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Early stakeholder involvement using Group Model Building to identify ecological research questions and nature management options

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ABSTRACT

Many tropical coastal ecosystems face human pressures related to tourism, land or sea use. We developed a practical procedure to involve stakeholders in an early stage of an ecological research project to map the Social-Ecological System (SES) in our case study Lac Bay, Bonaire island, as well as to identify and prioritize ecological research questions and nature management options in relation to a recent new threat: massive sargassum landings. In our procedure we used the Group Model Building methodology for identifying drivers, key variables and feedback loops in this SES. The underlying mechanisms of driving feedbacks were revealed and shared during these sessions. We identified and prioritized urgent ecological research questions for the conservation of seagrass beds and mangrove forests, and practical measures for nature management in Lac Bay. Both were used in follow-up scientific research and nature management plans, illustrating the applicability of our procedure for early science-stakeholder interaction.

1. Introduction

1.1. Major environmental threats in a Social-Ecological System (SES)

Coastal ecosystems are valuable in contributing to biodiversity, fish nursery, water quality, carbon sequestration and coastal defence (Duarte et al., 2013; Gillis et al., 2014; James et al., 2020). Large numbers of tourists are attracted by the natural beauty of Caribbean coastal ecosystems such as coral reefs and the clear waters supported by seagrass beds and mangrove forests. Caribbean coastal communities are highly dependent on the services provided by these ecosystems for their local tourism-based economies (James et al., 2019; Van der Geest and Slijkerman, 2019a).

Ecosystem services reflect societal goals, values and benefits and connect ecological systems to human welfare and well-being (Zaucha et al., 2016; Silva et al., 2019). By mapping the diversity of positive and negative interactions between people and nature, the benefits of healthy ecosystems for communities become more explicit. The perspective that societies depend on natural systems, provides a way of looking at the relationship as a *Social-Ecological System* (SES) (Folke, 2006; Cullen-Unsworth et al., 2014; Refulio-Coronado et al., 2021).

Pressures and threats to a SES can be manyfold. Tropical coastal

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ecosystems typically experience human pressures from tourism, residential development, fisheries or land erosion, but also from global threats such as sea level rise and increasing temperatures due to climate change. In the Caribbean, they have also been more recently threatened by recurring periodic massive landings of holopelagic brown seaweeds of the genus *Sargassum* spp. (hereafter sargassum) which suffocate coastal ecosystems and contribute to long-term eutrophication (van Tussenbroek et al., 2017; Wang et al., 2019; Chávez et al., 2020). Recently, Mohan and Strobl (2024) have pointed to the lack of empirical studies across the Caribbean region on the impact of sargassum on tourism and local economies. Human pressures like tourism can be locally managed, but global threats like climate change, or regional threats like sargassum landings have a much greater complexity. In the latter two cases, the threat itself cannot be managed at a local scale, so that the direct response to it often involves management of the consequences and pressures of these threats in our immediate surroundings (Elliott et al., 2017; Robledo et al., 2021; van Oosterhout et al., 2023).

1.2. The importance of early stakeholder interaction and mapping the SES

In scientific research projects early science-stakeholder interaction can provide several advantages. It may potentially lead to (i) improved understanding of the researchers as they learn about local circumstances and incorporate tacit knowledge including coherence and causalities between ecological, social and management factors; and (ii) enhanced facilitation of the research through cooperations that follows from the stakeholder involvement, e.g. regarding logistics, practical methods, and faster recognition of research pitfalls and opportunities. From the perspective of the stakeholders, early involvement in an ecological research program potentially leads to (i) enhanced articulation of their research and management options; (ii) answers to (part of) their questions; and (iii) shared logistics and (iv) improved knowledge. Obviously, these mutual benefits can only be scooped when this involvement takes place in an early stage, within the first years of a long-term research program. For management, in general, mapping the SES, i.e. clarifying, structuring and understanding processes at stake from a social-ecological context, and involving multi-stakeholder perspectives has several advantages: community building, knowledge sharing, identifying common and diverging goals (Leenhardt et al., 2015; Bennett et al., 2016). Such a process also provides more embedded, integrated and broader searching for relevant research questions as well as management options (Braunisch et al., 2012; Benham and Daniell, 2016).

1.3. A new approach to identify and prioritize ecological research questions and nature management options

In this study, we aim to develop a flexible and practical procedure to (1) map the SES, (2) extract research questions, and (3) explore management options in an early stage of an ecological research project. Early science-stakeholder interaction is crucial for all three aims. To facilitate this, we used a form of participatory modelling viz. *Group Model Building* (GMB). GMB is often used in the pursuit of improved understanding of the problem being investigated and for identification of relevant research questions, and GMB is tied to subsequent identification of more effective and readily implementable management strategies (Rouwette et al., 2002; Vugteveen et al., 2015). We evaluated the approach by (1) questioning participants about their agreement with the outcomes of the interaction sessions and (2) by compiling follow-up research and management measures.

The procedure consists of desk studies, open interviews with different SES stakeholders and three stakeholder meetings attended by marine ecologists, tourism stakeholders, nature managers and governmental representatives. The qualitative model of the SES of Lac Bay, Bonaire island, built during the first GMB session has been focusing on local pressures identifying topical research questions for ecological conservation, and urgent local management measures. We organized a follow-up stakeholder meeting focusing on the sargassum landings. Sargassum landings form a major threat in Lac Bay since 2017 (Van der Geest et al., 2024). This meeting focused on interests in Lac Bay and solutions for the consequences of the landings. Thirdly, another GMB session was performed to model the (un)expected problems caused by these landings for the SES of Lac Bay. Based on this session we inventoried and prioritized new research questions and new management options. At the end, we give an inventory of follow-up research and management measures, evaluate the procedure, and discuss in general how the GMB methodology can be helpful to enhance ecosystem-based management via early science-stakeholder interaction in coastal conservation and restoration projects.

2. Description of the study area: Lac Bay, Bonaire island

Bonaire was the first Caribbean island to have a marine park. This Bonaire National Marine Park has been established in 1979 surrounds the whole island, starts at the high-water mark and extends to 60 m depth, covering an area of 27 km^2. Lac Bay is part of this marine park and is managed on behalf of the island government by STINAPA, the national park foundation of Bonaire (Fig. 1). Lac Bay is home to endangered and key stone species such as green turtle (*Chelonia mydas*), queen conch (*Strombus gigas*), seagrass (*Thalassia testudinum*), and red (*Rhizophora mangle*), black (*Avicennia germinans*) and white (*Laguncularia racemosa*) mangrove trees. In Lac Bay mangrove forests and seagrass beds provide important ecosystem services. Mangroves protect the shoreline from erosion, filter harmful nutrients from land, and store carbon (Wolanski and Ridd, 1986; Donato et al., 2011). Above water, mangrove forests provide habitat for wetland birds and below water, mangroves provide a habitat for fish and invertebrates. Seagrass beds provide an underwater habitat and/or food to fish, birds, invertebrates and sea turtles, have high productivity, and have coastal protection and carbon sequestration functions (Hemminga and Duarte, 2000; Mcleod et al., 2011; James et al., 2019). Juvenile coral reef fishes depend on the shallow seagrass and mangrove biotopes in Lac Bay (Nagelkerken et al., 2000). Because mangroves and seagrasses are located between land and coral reefs, they retain terrigenous particles that are harmful to the reefs (Gillis et al., 2014).

