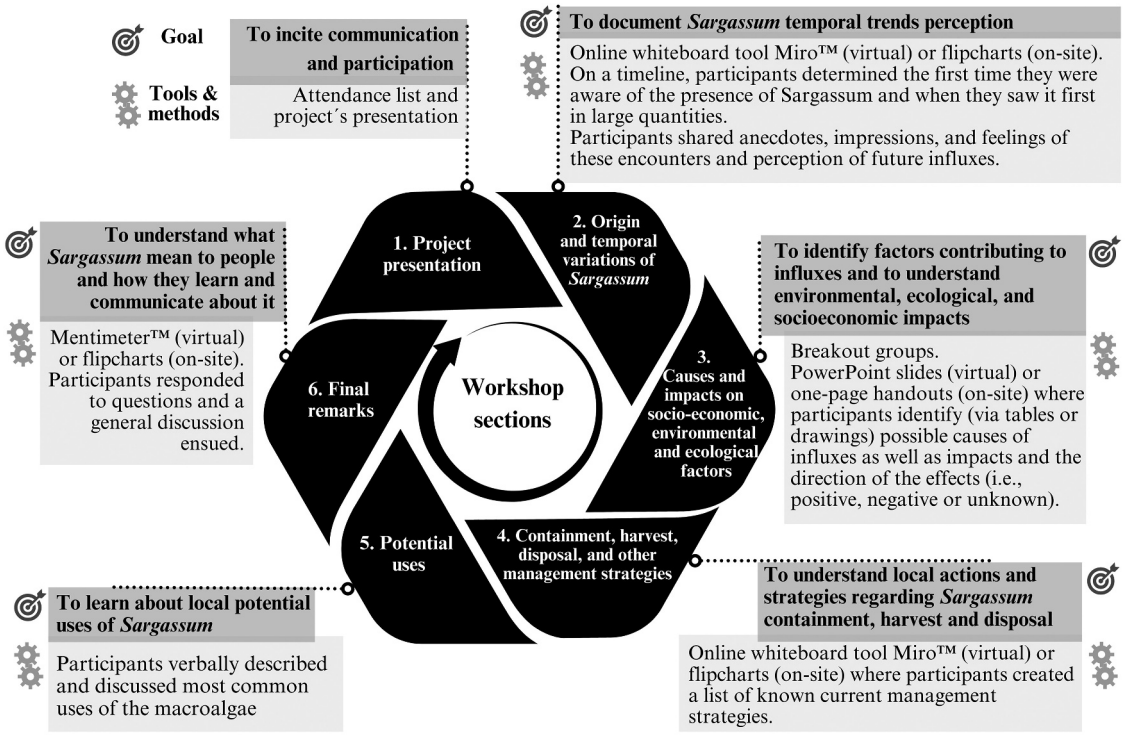

Figure 2. Sections of workshops conducted in Quintana Roo and Florida. The goal, main tools and methods applied are described for each section.

components' definitions to have consistency with the *Sargassum* topic (Appendix 2). Within each component, we defined specific effects of *Sargassum* according to participants' responses. We also recorded the link direction between *Sargassum* and the effect (positive or negative), since not all the *Sargassum* well-being effects were considered negative. We identified the most frequently mentioned well-being effects, and summarized example quotes in Appendix 2.

d. *Sargassum* environmental and ecological effects: We registered, listed and counted participant perceptions of ecological and environmental components being affected by atypical influxes. The direction of the effect was also recorded since not all the mentioned effects were negative. We identified the most frequently mentioned components and example quotes from participants were summarized in Appendix 2.
e. *Sargassum* present and future status perception: We registered, listed and counted participant status perceptions and grouped responses into five major categories: *Sargassum* arrivals are a natural occurrence, a problem, an opportunity, both a problem and an opportunity and both a natural occurrence and an opportunity. Participants' responses also generated the following categories characterizing the future of the phenomenon: will be cyclical, will remain the same as now and will stop/diminish.
f. *Sargassum* management and use practices: We registered, listed and counted participants' mentions regarding how *Sargassum* is currently and most commonly managed at sea and on the shore and what uses have been explored. We included self-management and self-use practices in each community. We identified the most frequently mentioned management strategies.

3. Results

3.1. Participants' statistics

Across all workshops and interviews conducted, we had 86 participants. Participants were 80% male and 20% female, with the gender proportion that we interviewed between the two regions being similar ($p = 0.069$). Most participants (71%) ranged 35–64 in age in both regions without significant differences in age structure among regions ($p = 0.574$). The represented sectors were as follows: Fisheries and fisheries research (29%), industry, hotels or private business (23%), research and education (22%), government (7%) and non-governmental organizations (NGOs) and others (7%). These percentages were similar between the two regions ($p = 0.907$).

3.2. *Sargassum* awareness timeline

In both Quintana Roo and Florida, most participants (96% and 58% of mentions, respectively) indicated that *Sargassum* had been present well before 2011. Awareness of the occurrence of *Sargassum* in massive quantities is a more recent phenomena, with reports of peaks in 2015 and 2018 by Quintana Roo participants (Figure 3). Florida participants responded that they have observed large quantities of *Sargassum* consistently from 2014 to 2021. Only a small percentage of participants reported seeing large quantities of *Sargassum* prior to 2011 in both regions (8% and 19% of mentions, respectively) (Figure 3).

3.3. Causes for Sargassum atypical influxes

Most Quintana Roo participants' mentions (82%) alluded to three possible explanations of *Sargassum* atypical influxes: climate change (global warming), changes in the patterns of winds and currents, and the input of fertilizers/nutrients to the sea. Florida participants specified winds and current patterns as the most important causal factor (62% of mentions) (Figure 4). Other possible causes (in lower numbers) identified by participants (e.g. deforestation, ecological imbalance) are summarized in Figure 4.