2.1. Local pressures

In recent decades, various human and natural developments, local as well as regional, have threatened the fragile coastal ecosystems of Bonaire, jeopardizing the foundations of the island's economy (Meesters et al., 2019; Siegel et al., 2019). Bonaire's rich coral reef ecosystem, attracts scuba diving and snorkelling tourists that often concentrate within a particular area, typically in the most fragile environments such as beaches, reefs or shallow lagoons. Especially Lac Bay is an area of high risk due to its shallow water and the growing number of cruise tourists visiting the lagoon for windsurfing and sunbathing. Stay-over tourists mainly visit the island for diving. Pressures are for example habitat loss due to construction of tourist facilities or trampling on seagrass beds, pollution (eutrophication, litter, sunscreens) and disturbance of species (turtles, flamingos) (Slijkerman and Henkens, 2019; Verweij et al., 2020). The number of one-day visitors from cruise ships before the COVID crisis in 2019 was about 460,000 tourists. After the crisis, visitors started coming again with the return of the cruise ships in September 2021 (CBS, 2022).

There are approximately 45 fishers registered as members of the local fisheries cooperative Piskabon on Bonaire. Most of them have fisheries as their primary source of income but some could be classed as part-time, seasonal or recreational fishermen. There is no centralized landing of catches on Bonaire which makes accurate monitoring of catches nearly impossible (SFP, 2019). In Lac Bay we only find artisanal fishery. Due to a lack of historical records of the fishery it is not possible to quantify any positive or negative trends related to changes that may

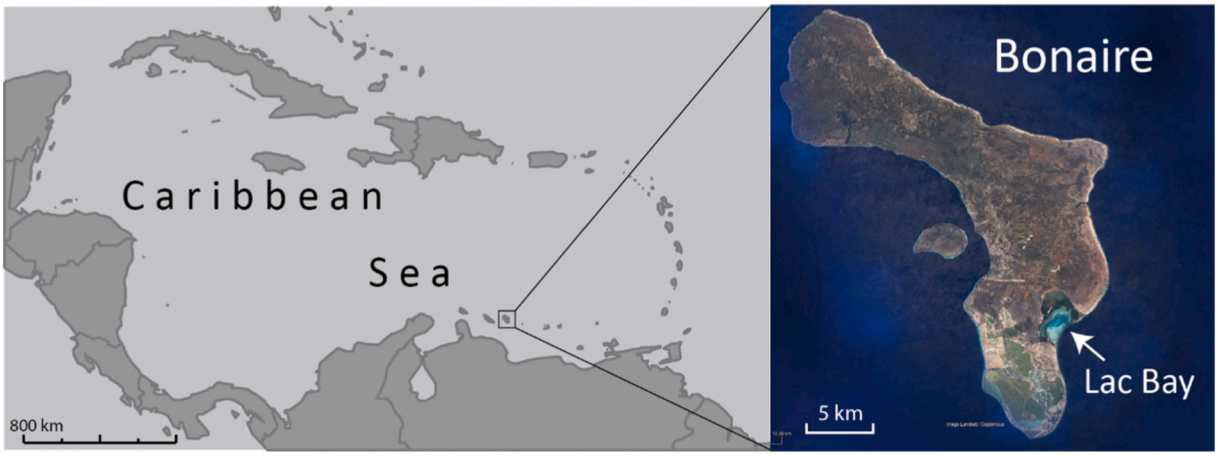

Fig. 1. The Dutch Caribbean Island of Bonaire, located in the Caribbean Sea, with Lac Bay on the South-eastern side of the island.

have occurred over time in catch, effort, and species composition (De Graaf et al., 2016). Lac Bay has been a fishing ground for local fishermen for queen conch for generations, as evidenced by the conch mounds found on the beaches of in the bay. Although once plentiful, the queen conch is now a protected species close to extinction. Most of its life cycle takes place in the seagrass beds of Lac Bay and it takes about four to five years to become mature and start reproducing (Kough et al., 2017).

Land-based sediment infilling and related salinization of the backwaters of Lac Bay has caused mangrove die-offs over there, while seaward expansion of the mangrove forest can be attributed to natural succession (Debrot et al., 2019; Casal et al., 2024). This has caused mangrove pools in the backwaters to become too saline for seagrasses or mangroves to grow and the area of open water in Lac Bay to reduce. Terrestrial erosion control is one of the challenges that must be addressed. There are more than 30.000 free roaming goats on Bonaire. Although goats are part of its cultural heritage, these large numbers are harmful to the vulnerable nature of the island due to overgrazing increasing soil erosion (Van der Geest and Slijkerman, 2019b).

2.2. Regional threats

Cruise tourism at Bonaire is largely influenced by the competitive character of the Caribbean cruise market, where the economic stakes are high and both cruise companies and coastal destinations advocate increasing flows of cruise ships and passengers. Unequal power relations between cruise companies and island communities prioritize the economy over the environment. An increase in the number of cruise passengers and investments in infrastructure and facilities will likely put extra pressure on the island's marine ecosystems, which function as the main tourist attraction at Bonaire (Van Bets et al., 2017).

Holopelagic *Sargassum* seaweeds, viz. *S. natans* and *S. fluitans*, have always been present in the North Atlantic Ocean, but since 2011 they have been blooming in the Northern Tropical Atlantic and becoming a new regional threat to the island. Johns et al. (2020) proposed that seaweeds from the Sargasso Sea were transported southwards during an extreme negative phase of the North Atlantic Oscillation (NAO); which then formed the seed populations for further proliferation in the northern tropical Atlantic between West Africa and Brazil. Wang et al. (2019) and Lapointe et al. (2021) suggested that unusual large nutrient flows from major rivers such as the Amazon and Orinoco could have induced the sargassum bloom, and interannual fluctuations in the blooms have been associated with north-south movements of the Intertropical Convergence Zone (Skliris et al., 2022). Although the precise causes and mechanisms of the blooms have not been revealed until date, the drifting masses extend from Africa, Brazil, the Caribbean into the Gulf of Mexico, forming the 'Great Atlantic Sargassum Belt'. These seaweeds are now washing up in huge quantities, the so called 'sargassum brown tides', on the Caribbean coastlines (Van Tussenbroek et al., 2017; Wang et al., 2019; Chávez et al., 2020).

In March 2018 large amounts of sargassum entered the coastal bays of Bonaire (i.e. Lac Bay and Lagun) and were found along 70 ha (30 %) of mangrove forest including a network of mangrove channels and lagoons, and on 29 ha (11 %) of shallow seagrass beds (Engel, 2018). Similar events happened in the period 2019–2022 (Van der Geest et al., 2024). The thick mats of sargassum wash up on the beach or get caught between the roots of mangrove trees. When the algae decay and sink to the bottom, they remove all oxygen from the water and the seafloor and cause a build-up of hydrogen sulfide - a highly poisonous substance for plants and animals (Lamers et al., 2013). This causes death of seagrasses and associated fauna (Van Tussenbroek et al., 2017) and mangroves (personal observations, Hernández et al., 2021). In the long term sargassum landings and subsequent sargassum degradation may result in eutrophication, a progressive nutrient enrichment, of Lac Bay. Seagrasses cannot survive in a nutrient-rich environment as it causes excessive algae growth that block out the light. Once a critical amount of nutrients has been reached, seagrass beds can disappear rapidly (Burkholder et al., 2007; Govers et al., 2014); once disappeared, seagrass beds are difficult to restore (Van Katwijk et al., 2016).

Also the invasive seagrass species *Halophila stipulacea* has invaded the native seagrass beds in the Caribbean since 2011 (Willette et al., 2014; Christianen et al., 2019). *H. stipulacea* has small leaves with lower wave energy reduction capabilities, and thin and more shallow-rooting rhizomes with limiting ability to stabilize sediment; thus, this invasive species is less capable of withstanding large storms than the native ones (James et al., 2020). Current research has shown a preference for native seagrass (turtle grass, *Thalassia testudinum*) over invasive seagrass species by green turtles, which means that sea turtle grazing can accelerate native seagrass decline (Christianen et al., 2019). In contrast herbivorous parrotfishes (*Nicholsina usta*, *Scarus iserti* and *Sparisoma aurofrenatum*) were found to limit *H. stipulacea* expansion, highlighting the importance of diverse and abundant herbivore communities (Smulders et al., 2022). There are no records available of these species being caught by fisheries on Bonaire (personal communication Sabine Engel). Sea turtle conservation is successful within the Caribbean, results of which can be seen locally with the increase of the green sea turtle populations within Lac Bay (Van der Zee et al., 2019; Christianen et al., 2022). Nevertheless, management measures to protect these important seagrass habitats are not only urgent, but also must be designed thoughtfully (Leemans et al., 2020; Christianen et al., 2022) (Fig. 2).

Fig. 2. Above healthy seagrass (*Thalassia testudinum*) and mangroves (*Rhizophora mangle*) in Lac Bay, Bonaire island, and below dead seagrass and mangroves as the result of *Sargassum* spp. landings in Lac Bay, since 2018.

2.3. Bonaire national marine park management plan

The national *Nature and Environment Policy Plan Caribbean Netherlands 2020–2030* provides an integrated framework addressing responsibilities, policy targets, and legal obligations related to management of the natural environment in the Caribbean Netherlands: Bonaire, Saba and Sint Eustatius (NEPP, 2020). From this national plan, the public entities of each of the three islands will develop their own nature plans and implementation agenda's. Recently (2022) the Public Entity Bonaire commissioned the *Bonaire National Marine Park Management Plan 2022–2028*, issued by STINAPA which also addresses the sargassum landings (De Meyer et al., 2022). In general, STINAPA has identified the following conservation strategies: (i) optimize protection for key marine habitats and species; (ii) improve sustainable recreation; (iii) encourage sustainable fishing; (iv) control invasive species and disease; (iv) support restoration of key habitats and species; and (v) influence policy and legislation to improve park management.

Sargassum landings form a new threat and are expected to maintain or increase in the near future, both in frequency and volume. This calls for immediate measures to minimize repeated and long-term damage to marine ecosystems as well as costly clean-ups. Removal guidelines have been developed for sargassum landings on beaches, but shorelines with mangrove forests and shallow seagrass beds require different approaches due to their vulnerability and inaccessibility. Meanwhile, Bonaire has prioritized responding quickly and effectively to the sargassum influx. The main stakeholders want to prevent and mitigate the effects of sargassum on local ecosystems (DCNA, 2019). Sargassum removal strategy on Bonaire so far consists of removing it where it ends up on beaches, and using 'oil booms' to guide the seaweed towards a beach for clean-up. However, over the past years STINAPA has only been able to remove less than 5 % of the sargassum due to insufficient funding and capacity (De Meyer and MacRae, 2023).

Nature-oriented ecotourism has seen a rise in recent years, evident by Bonaire's push to become a so-called *Blue Destination*. The brand Blue Destination Bonaire also wants to raise more awareness among the local population and tourists in the field of sustainable development for the benefit of nature, local economic prosperity, as for preservation of the island's cultural heritage resources (Slijkerman and Henkens, 2019; Van Bremen, 2021).

3. Materials and methods

3.1. A practical procedure for early stakeholder involvement

To involve stakeholders in an early stage in the formulation of research questions and possible management options, we organized three stakeholder meetings attended by marine ecologists, tourism stakeholders, nature managers and governmental representatives. The three meetings were preceded by desk research and open interviews with different SES stakeholders, and were concluded with a ranking of relevant questions for underpinning further ecological research and necessary management measures. Two of these meetings were used to map the SES of Lac Bay before and after the sargassum landings, for this we used Group Model Building (GMB) in both sessions. GMB is a diagnostic participative tool for identifying drivers, key variables and feedback loops in a system (Rouwette et al., 2002). The goal of a GMB session is not only to develop a model of the SES examined, but also a shared understanding of the experienced issues and a common contribution to relevant questions for further ecological research and possible management measures as participants might have different and ambiguous

opinions about these issues (Vugteveen et al., 2015; Rouwette et al., 2016).

In the modelling sessions participants identified and connected the variables that play a role in the socioeconomic as well as the ecological systems of Lac Bay. Relations between variables can combine to form feedback loops, which are seen as key elements of the mechanism explaining development over time. Between the two GMB sessions, another stakeholder meeting was organized to identify interests and threats in the Lac Bay system, as well as to explore possible solutions. At the base of our practical procedure are (i) the involvement of one or more local experts rooted in nature management as well as in marine ecology, and (ii) a flexible, almost ad hoc organization of sessions, using opportunities such as concurrent availability of stakeholders and experts, or enhanced motivation for participation during and right after severe events i.e. sargassum landings.

3.2. Group Model Building

GMB is a method in which a system is visually represented using system dynamics to support a group in decision-making on complex problems. The aim is to structure a group process in which involvement in and reaching consensus about the problem and decisions to take, is central. Next to the model of the SES built, GMB also supports shared understanding of the experienced issues among participants, and facilitates a common contribution to relevant research questions and possible management measurement (Vennix, 1999). Therefore, the loop diagrams that are created are the means to achieve this consensus and the shared identification of relevant ecological questions and urgent management requirements for the SES of Lac Bay. GMB has shown its merit in facilitated modelling of complex, feedback-rich systems in general (Rouwette et al., 2011) and social-ecological systems in particular (Vugteveen et al., 2015).

GMB offers several benefits when applied to complex multi-dimensional SES issues. Noted benefits include the flexibility and transparency of the method, the capacity to integrate qualitative and quantitative information, the ability to integrate a wide range of input parameters or variables in a meaningful way reflecting their inherent interactions and feedbacks, and explicit recognition of multiple forms of uncertainty (Rouwette et al., 2011; Haji Gholam Saryazdi et al., 2020). Importantly, the GMB approach provides a tool for involving stakeholders and making SES management relevant to local concerns. Participating in the modelling process helps participants to develop a shared representation of the scope and complexity of the different problems and enables the exchange of knowledge and individual perspectives (Tan et al., 2018; Guariguata et al., 2020).

In a complex, feedback-rich system like Lac Bay, GMB can help to identify and articulate critical information about structures and feedback loops underlying the various SES variables within the system. The formulation of concrete 'cause-effect-chains' between variables can provide a foundation for identification of relevant questions for ecological research, as well as for nature management. By facilitating the exploration of salient social-ecological feedbacks, the model, viz. the 'causal loop diagram', also provides fundamental understanding of leverage points for sustainable solutions and derived management measures.

By integrating GMB involving key stakeholders with empirical studies, we expect to (i) reveal novel insights into the key feedback loops in and between the socioeconomic as well as the natural seagrass-mangrove-beach systems of the bay, and (ii) develop innovative tools to improve resilience and sustainability of both the tourist activities (scuba diving, snorkelling, windsurfing, kayaking) and the ecological systems of Lac Bay.

3.3. The five steps of our practical procedure

Fig. 3 shows a diagram illustrating the successive steps in our flexible and practical procedure to involve stakeholders in an early stage of an ecological research project. These different steps are briefly described.