3.4. Sargassum well-being effects

The most affected well-being categories according to Quintana Roo participants were the economy (22% of mentions) and the environment (24% of mentions). Within these categories, employment and income, and resource abundance and distribution, were the most affected well-being components (Figure 5a). Across all well-being categories, nine effects of *Sargassum* were the most mentioned (56%): Species abundance and their habitat condition (i.e. mortality of marine organisms, ecosystem deterioration); beach scenic components (i.e. beach landscape deterioration, loss of turquoise blue seawater color); skin lesions/itchiness (i.e. swimming in *Sargassum* and/or the exposure to toxic gases derives in several skin conditions); scientific and technological development (i.e. innovations related to the potential uses of the macroalgae); tourism (i.e. tourists staying less time on site, tourists not coming off cruise ships); fisheries (i.e. mortality of lobsters); water quality (i.e. polluted water, anoxic water, anomalously warm water); regulations, policies and government coordination (i.e. lack of clear policies for *Sargassum* management, lack of interinstitutional and multisectoral cooperation); and being heard by decision-makers (i.e. insufficient

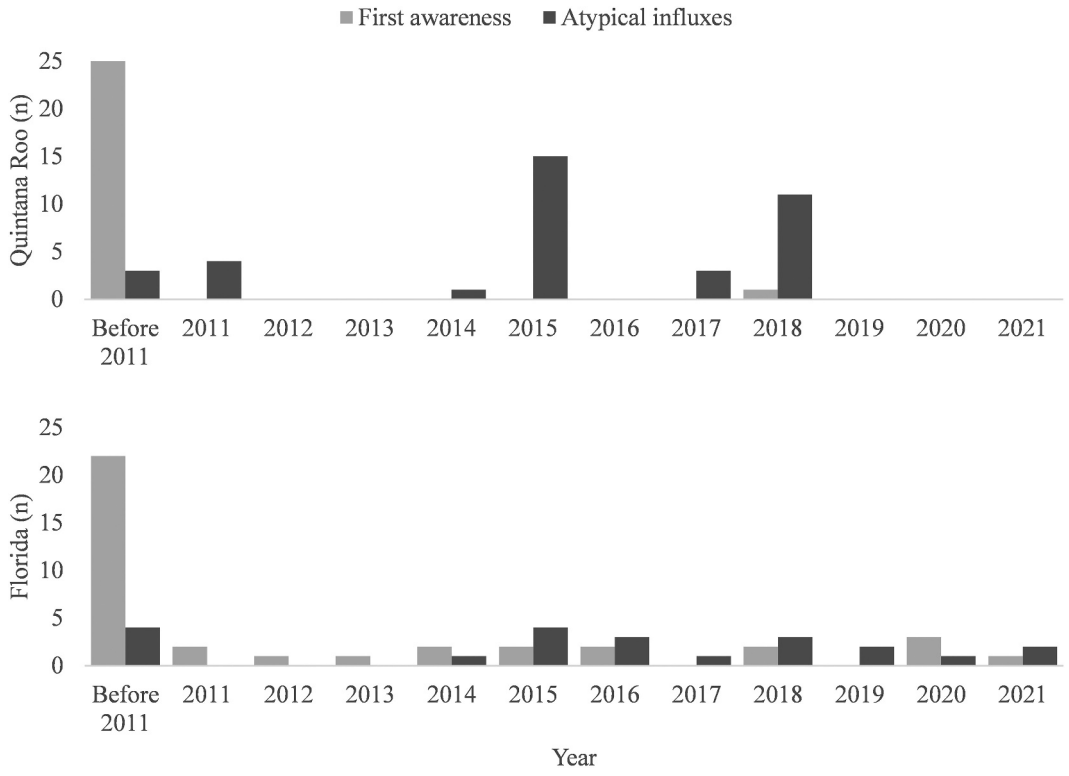

Figure 3. Timeline of *Sargassum* awareness by participants of workshops and interviews conducted in Quintana Roo and Florida. Light gray bars show the first time the participants were aware of *Sargassum*, and dark gray bars represent the first time they were aware of it in massive quantities; *n* = number of mentions of a specific year by participants.

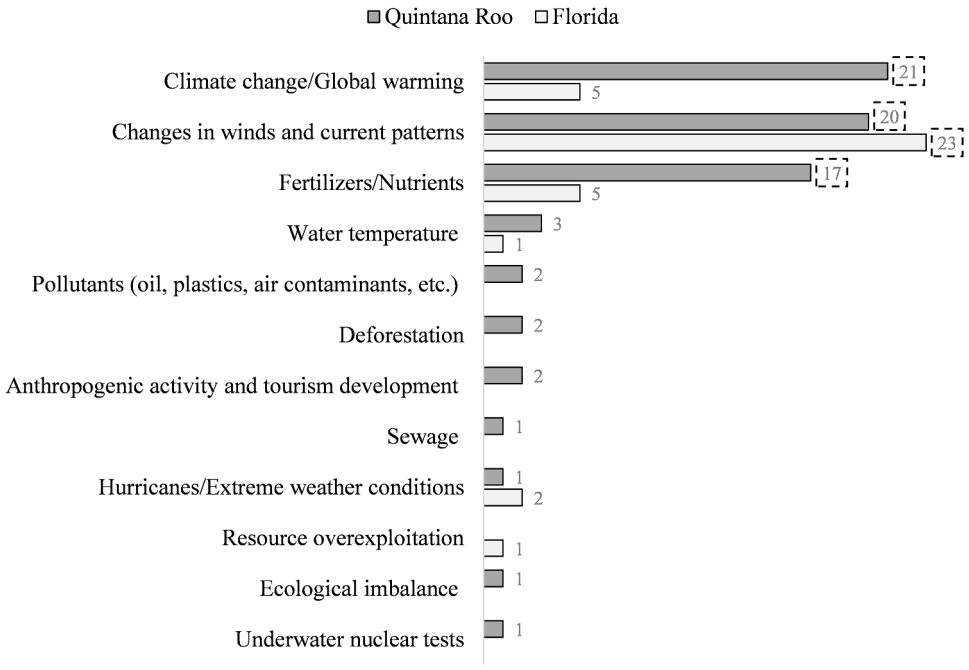

Figure 4. Factors mentioned by Florida and Quintana Roo participants as those responsible for *Sargassum* atypical influxes in recent years. The most mentioned factors in both communities are marked with a dashed box and the number within represents the number of mentions for each factor. Absence of a bar indicates no mention of a specific factor.

and inefficient communication between Quintana Roo community members and decision takers). Mayan participants also alluded to the exclusion of the Mayan community as an indirect effect of *Sargassum*, because of the displaced attention of authorities to touristic areas. All these effects were negative (i.e. *Sargassum* is having a negative or diminishing effect) with one exception: scientific and technological development. Overall, 80% of *Sargassum* effects were considered negative by Quintana Roo participants and all are depicted in Figure 5a.

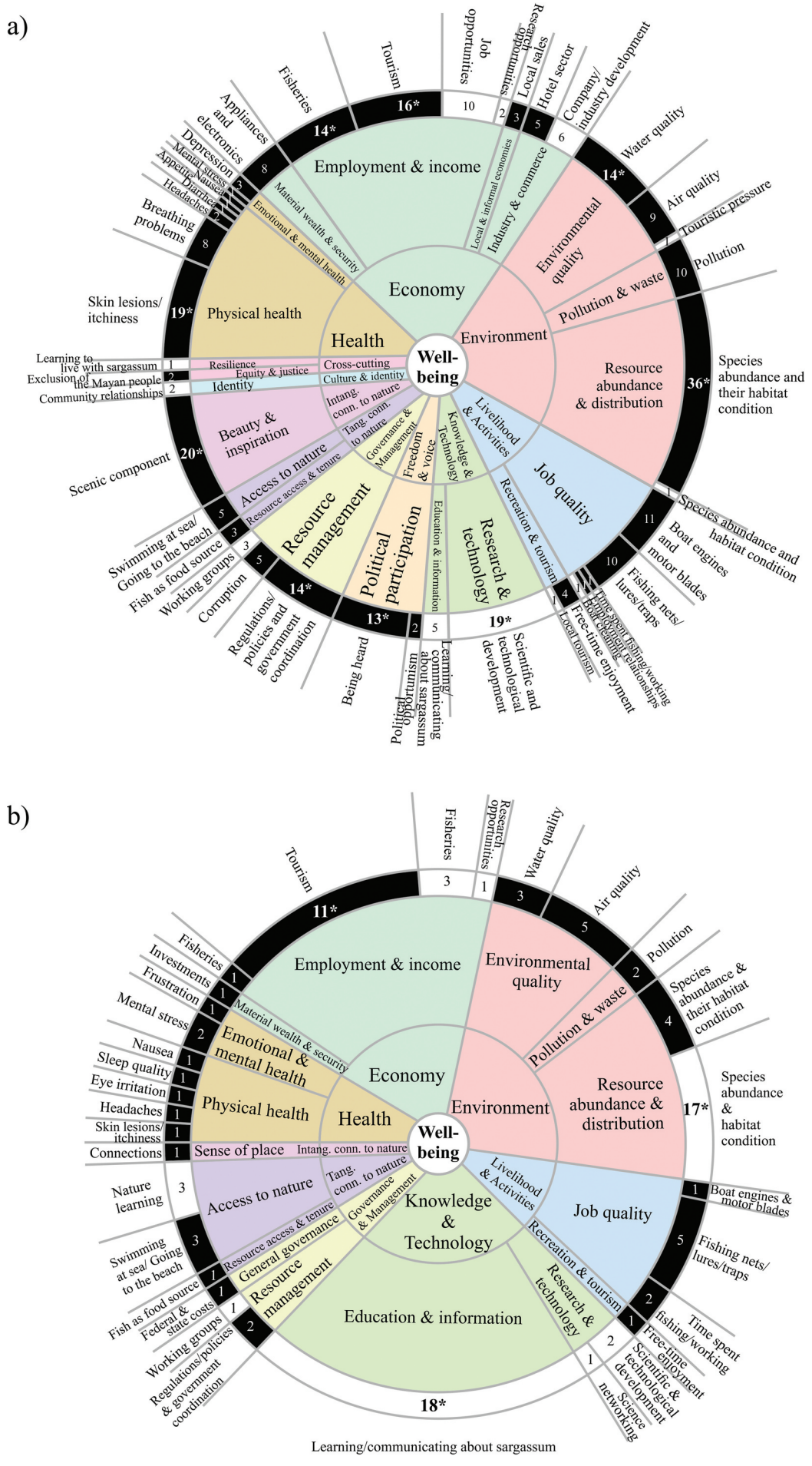

Figure 5. Well-being categories (internal circle) and well-being components (middle circle) affected by atypical influxes of *Sargassum* according to (a) Quintana Roo and (b) Florida participants. Positive (white) and negative (black) effects of *Sargassum* are shown (external circle). The number of mentions for each effect are also shown and the most mentioned effects by participants are marked with an (*).