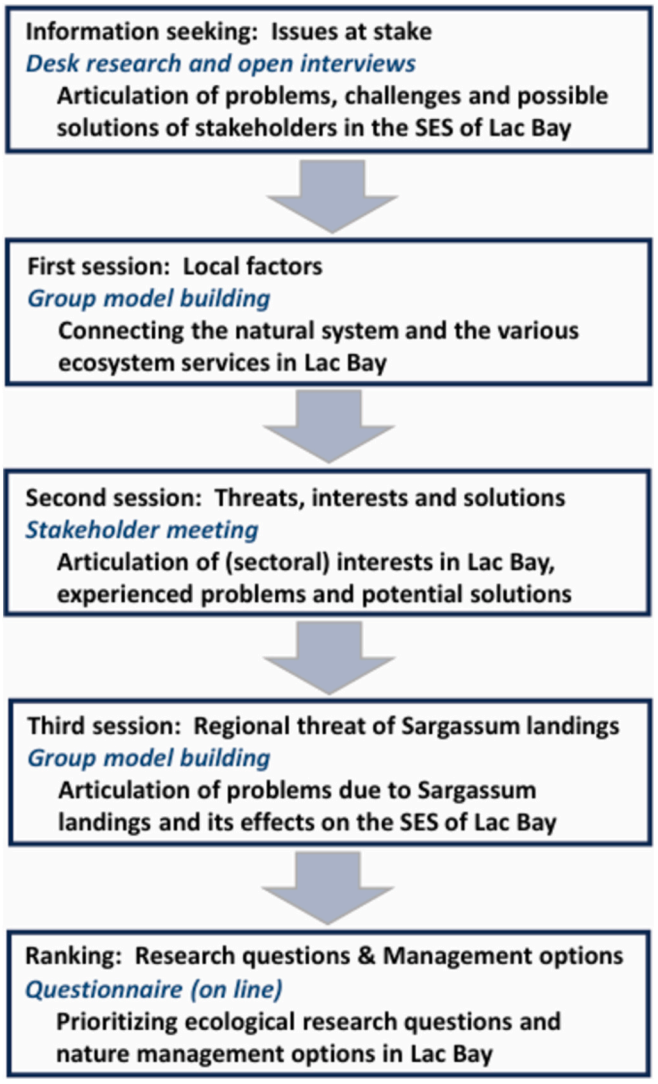

Fig. 3. A practical procedure for early stakeholder involvement using Group Model Building to identify ecological research questions and nature management options.

3.3.1. Information seeking: issues at stake

To identify the local pressures and regional threats to the social-ecological system of Bonaire and Lac Bay in particular, we first performed a comprehensive desk study of policy studies and research reports. To further articulate problems, challenges and possible solutions for the Lac Bay SES open interviews were held with stakeholders from tourism industry, nature management, island government and marine ecology already working on the island. A list with the questions used in these interviews is shown in Appendix A. The results of the desk study and interviews were used to inform the subsequent meetings.

3.3.2. First session: local factors

The first session in which we used GMB was held in Kralendijk, Bonaire on February 18th 2019 with facilitators and nine participants from the tourism industry, nature management, island government, and marine ecology. The participants were selected based on the results of the desk study and open interviews. In the session, participants together built a qualitative causal loop diagram of the different variables and connections within the natural system of Lac Bay, the ecosystem services

provided, and other relations through which Lac Bay is connected to the economy of the area. The model was built by the facilitators with variables elicited during the group model building session with the Lac Bay stakeholders. The only variable that was added afterwards by the facilitators is the 'island economy'. The final model was approved by all participants.

3.3.3. Second session: threats, interests and solutions

A facilitated in-depth stakeholder meeting was held on October 9th 2019 in Kralendijk, Bonaire with two facilitators and eight participants from the tourism industry, nature management, island government and marine ecology, two of them also participated in the first GMB session in February. Based on the causal loop diagram developed in February these participants openly shared their interests and insights. Also, they articulated which problems they experienced in particular and what specific knowledge they were missing. Possible management measures and research questions for the underpinning of ecological conservation and restoration became more tangible. In the first round an inventory was made of the *different interests and experienced bottlenecks*. In the following round *possible solutions and expected obstacles* were inventoried and agreed upon.

3.3.4. Third session: the regional threat of sargassum landings

To model the expected and unexpected sargassum problems for the SES of Lac Bay, and to formulate crucial research questions and urgent management requirements we organized a second GMB session in Nijmegen, The Netherlands, on November 27th 2019. In this session, a facilitator participated together with seven experts from nature conservation on Bonaire and from marine ecology with expertise in sargassum landings in particular. A causal loop diagram was made of the problems regarding sargassum brown tides in Lac Bay, the effects of sargassum on its SES, and the efficacy and feasibility of solutions for the prevention and removal of landed sargassum. Relations between variables were drawn partly during the session, and partly afterwards, based on what participants said during the session. The resulting causal loop diagram was approved by all participants.

3.3.5. Ranking: preferred research questions and management options

After the second GMB session, the facilitator asked participants to indicate which analysis variables or arrows in the model they wanted to know more about, or what they still considered uncertain in the model. These issues were formulated in specific questions for new ecological research, and in questions for underpinning effective management measures. This resulted in a list of twenty questions, see Appendix B. This list was sent to and ranked on relevance by the participants afterwards.

4. Results

The two GMB sessions resulted in two causal loop diagrams. The first diagram models the local pressures such as tourism and soil erosion on the ecosystems of Lac Bay; whereas the second diagram models the pressures of sargassum landings. A powerful application of building causal loop diagrams is the identification of 'feedback loops', which reveal variables that have a large influence on the behaviour of the system, for example through cascades, and indicate possible management intervention points as well as inflexion or leverage points. Feedback loops can either be 'reinforcing' or 'balancing'. A reinforcing feedback loop is found whenever behaviours or events inside the loop produce a result which influences more of the same action, thus resulting in growth or decline. A balancing feedback loop is a mechanism that counters change in one direction with a change in the opposite direction; it stabilizes a system.

4.1. First session: local factors

The first causal loop diagram (Fig. 4) was built of the different components of the natural system of Lac Bay, the provided ecosystem services as well as the human activities - especially tourism - through which Lac Bay is connected to the people and the economy of Bonaire. To protect Bonaire's natural resources a better understanding of human co-use related to nature is needed. Therefore, the pressures of these human activities on the natural system are depicted in a causal loop diagram.

During construction of the causal loop diagram, multiple feedback loops were identified, indicating the local pressures on the SES of Lac Bay. Seagrass is involved in two reinforcing feedback loops. Seagrass has a positive effect on water quality and causes sediment stabilization, which also has a positive effect on water quality. A better water quality in turn has a positive effect on seagrass, completing the loop. The implication for management is that the more seagrass disappears, the more effort it will take to improve water conditions to facilitate seagrass restoration (Van der Heide et al., 2007; Van Katwijk et al., 2016).

The number of tourists, and the direct and indirect impacts of tourism (hereafter together: tourism) are involved in four balancing feedback loops. Tourism affects not only corals, but also marine biodiversity in a broad sense on which it depends. In the model the variable 'marine biodiversity' encompasses biodiversity from coral reefs, seagrass beds, mangrove forests, sandy beaches, and other related habitats of Lac Bay's saltwater ecosystems. Tourism also affects water quality and seagrass, which in turn affect corals and marine biodiversity. It should be noted that the large balancing loop, which is indicated in the diagram with red arrows, and integrates the aforementioned *seagrass-water quality-sediment stabilization* loops and the *tourism-coral-marine biodiversity* loops, shows that reinforcing interactions still affect tourism. This means one cannot view this social-ecological system as self-regulating (i.e. decrease in coral leads to a decrease in tourism which will lead to an increase in coral again), because destabilizing reinforcing interactions also play a role (e.g. resulting environmental conditions may not be sufficiently good for recovery of corals or seagrasses).