In the case of Florida, most affected well-being categories according to local participants were the economy (19% of mentions), the environment (24% of mentions) and the knowledge and technology (24% of mentions). Within these categories, employment and income, resources abundance and distribution, and education and information, were the most affected well-being components (Figure 5b). Three were the most mentioned effects across all well-being categories (41%): Species abundance and habitat condition (i.e. *Sargassum* mats representing a floating nursery that brings more fish), tourism (i.e. tourists staying less time on site, tourists labelling a site as 'smelly') and learning/communicating about *Sargassum* (i.e. it is a prevalent topic of conversation, it is possible to learn a lot about a new phenomenon). Economic effects of *Sargassum*, via tourism, were all considered negative. In contrast with most Quintana Roo participants' responses, Florida participants considered that *Sargassum* is having a positive effect on species abundance. Also, learning about a new topic and the opportunity of transmitting this knowledge to other members of the community, or with tourists, was considered something positive. Overall, 60% of *Sargassum* effects were considered negative by Florida participants and all are depicted in Figure 5b.

3.5. *Sargassum* environmental and ecological effects

Quintana Roo participants noted that *Sargassum* has a detrimental effect on their artisanal fisheries (e.g. lobsters), mainly due to water conditions (e.g. lack of oxygen, toxic leachates, increased temperature) (38% of mentions). Negative effects on turtles (via excessive macroalgae accumulation on the beach), and on the coastal ecosystem due to erosion and sand compaction (via cleanup efforts with heavy machinery), were also relevant for Quintana Roo participants (28% of mentions). In contrast, Florida participants focused their responses on *Sargassum* mats being beneficial for fish due to their role as a nursery habitat and, therefore, it was considered positive for their local fisheries (34% of mentions) (Figure 6). Other possible environmental and ecological (albeit in lower numbers) effects identified by participants (e.g. seagrass, coral reef, oxygen levels in water) are summarized in Figure 6.

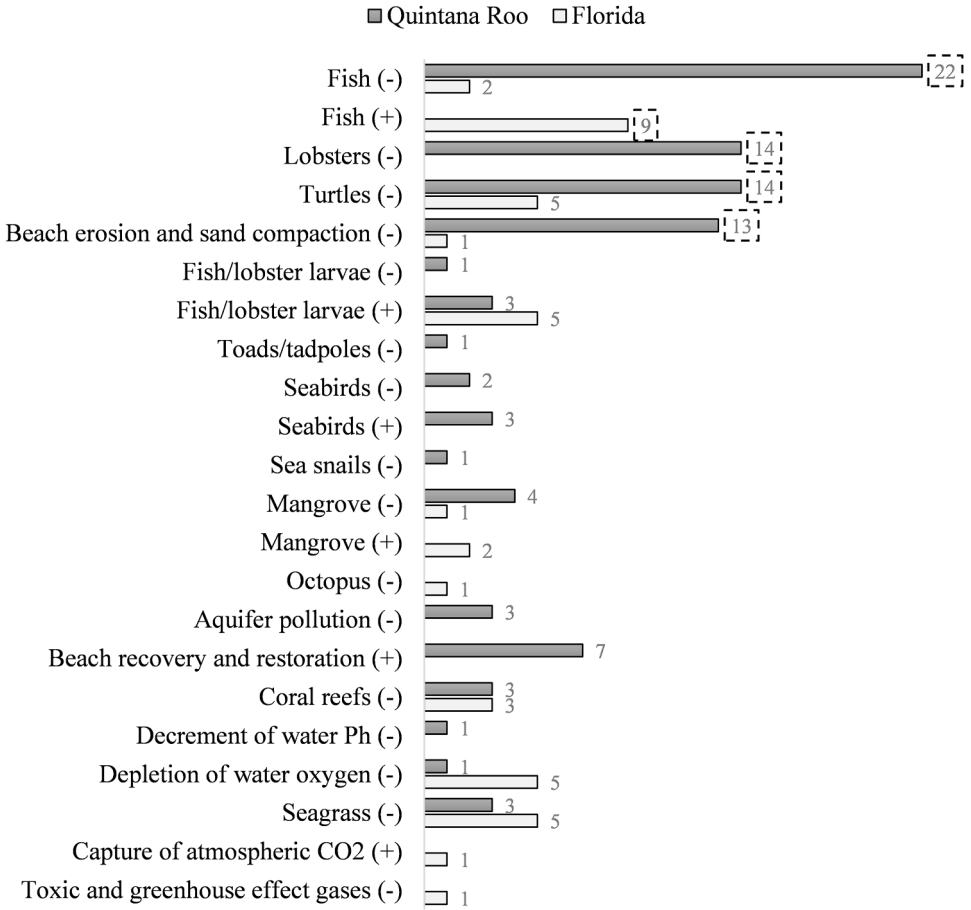

Figure 6. Environmental and ecological effects of atypical influxes of *Sargassum* (and the direction of the effect) according to participants of both regions. The most mentioned factors in both communities are marked with a dashed box. Absence of a bar indicates no mention of a specific factor.

3.6. Sargassum present and future status perception

The perception of *Sargassum* as a problem was more pronounced in Quintana Roo (50% of mentions) than in Florida (36% of mentions). In contrast, the perception of *Sargassum* as an opportunity, predominantly an economic one (e.g. *Sargassum* being used as fertilizer), was less pronounced in Quintana Roo (16%), than in Florida (31%). A similar percentage of responses in both regions (30% and 20%, respectively) defined *Sargassum* as a natural occurrence. A small percentage of responses by participants of both regions (3% and 13%, respectively) characterized *Sargassum* as being a problem and an opportunity at the same time.

In both Quintana Roo and Florida, 55% of the participants' responses characterized *Sargassum*'s future as unchanging in comparison with current levels. In Quintana Roo, 22% of responses indicated that *Sargassum* would increase in the future, in contrast with 5% by Florida participants. A small percentage of responses by participants in both regions (9% and 15%, respectively) believed that *Sargassum* will stop or diminish in the future. In terms of *Sargassum* being something cyclical (i.e. influxes happen repeatedly in a fixed pattern), 13% of the responses by Quintana Roo participants characterized it that way, compared with 25% by Florida participants.

3.7. Sargassum management and use practices

The most common management practices mentioned by Quintana Roo and Florida participants included strategies to remove *Sargassum* from beaches, harvest *Sargassum* for alternative uses (i.e. transforming *Sargassum* in compost or fertilizer), or 'no management' (i.e. 'let nature do its job') (Table 1). Removing *Sargassum* from beaches (either manually or by heavy machinery) was the most popular management strategy used in both regions and referred to moving *Sargassum* from the intertidal zone to a place where it can be sun-dried as fast as possible. Quintana Roo participants also commented that *Sargassum* provides a temporary employment opportunity (for beach cleanup), and therefore an additional income, for many people, including fishers during fishing closures (Table 1). Other mentioned management strategies (albeit in lower numbers) (e.g. barrier installation, use of marina bubblers, charging an environmental tax) are summarized in Table 1.

4. Discussion and conclusion

4.1. Differences and similarities of communities and its impact on LEK

In terms of participants' age, gender and sector, Quintana Roo and Florida communities were similar. An explanation of the differences in *Sargassum* perception may be related to the magnitude of the effect of these atypical influxes, with larger events in Cancun than in Florida. According to data provided by local hotels and government agencies in the summer of 2019 (Zhang et al. 2022), the removal of *Sargassum* in a Cancun beach was ~100–150 tons/day/km while in a Ft. Lauderdale beach it was ~8.3 tons/day/km. This contrast in magnitude was also consistent with the findings of regionally accumulated *Sargassum*, as reported by Iporac et al. (2022).

Since the amount of *Sargassum* that arrives in Florida is less than the amount that arrives in Quintana Roo, there should be differences in how these communities have experienced the phenomenon to date. For example, the Mexican Caribbean coasts have experienced faunal die-offs from *Sargassum* influxes (Rodríguez-Martínez et al. 2019) that have not been reported in a similar magnitude in Florida. This exemplifies one of the reasons why we observed a higher negative perception of this

Table 1. Management strategies employed in Quintana Roo and Florida to address atypical influxes of *Sargassum*.

Management or use practice	Type of management strategy	Quintana Roo (*n*)	Florida (*n*)
To move the *Sargassum* where it can sun-dry fast/beach cleaning	Removal	15	6
Temporary employment	Removal	7	0
Burying the *Sargassum*	Removal	6	0
Compost or fertilizer	Alternative use	5	5
Harvest *Sargassum* at sea	Removal	4	1
Daily logs	Monitoring/education	3	0
No management	None	2	5
Beach recovery and dune restoration	Removal	2	0
Environmental Sanitation Tax (applied to tourists for hotel occupancy to obtain municipal financial resources for beach cleanup (Jornada 2018))	Removal	2	0
Breakwater construction	Removal	1	1
Sargassum barriers	Removal	1	3
Marina bubblers	Removal	0	1
Use in personal fish tanks	Alternative use	0	1

n = number of mentions by participants. Those most mentioned by participants of both communities are shaded in grey.

phenomenon by Quintana Roo participants in comparison with Florida participants.

Besides the magnitude of these *Sargassum* influxes, it is important to consider other socioeconomic and political factors that might be influencing different perceptions between regions. While Florida's economy is comparable with the economy of an entire country (i.e. representing the 15th largest economy in the world) (Florida Chamber of Commerce 2021), 44.8% of the population of Quintana Roo is in a situation of poverty (CONEVAL 2020). Therefore, if subsistence activities of Quintana Roo communities are negatively and substantially impacted by this phenomenon, it is less likely they can overcome unfavorable scenarios as easily or rapidly as an economically stronger community. This could result in a more negative perspective towards this phenomenon, as exemplified by a Quintana Roo participant quote 'There's no hope. We are desperate because our businesses are closing'.

We also noted regional differences in political attitude. For example, in Florida, during the on-site interviews, voice recordings were generally not preferred and there was rarely trust in government-based solutions to problems. Participants in Florida were often brief in their description of knowledge of *Sargassum* and would focus on minimal intervention strategies. Those who did suggest intervention strategies typically focused on private-sector solutions, with profit incentive being top priority. There were also occasional refusals to be interviewed due to the recording of demographic information, which was expressed in multiple instances as a desire for no personal information to be traced by an academic or government-associated institution. In contrast, Quintana Roo participants generally felt more confident in sharing their knowledge and experiences, as reflected in the average time spent conducting interviews. Also, these participants were vocal (even when recording was consented) about flaws in current government management strategies and the need to address this phenomenon in an integrated manner.

4.2. Sargassum awareness timeline, causes and present and future status perception

The presence of *Sargassum* in the tropical and subtropical Atlantic Ocean and its beaching in many Caribbean countries is not recent and it has been documented in writing since 1492 (Godínez-Ortega et al., 2020). The awareness of the macroalgae as part of a natural and healthy ecosystem was voiced by many participants of both regions with many making statements such as 'it has always been here'. Atypical influxes, however, started in 2011 (Sosa-Olivier et al. 2022). According to Florida participants, there was more homogeneity in influx intensity from 2015 to 2021 while for Quintana Roo participants 2015 and 2018 were clearly the most devastating years due to the large amount of biomass that stranded on their coast. This again shows a likely correlation between awareness and the magnitude of the impact.