The causal loop diagram shows that nature and tourism in Lac Bay are tightly interconnected in the social-ecological system. The vital variables involved in the feedback loops at the model's core can be influenced in several ways. Tourism impact is influenced not only by the number of tourists, but also by more sustainable behaviour of Lac Bay's visitors. Marine biodiversity is positively influenced by nature management and sustainable fishery practices. Attendees agreed that a unified policy vision on Lac Bay's future, including enforcement but also education and knowledge dissemination, can further decrease the detrimental effects of tourism on the different ecosystems of Lac Bay.

4.2. Second session: threats, interests and solutions

To better understand how management responses might decrease the human pressures on Lac Bay, a facilitated in-depth stakeholder meeting was held on October 9th 2019 in Bonaire with eight participants from the tourism industry, nature management, island government and marine ecology. Two of them also participated in the GMB session in February. Based on the approved GMB diagram (Fig. 4) participants then openly shared their concerns and interests with each other. They articulated which obstacles they experienced, particularly in the relationship between human activities like tourism and nature conservation. In doing so, possible management options became more tangible (see Fig. 5). In the first round an inventory was made of the different interests and potential threats of their interests. In the following round possible solutions were mentioned. Participants expressed that their core interest is a shared use of nature for tourism in Lac Bay. Of crucial importance for this shared use is preserving ecological carrying capacity, for which healthy ecosystems and rich biodiversity is needed. This is of interest to sustainable tourism entrepreneurs (e.g. beach restaurants, scuba diving,

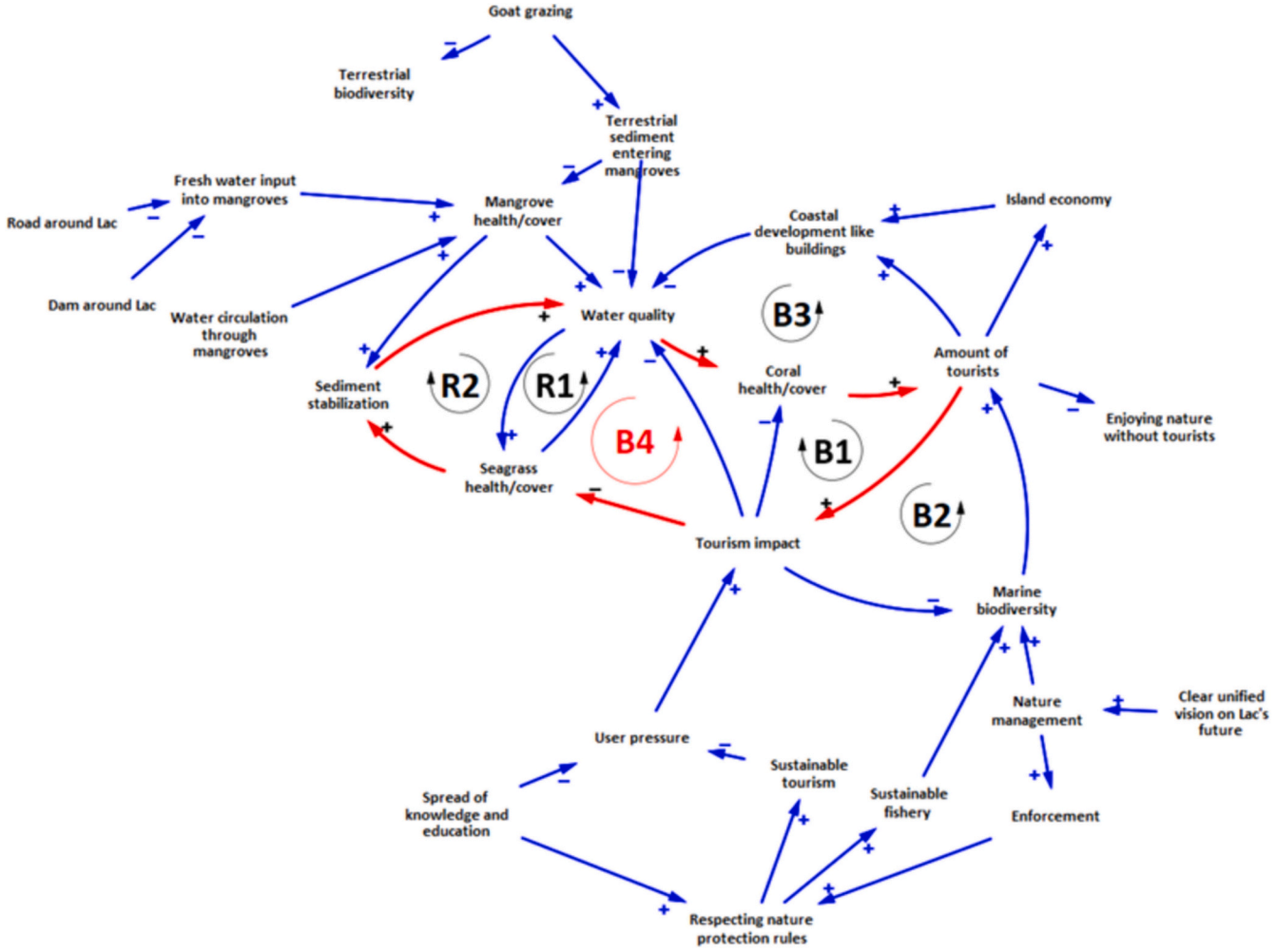

Fig. 4. Causal Loop Diagram of the SES of Lac Bay, Bonaire without the impact from sargassum influx. R = reinforcing feedback loop, B = balancing feedback loop. One complex balancing feedback loop is indicated with red arrows and red B; it encompasses multiple other loops.
R1: Seagrass has a positive effect on water quality.
R2: Seagrass stabilizes sediment, which improves water quality, which benefits seagrass.
B1: Amount of tourist increases tourism impact, decreasing coral health/cover, causing a decline in tourism.
B2: Amount of tourist increases tourism impact, decreasing marine biodiversity, causing a decline in tourism.
B3: An increase in tourists causes extra coastal development. This decreases the water quality, and with it the corals, on which tourism relies.
B4 (red): A complex balancing feedback loop that encompasses several other loops. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

kayak rental, windsurfing), but also to nature managers and government representatives as Lac Bay is part of the Bonaire National Marine Park, and there is an obligation for good management of Lac Bay, due to various (inter)national treaties.

Attendees observed a strong increase in human activity at Lac Bay in recent years, but policies are lagging behind this change in activity. Enforcement of the current nature protection policies would help but has been difficult and inconsistent. Lac Bay is threatened by plastic pollution, land erosion leading to sediment infilling of the bay, and the new sargassum landing events. In dealing with all of these problems, there has been insufficient communication among stakeholders. When asked what the most important obstacles were, participants expressed that indecisiveness and waiting for the other party to take the initiative have often led to a loss of support for action and momentum.