The atypical and sustained growth of *Sargassum* and its consequent beaching is due to a combination of processes and variables at different temporal and spatial scales that have not yet been fully determined (Carrillo and Sheinbaum-Pardo 2020). Several hypotheses have been described in the scientific literature, including that influxes are linked to various anthropogenic factors (e.g. excessive use of fertilizers and untreated water discharges) (Djakouré et al. 2017; Tagliabue et al. 2017; Häder et al. 2020; Jouanno et al. 2021). Quintana Roo participants associated influxes with both global phenomena (e.g. 'global warming', 'pollution from the Amazon River') and local scale processes (e.g. 'wind changes due to weather conditions'). Meanwhile, Florida participants associated causes more with the latter. These differences may be due to the influence of a wider and constant dispersion of scientific information of this phenomenon in local media (e.g. newspaper, television, radio) in most affected regions. This media exposure to scientific information can permeate LEK (Yli-Pelkonen and Kohl 2005) and be reflected in many participants' quotes.

In most affected countries, efforts to address this phenomenon have focused mainly on containment at coastal waters and beach cleanup. This has been costly, not only in terms of money spent by state and federal governments but also in terms of the need for an intense labor force (CONACYT 2019; Oxenford et al. 2021). Along with the socioeconomic context, this may explain why the current perception of *Sargassum* was also contrasting among both regions. Florida participants were less prone to consider *Sargassum* as a problem, stressing instead that *Sargassum* 'Is an important part of the ecosystem'. In contrast, in Quintana Roo, half of the participants portrayed it as a problem with phrases such as '*Sargassum* affects us in many ways' and 'It is an annoyance'. We also observed differences in terms of *Sargassum* perception as an economical opportunity, with Florida participants more inclined to the possibility that *Sargassum* can be transformed into an economically relevant resource. This was surprising, since many scientific and technological advances in the potential use of the macroalgae have been developed in Mexico (Desrochers et al. 2020; Rosellón-Druker et al. 2022). However, the number of researchers or entrepreneurs that use *Sargassum* as raw material and transform it into a commercial product, is small in comparison to the number of people that have to participate in containment and cleanup efforts during several months each year.

The recurrent beaching of *Sargassum* over recent years indicates that this is likely a phenomenon that 'is here to stay' (Skliris et al. 2022) especially if origin is linked with climate change and oceanographic processes (Johns et al. 2020). Participants of both regions agreed with this hypothesis with phrases like 'It will be the new normal', or 'It is not going to decrease'.

4.3. Sargassum well-being, environmental and ecological effects

Atypical influxes have affected the abundance, diversity and population structure of many species that inhabit the Mesoamerican Reef System and other coastal ecosystems, including mangroves and cenotes (Ramlogan et al. 2017; van Tussenbroek et al. 2017; Aguirre Muñoz 2019; Rodríguez-Martínez et al. 2019; Chávez et al. 2020). Not surprisingly, participants in Quintana Roo were concerned with the degradation of the environment and many of them stressed that the sea and freshwater quality of the region is decaying, as pointed out by a participant, 'Sea water becomes contaminated when a lot of *Sargassum* arrives'.

Rodríguez-Martínez et al. (2019) reported the mortality of several fish and crustacea of commercial importance for the region (e.g. snappers, crabs, jacks, lobsters, etc.) during an atypical influx in Quintana Roo. Participants also observed *Sargassum*'s potential to be detrimental to many species and one participant stated that 'Everything dies along the coast'. For example, although a direct link between *Sargassum* and turtle mortality has not been yet fully established in the literature (Maldonado-Saldaña 2020), participants were vocal about the negative effect of *Sargassum* on these marine organisms, as mentioned by a participant: 'Baby turtles cannot pass through stranded *Sargassum* and die from the high temperatures'. Also, lobster fishers had a negative perception of *Sargassum* because it has had detrimental effects on the fishery and it has impacted fishing effort (e.g. increased number of hours or days spent fishing). Fishers affirmed that 'Sargassum influxes had a huge impact on our fisheries'. In terms of fishing effort, they expressed that 'Lobster cages must be put far away from the coast, so the polluted water does not kill our lobsters. We have to travel farther offshore than before to retrieve the lobster cages'.

In contrast, Florida participants, mainly fishers, had a positive view of *Sargassum* ecological effects because of its role as a nursery area (Wells and Rooker 2004). For example, a participant there stated that Sargassum 'It is a floating nursery. I often bring it on the boat when I am fishing with kids and I shake it out for the kids to see the baby billfish and mahi that comes with it' while another participant stressed that 'You can't get rid of it, it is the lifeblood of our oceans'. This assertion is consistent with a breadth of literature, which identifies pelagic *Sargassum* as an important habitat for sea turtles (Witherington et al. 2012) and juveniles of commercially important fish (Wells and Rooker 2004; Hoffmayer et al. 2005; Casazza and Ross 2008).

As described in the SEMARNAT guidelines, the constant *Sargassum* cleanup on the beach can lead to alteration and destabilization of beach profiles, loss of sediment and soil compaction (Innocenti et al. 2018; SEMARNAT 2021), especially if heavy machinery is used. The compaction of the sand is critical since it eliminates geomorphological features of the beach, which increases the angle of incidence of the wind, increasing in turn the erosion and therefore causing damage to the marine-coastal zone (Escudero-Castillo et al. 2018). This was a common concern among Quintana Roo and Florida participants as stated by one participant: 'During *Sargassum* cleanup, you also take out a lot of sand which erodes the beach'.