In the short term, according to the participants, a joint action plan for Lac Bay including an approach to consistent enforcement should be made and implemented. There should be clarity and agreement about which knowledge is missing and what needs to be investigated about ecological functioning and conservation; and about the impact of human pressures on carrying capacity and resilience of Lac Bay. Implementing such a joint action plan was suggested to be particularly effective when situated measures and a more integrated approach are used. Therefore, it was believed that a connection with the conservation strategies in the new *Bonaire National Marine Park Management Plan* must be made. According to the participants, the finances for the implementation of the plan could (partly) be arranged by increasing the head tax of visitors, entrance fees to the bay, or by collecting revenues from cruise ship tourists visiting the island. Also, a part of the increased touristic revenues could be used for poverty reduction, and thus enhancing the sense of ownership to the users of Lac Bay and residents nearby. In a broader sense, awareness of the Bonaire National Marine Park could be boosted with a *Proud of Bonaire* campaign. Information and education about nature especially for local children but also other residents and incoming tourists are essential for raising awareness about the entanglement of natural and economic value, and support for nature conservation measures. These actions can contribute to a more sustainable, nature-oriented ecotourism, without sacrificing the cultural heritage or depleting the natural resources.

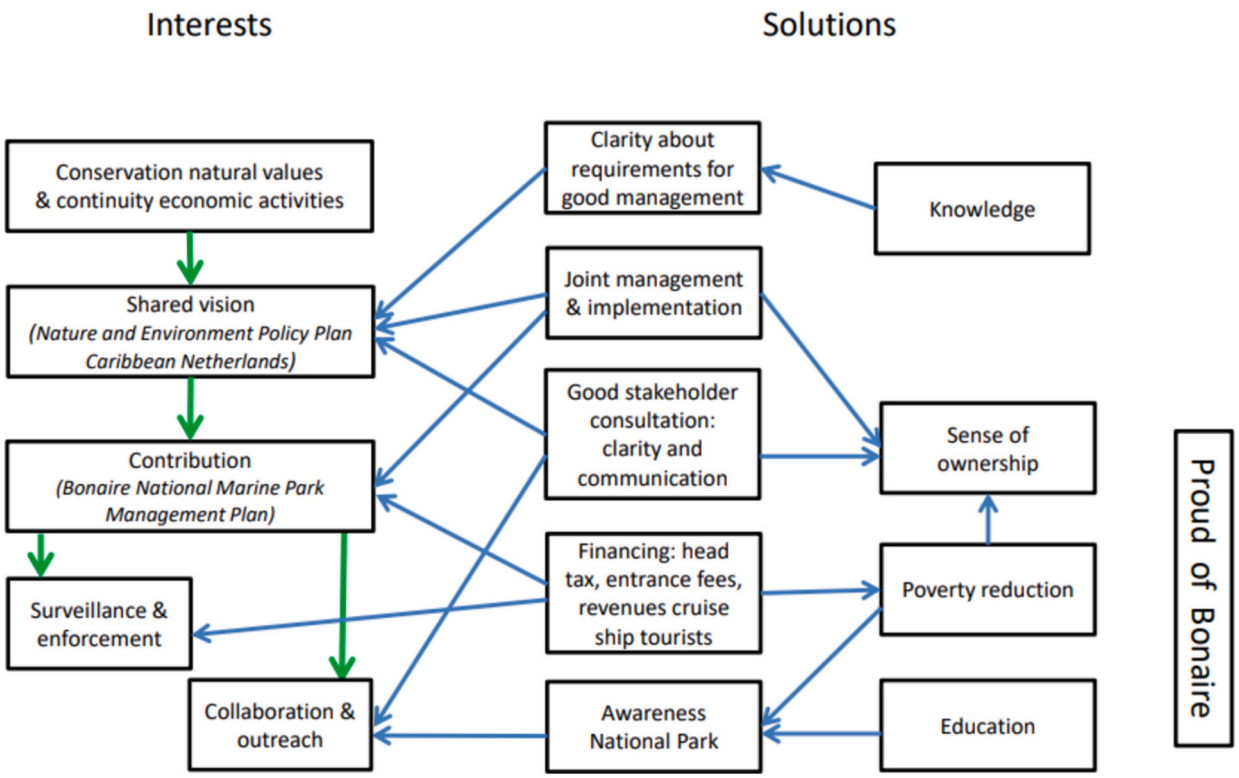

Fig. 5. A schematic overview of the main interests resulting from the in-depth stakeholder meeting and proposed solutions. Green arrows indicate 'requires'. Blue arrows indicate consequences, they represent 'leads to' or 'enhances'.

4.3. Third session: the regional threat of sargassum landings

Based on the expert session held on 27th November 2019 in Nijmegen (The Netherlands) a 'causal loop diagram' model was built of the problems regarding sargassum tides in Lac Bay and more specifically the effects of sargassum on its social-ecological system. The efficacy and feasibility of solutions for prevention and clean-up of these sargassum landings are depicted in the model. Relations between variables were drawn partly during the session, and partly afterwards, based on what participants have said during the session (Fig. 6). Additional goals in this session were to identify relevant questions for ecological research and management requirements based on the model, and to make a prioritization of these questions by all participants.

This model consists of balancing feedback loops. The amount of sargassum increases the perceived urgency of problems, which stimulates management measures, such as using booms, boats and conveyor belts to remove sargassum from the bay or removing the seaweed when still in the ocean. During a sargassum brown tide, the seaweed is present on multiple locations: floating in the ocean in front of Lac Bay, floating in the bay itself, on the beaches, or sunken and decaying. Participants agreed that at present it is easiest to remove the seaweed from the beaches. Using booms, normally used for oil spills, some of the sargassum floating from the ocean into Lac Bay is brought to the beach to be removed. Beached sargassum is at present the largest direct threat to tourism, while sinking sargassum in the bay degrades seagrass and mangrove ecosystems. In the longer term, the degradation of these natural systems will also harm tourism and its revenues ('economical damage'). A small balancing ecological feedback loop was articulated indicating that the sargassum decay rate increases with oxygen concentration in the water but also decreases the oxygen concentration itself again.

We sent all participants in both GMB sessions a short questionnaire (see Appendix C) for an evaluation of their meeting, and received a 70 % response. Participants appreciated how the structured group model building process was facilitated and helped communication and learning. Attendees stated that the approach allowed them to develop a more comprehensive understanding of the SES of Lac Bay, better listen to each other, and that they had a positive personal experience.

4.4. Prioritizing key questions for ecological research and management measures

At the end of the session, participants were asked to (1) identify relevant research questions concerning the impact of sargassum-related problems on Bonaire and Lac Bay in particular, and (2) to identify questions underpinning effective management measures for clean-up and prevention of these sargassum brown tides in lagoons and on beaches (see Appendix B). Next each set of questions was prioritized by asking participants to rate them on urgency and feasibility (see Table 1).

4.5. Current and new initiatives for ecological research, monitoring and management

The key research questions (Table 1) have helped to target the ongoing ecological research in Lac Bay by the Radboud University in cooperation with STINAPA. In 2019, a monitoring program was set-up from our research program along 12 transects close to the shore of Lac Bay. Seagrasses, algae and mangroves are monitored in detail (cover, density, nutrient and elemental content), along with sediment and sediment pore water characteristics (sulfide, oxygen, pH, nutrient and elemental contents). Monitoring was performed before, during and after sargassum brown tides for several years, to investigate ecosystem changes and possible drivers. This monitoring data can be integrated with previous monitoring data collected by STINAPA (Engel and Johnson, 2022). Currently, two publications are underway which make use of this monitoring data. One paper describes the effects of sargassum on mangroves in Lac Bay (research questions 2 and 3), making use of monitoring data and data from a field experiment. Another paper tries to