Environmental and economic concerns were closely connected as participants of both regions repeatedly stressed that the changing environment heavily impacts the success of the tourism industry. For example, a Florida participant mentioned that '*Sargassum* encroached the whole beach front, so investments for a new resort are now on hold'. Stakeholders of both regions were concerned about 'Getting a bad reputation as a smelly place' and 'Tourists not wanting to participate in any water-related activity' or 'Tourists making complaints, leaving, and stop generating income'. Quintana Roo participants were also concerned about losing the beauty of their beaches, not only in terms of a negative impact to tourism but also as an intangible connection to their surrounding ecosystem as stated by a participant 'My landscape is now depressing'.

Other prevalent well-being effects mentioned by Quintana Roo participants referred to health impacts via direct contact with the macroalgae, their leachates or their released toxic gases. Hydrogen sulfide, for example, can be a human health hazard in high concentrations, especially under chronic exposure (Legator et al. 2001; Sundblad et al. 2004; Resiere et al. 2021; de Lanlay et al. 2022). Some participants stressed that breathing problems occurred during peaks of arrival. Furthermore, hydroids are frequent epibionts on floating *Sargassum*. These small animals have a stinging capacity and the ability to cause painful skin rashes and papules on humans (Mendoza-Becerril et al. 2020). Many fishers referred to skin lesions caused by *Sargassum*, explaining that 'When you go inside water to retrieve lobster cages you get a very red skin and lot

of itchiness' and 'It is like acid to the skin' or 'Skin lesions become easily infected'.

Sargassum was also perceived as a political and governmental issue. Quintana Roo participants complained about not being heard by their local authorities as well as the lack of coordination of government institutions to have clear and mandatory regulations for the management and use of *Sargassum*. The Secretaría de Marina (SEMAR) (i.e. Mexican navy) has been coordinating *Sargassum* containment and management efforts by since 2019 (SEMAR 2021), however, interinstitutional coordinated actions to address the *Sargassum* phenomenon in an integrated way are still lacking (Rosellón-Druker et al. 2022). For example, one participant mentioned that 'There is no guiding voice, and the people in the villages are disappointed. We cannot do much because SEMAR decides everything'. Other participants said, 'We perceive apathy and disinterest on the part of the municipality' and 'The government initiatives do not work because there is a lack of inter-institutional coordination between SEMAR, the state and the municipality'.

Participants from Mayan communities were vocal about the inequity they experience due to the *Sargassum* phenomenon. They conveyed that the state government focuses all efforts on cleaning beaches in touristic areas (e.g. Cancun, Playa del Carmen) during influxes neglecting in turn Mayan cultural tourism promotion (e.g. in the Sian Ka'an region). Mayan participants also mentioned that recreational opportunities like visiting an aquatic park or a beach club were affordable to them only during peaks of *Sargassum* influxes, when international tourism might be reduced.

Finally, there was a positive perception in both regions regarding how this 'problem' has offered opportunities to create solutions. For example, different companies using *Sargassum* as a resource in several products like shoes, bricks, concrete, biofertilizers, etc., are well established (Desrochers et al. 2020). Governments are encouraging technological development for use of the *Sargassum* that can be replicated locally and regionally, as well as the generation of value chains (CONACYT 2019). The boost of technological development and scientific research has contributed to new knowledge we have on *Sargassum*, the dissemination of that new knowledge, and the creation of a consciousness about how its excessive growth may be a response of nature to anthropogenic pressure (Fraga and Robledo 2022).

4.4. Sargassum management and use practices

According to participants of both regions, the most important objective pertaining to *Sargassum* management is the cleanup of beaches. Therefore, a common strategy is to move *Sargassum* away from the water where it can dry up naturally through direct solar radiation, ambient air temperature, relative humidity and wind (Mujumdar and Devahstin 2000), avoiding in turn the obnoxious smell from anaerobic decomposition (Yuhendra et al. 2021). Interestingly, several Florida participants mentioned that 'There is no need to manage it so far. It is hard to manage a naturally occurring phenomena' and 'Last thing I would want to see is harvesting it offshore for a product. That would be disturbing the natural flow of the ecosystem'. Therefore, 'no management' or 'leave nature alone' was a shared perspective among many Florida participants.

In terms of potential use, converting *Sargassum* into compost and fertilizers has been a widespread practice among participants of both regions. This response is in line with current *Sargassum* uses exploration, where composting is one of the most economical and practical methods for using the macroalgae, while the development of biofertilizers has become visible worldwide and has even reached commercialization stages (Desrochers et al. 2020; Rosellón-Druker et al. 2022).

4.5. Relevance of LEK and the binational and multisectorial collaboration experience

Despite the boom of scientific publications in the past decade, there remain several identifiable knowledge gaps about different aspects of the origin, effects and management of *Sargassum* atypical influxes (Fidai et al. 2020). Therefore, it is important to document, analyze and communicate different types of knowledge that could help to improve the accuracy in describing such a complex social-ecological issue.

Local perceptions and LEK provided here is an important base of new knowledge, especially in regards of *Sargassum* influxes effects on the daily life of these local communities. The integration of LEK into resource management decisions can improve the overall capacity of interpreting local biological, social, economic and ecological dynamics. Decision makers in resource management should incorporate LEK as part of the basis to develop public policies for a successful implementation (Wadsworth et al. 2014; Glass et al. 2015). We summarize a few examples of how the perceptions of different stakeholders compiled in this research can be used to shape management decisions and policies, resulting in a vulnerability risk amelioration to these coastal communities:

4.5.1. Delineation and prioritization of research needs

The LEK compiled here helped to describe the most pressing well-being effects of *Sargassum*. For example, many Quintana Roo participants expressed

concern regarding *Sargassum* health impacts. The high concentration of hydrogen sulfide gas that has been measured in areas where the macroalgae accumulates and decay, not only has undetermined health hazards (Resiere et al. 2021) but it seems to be high enough to promote corrosion of anything made with silver and copper causing rapid deterioration of electronic components and equipment (Valdez-Salas et al. 2012). This was reported by many Quintana Roo fishers living in fishing villages located right in front of the beach (Appendix 2). Therefore, understanding and measuring health impacts associated with *Sargassum* influxes must be a priority of any government agenda addressing this phenomenon.

4.5.2. Integration of functioning policies/practices into future management strategies

Many Quintana Roo participants expressed how *Sargassum* beach cleanup has become a source of employment (Table 1). Many fishers mentioned that, in 2018 the CONANP (Comisión Nacional de Áreas Naturales Protegidas) implemented a temporary job program during lobster off season that allowed fishers to receive a salary in exchange for *Sargassum* cleanup. These fishers had a very positive perception of this program since it allowed them to stay in their fishing villages while diversifying their economy and increasing their annual income (Appendix 2). This exemplifies a successful policy, according to participants' perception, which the state government could consider as a permanent program.

4.5.3. Development of scale-appropriate socioeconomic and environmental indicators

This research highlights the importance of understanding and documenting LEK not only at a regional level but also at smaller spatial scales, since scientific knowledge about this phenomenon is scarce in remote locations, specially away from touristic hotspots (Rosellón-Druker et al. 2022). For example, Felipe Carrillo Puerto participants provided new information about how this phenomenon impacts the Mayan community. Also, fishers from Banco Chinchorro mentioned they generate daily logs with information about how much *Sargassum* they harvest during their daily routine. All this may provide baseline data to develop a series of local environmental indicators. Developing differentiated-by-zone *Sargassum* management plans (e.g. for marine protected areas, uninhabited areas, rural areas, fishing areas, etc.) needs LEK to reduce existing knowledge gaps at different spatial and temporal scales.

4.5.4. Redirection of conservation efforts

Many Florida participants, mainly fishers, centered their discussion on why *Sargassum* mats constitute an ecosystem with a diversified associated fauna. These observations may provide information about local endemic species to pelagic *Sargassum* as well as feeding behavior of migratory species. For example, Martin et al. (2021) found many rare motile epifauna within *Sargassum* assemblages as well as a temporal shift in previously observed dominant species. A more local assessment of the biodiversity associated with *Sargassum* is important to redefine management and conservation efforts at local scales.

We acknowledge important caveats of our research. The representativeness of our findings is limited to areas and stakeholders that participated in this study; thus, these findings should be explored at a Caribbean basin scale especially if the goal is to understand wider well-being impacts of the *Sargassum* phenomenon. Furthermore, the *Sargassum* atypical influxes are recent, thus, documenting and understanding LEK is limited by a temporal window. Local experts gained that experience on par with the duration of the phenomenon. This may explain the stakeholders' representation during this study. Most participants (74%) were local fishers, researchers and private business owners. Although we tried to include more participants from indigenous communities, the interest and willingness to participate on this study emanated mainly from these stakeholders. Fishers, hotel and restaurant operators, tour operators, scientists, environmentalists, etc., they all constitute the affected community together, as the massive arrival of *Sargassum* has changed their everyday life. While we acknowledge that their methods and sources for producing and disseminating knowledge about *Sargassum* may vary, we recognize that based on their close experiences with this phenomenon, they all produce LEK together. The academic and education sector of these communities has been affected by *Sargassum* influxes in many ways, including that researchers had to refocus or even change their research topic. Therefore, this phenomenon had personal and professional impacts on this sector that needed to be explored. An example of the latter may be best described quoting a scientist participant of Puerto Morelos: 'I have been interested in the problem of *Sargassum* since 2014. I integrated *Sargassum* in my job and research activities because I knew that it would be needed for management purposes. On the other hand, I was interested in this problem because I have a house 50 meters from the sea and I wanted to know the effect *Sargassum* has, the impact in every way. I have been concerned about health issues, not only because it is mentioned in the press but also because in the summer months I have seen how it affects the skin on my arms. I have learned a lot about it every afternoon that I go to the beach to let my dogs run. The changes that occur due to winds and waves'.

Finally, this research also represents a novel approach in binational community-based experience and collaboration where mirror methodologies were implemented in communities of two different countries that are exposed to a socio-environmental problem. In complex problems that require robust solutions, such as biodiversity loss, ocean litter, ocean acidification and macroalgae blooms, no single country can fully address these problems on its own (OECD 2020). The atypical beaching of *Sargassum* is one of these emerging issues that require an integrated approach, collaboration at many levels with joint management efforts at different time and space scales. Effective binational/multinational cooperation and exchange is required to provide options to reduce the effects of these arrivals on coastal ecosystems and its services. Joint efforts involving international cooperation through alliances and networks can bring together expertise of scientists, stakeholders and local communities to co-design actions and find solutions specific to each nation's needs. The inclusion and involvement of all voices in this collaborative process is fundamental and, as has been recognized by Tengö et al. (2014) treating each knowledge system with equity, socially balanced into an ecosystem approach (Pinkerton et al. 2019). Binational/multinational collaborative and integrated marine activities can offer transferable insights derived from multiple knowledge systems to develop stronger management approaches (Vierros et al. 2020). The inclusion of local knowledge in co-design, co-development and co-delivery of solutions to atypical beaching of *Sargassum* in this way has potential to deliver local long-lasting actions that are in line with multiple stakeholder objectives.

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