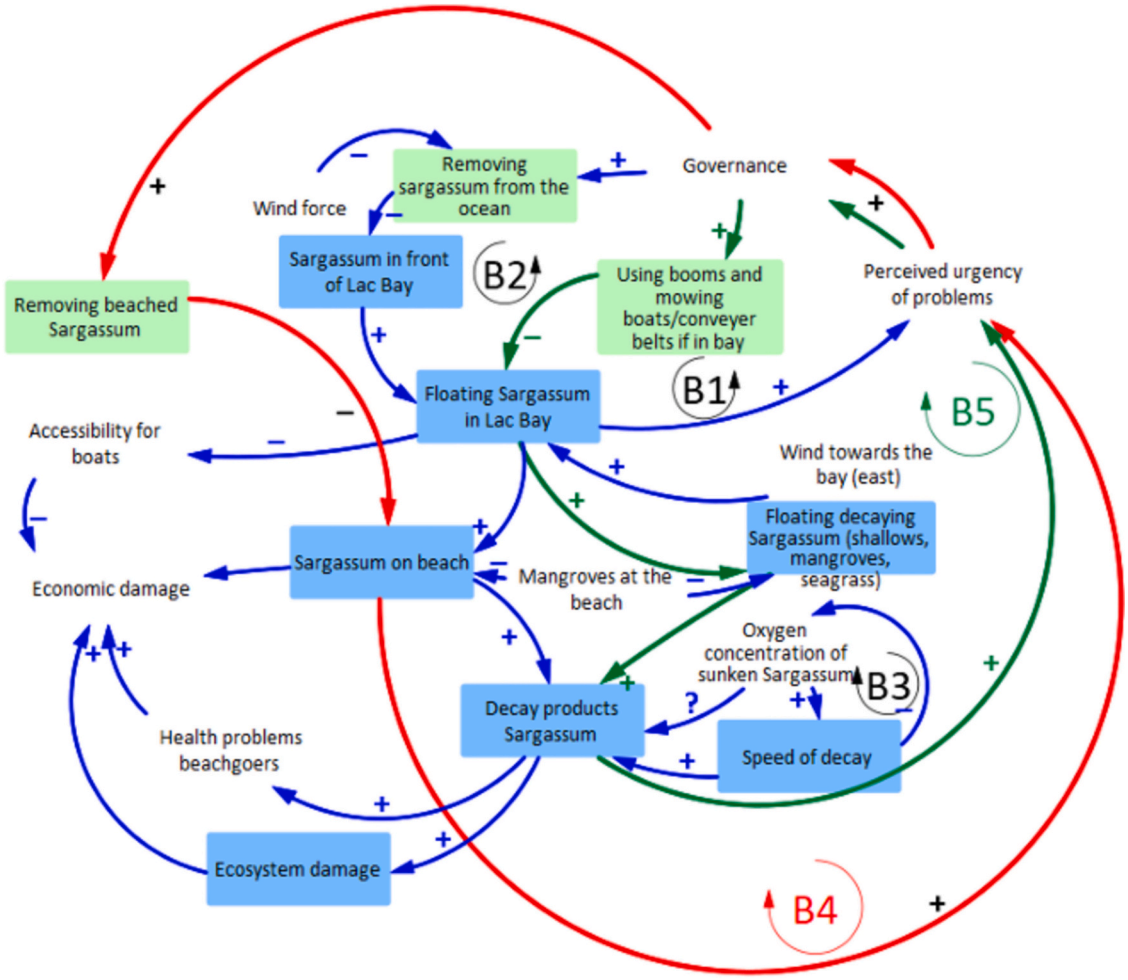

Fig. 6. Causal Loop Diagram of the SES of Lac Bay, Bonaire with the impact from sargassum influx. B = balancing feedback loop. The two loops indicated by arrows in red and green (for clarity) are also balancing feedback loops.
B1: Sargassum in Lac Bay increases perceived urgency, which stimulates removal of floating sargassum, decreasing (perception of) the problem.
B2: Sargassum in Lac Bay increases perceived urgency, which stimulates efforts to remove sargassum from the ocean, which prevents it from nearing Lac Bay and ending up inside Lac Bay.
B3: Sargassum decay decreases oxygen concentration in the water, which slows down sargassum decay.
B4 (red): Beached Sargassum increases perceived urgency, which stimulates removal of beached sargassum, decreasing (perception of) the problem.
B5 (green): Sargassum in Lac Bay decays, releasing decay products, which increases perceived urgency, which stimulates removal of sargassum. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Results of the prioritization of urgent ecological research questions and adequate management measures.

Five Key Questions concerning urgent ecological research
1. What amount (weight or volume) of sargassum influx enters Lac Bay per unit of time (week, season, year)?
2. What are the cumulative harmful effects of the sargassum influx and its degradation on Lac Bay's ecosystems?
3. At what load or density does the sargassum influx become critical; the so-called critical load?
4. How do the various degradation processes proceed, are they depending on the composition of the sargassum itself, and what are the (un)favourable environmental conditions for degradation like, light, oxygen, and flushing rate?
5. What are the detrimental effects resulting from the degradation of sargassum on other parts of Lac Bay through the dispersal of nutrients, particulate organic matter and other degradation products (such as potentially toxic metals and metalloids)?

Five Key Questions concerning adequate management measures
1. How do you dispose of the removed sargassum in a safe way for the environment and human health?
2. How do we ensure good coordination for taking the right prevention and clean-up measures in a specific area?
3. How do we ensure that proper regulation is put in place and enforced?
4. There is a grid of seagrass monitoring points in Lac Bay. In this way, data from 2011 and beyond - from before and after sargassum landings - can be compared. Can STINAPA as manager of the Bonaire National Marine Park pick this up?
5. Can we ensure an adequate monitoring program for the sargassum problems in the long term, for example in the new Bonaire National Marine Park Management Plan?

answer question 2 and 3 for seagrasses, again making use of a field experiment. In this paper we also consider long-range effects of sargassum degradation products (research question 5). An effort to estimate sargassum load (research question 1) will also be included in this paper, as will the results of a sargassum degradation experiment (research question 4). Furthermore, with partner researchers from Wageningen University & Research, a greenhouse experiment has been performed in the Netherlands with sargassum, which showed that sargassum decomposition can release large amounts of nitrous oxide, a potent greenhouse gas (Cobacho et al., 2024). Moreover, using satellite imagery (Van der Geest et al., 2024) provided the first assessment of the approximate volumes of sargassum biomass arriving at specific locations in Lac Bay (and elsewhere) over time. This information will aid identification of suitable uses of sargassum and the scale of potential sargassum-based enterprises on Bonaire, and will help identify priority areas for coastal management of these sargassum influxes (Van der Geest et al., 2024).

The key questions concerning management measures (Table 1) have contributed to the further completion of the new management plan. Additionally, practical management advice has been given to STINAPA for targeted prevention and clean-up measures. The findings about sargassum degradation in Lac Bay and ecosystem effects have helped select optimal locations for sargassum extraction using booms. Ecological recovery of affected areas is not possible as long as sargassum keeps coming in. Finding out if Lac Bay is eutrophicating, is important to gauge sargassum removal efforts. In the new Bonaire National Marine Park Management Plan 2022–2028 specific measures have been announced to minimize the impact of sargassum on seagrass beds and mangrove forests in Lac Bay (De Meyer et al., 2022). *Bonaire's Sargassum Response Plan* was implemented in 2022 and is coordinated by STINAPA (De Meyer and MacRae, 2023). Meanwhile STINAPA is using excavators and lorries to collect and dump sargassum landings on dedicated locations. STINAPA has also designed specific sargassum booms that allow waterflow and retain sargassum and can direct the large fields of washed-up seaweed more effectively to a collection point on the beach.

As the accumulation of sargassum on Caribbean islands and coasts appears to be becoming a more seasonal phenomenon, also Dutch Caribbean islands are looking for innovative ways to get rid of this nuisance. As long as the ecosystem and human health effects are not clear, it is wise not to use sargassum directly for food production. Nevertheless, valorization of the collected sargassum biomass offers possibilities for biomaterials, biofuels and agricultural products (i.e. fertilizer, animal feed supplement). These possible valorization products seem promising for the Dutch Caribbean islands, since they contribute to more sustainable energy and food security, while reducing the environmental impact of the energy and agricultural sector. However, the uncertain availability of sargassum and its toxic properties can limit the production and marketing of the mentioned bioproducts (López-Contreras et al., 2021; Liranzo-Gomez et al., 2021; López-Contreras et al., 2022).

5. Discussion

A precondition for achieving more sustainable forms of human co-use is the participation of relevant SES stakeholders in reaching consensus and contributing to the formulation of a shared vision and an integrated management plan. For this, we developed a practical procedure with desk study, in-depth interviews, and stakeholder meetings - two of them using GMB, with input of tourism entrepreneurs, nature managers, government representatives and marine ecologists for modelling 'causal loop diagrams' and 'feedback loops' in the social-ecological system of our case study Lac Bay, Bonaire island. Applying the procedure allowed us to reveal novel, substantiated and shared insights in the underlying mechanisms of driving feedbacks in the socio-economic (viz. tourism) as well as the ecological (viz. seagrass-mangrove) system. For Lac Bay we have come up with topical research questions for the conservation of seagrass beds and mangrove forests; practical measures for nature management as well as the prevention and cleaning-up of sargassum landings in Lac Bay; and recommendations for more cooperation among tourism entrepreneurs and island government, also in their outreach activities. At the base of our practical procedure are (1) the involvement of local experts rooted in nature management as well as in marine ecology, and (2) a flexible, almost ad hoc organization of sessions, using opportunities such as concurrent availability of stakeholders and experts, or enhanced motivation for participation during and right after severe events (such as sargassum landings). The applicability of our procedure has been demonstrated in the increased support for ecological research and nature management in the area, and several follow-up studies.

5.1. Participatory modelling enables a shared understanding of the different SES issues

In GMB, the input to a model consists of participants' understanding of the issues at stake. As such the approach provides a mechanism for integrating scientific knowledge with more tacit knowledge. There was no opportunity to check statements and facts real-time against other data sources that could have revealed potential biases in participants' assumptions. Unlike a formal model, the qualitative models built for both cases cannot be simulated over time, which means that their validity can only be assessed to a limited extent. Although the sessions did not result in formal models, the elicitation of key SES variables and their feedback loops that were important to all participants and the development of conceptual models contributed to the process of learning, consensus-building, and the consent on key questions for further ecological research and management measures. The complex multi-dimensional issues, uncertainties and feedbacks between the social and ecological systems urges for new and improved methods and tools to obtain and produce the best available knowledge and urgent follow-up questions (Hanger-Kopp et al., 2024). We show that GMB offers a method with added value for facilitating knowledge generation and enabling more systematic scoping work early on in ecological research processes.

5.2. The new procedure results in more support for ecological research and nature management

The early science-stakeholder interaction has provided more support for research into the ecological conservation of Lac Bay, and resulted in an informal network of local experts who could be consulted throughout the research project. In using GMB for mutual exchange and understanding we integrated tacit knowledge of different stakeholders with new experimental ecological knowledge to enhance coastal conservation efforts. This occurred not only at the start of our five-year research project in formulating research questions, improving contextual knowledge, agreeing on site selection, and finding local collaboration, but also during the lifetime of the project in interpreting results of completed research and in formulating conservation and management measures to improve the ecosystems in Lac Bay, and for the clean-up and further processing of sargassum landings in achieving local sustainable actions more in line with the interests of all SES stakeholders. Our results demonstrate the importance of involving local knowledge in the joint design, development and delivery of management solutions, as was previously stressed by Oxenford et al. (2021) and Rosellón-Druker et al. (2023). The application of our procedure is underlined by follow-up studies addressing the research questions and management measures identified in our study (e.g. Cobacho et al., 2024; Van der Geest et al., 2024).

6. Conclusions

Accomplishing sustainable human co-use in coastal zones, especially

nature-based ecotourism, is a continuous process and requires constant monitoring of impacts, introducing the necessary preventive and corrective measures whenever necessary. Management programs have to include monitoring and forecasting of the arrival of sargassum in order to organize the harvest of the seaweed, its preparation, the possible valorization, or the final storage all safely for human and ecosystem health (De la Barreda-Bautista et al., 2023). This is (partly) institutionalized in the new *Bonaire's Sargassum Response Plan*. STINAPA is the co-ordinating body for the response plan within Lac Bay (De Meyer and MacRae, 2023).

Our study was performed in a typical coastal Caribbean bay of the island of Bonaire. Bonaire has a large socioeconomic dependence on tourism, particularly focussing on the underwater beauty similar to most islands and coasts in the wider Caribbean. Also similar to other Caribbean islands and coasts, Bonaire is frequented by sargassum landings causing massive damage to its coastal ecosystems and threatening an important source of income on the island. The practical procedure that we developed for early stakeholder involvement to extract research questions and management options, is transferable to other vulnerable tropical islands and coastal regions, and may help to accomplish a more integrated and ecosystem-based management in which marine ecologists, tourism entrepreneurs, nature managers, and government representatives seek to balance long-term ecological and socioeconomic objectives within natural limits. Together they may develop supported and substantiated approaches to research and manage their social-ecological systems in a more sustainable manner.

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CRediT authorship contribution statement

Lucien Hanssen: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luuk H. Leemans:** Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Sabine Engel:** Writing – review & editing, Resources, Investigation. **Matthijs van der Geest:** Writing – review & editing, Resources, Investigation. **Leon P.M. Lamers:** Writing – review & editing, Supervision, Conceptualization. **Alfons J.P. Smolders:** Writing – review & editing, Supervision, Conceptualization. **Brigitta I. van Tussenbroek:** Writing – review & editing, Resources, Investigation. **Etienne Rouwette:** Writing – review & editing, Visualization, Resources, Methodology, Formal analysis. **Marjolijn J.A. Christianen:** Writing – review & editing, Resources, Investigation. **Marieke M. van Katwijk:** Writing – review & editing, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Questions used in the open interviews

1. What is your profession/at which organization do you work?
2. Can you tell something about your relation to Lac Bay?
3. Which natural resources/ecosystem services do you use? Examples of ecosystem services are fisheries, tourism, coastal protection, experiencing nature.
4. Have you witnessed any changes in those resources or ecosystem services?
5. If so, which one(s)?
6. If not, have you seen other changes in or around Lac Bay?
7. Have these changes caused any problems for you?
8. If yes, which one(s)?
9. If not, do you expect problems in the coming years?
10. What might be possible solution for these problems?
11. Is there something you or your organization could do about this?
12. What and who could help you with this? Funds, a better functioning ecosystem in Lac Bay, a change in management, something else?
13. Could ecological research help with finding solutions to your problem(s)?
14. Have you collaborated with (ecological) researchers in the past?
15. If so, what were the positive and negative aspects of this collaboration?
16. Are there other stakeholders with whom you share these problems?
17. Are you aware with (the problems concerning) sargassum brown tides, and can they affect you?

Appendix B. Derived questions for new ecological research and effective management measures

Questions concerning ecological research for Lac Bay

1. What amount (weight or volume) of sargassum influx are we talking about in Lac Bay per time unit (week, season, year)?
2. How do the various degradation processes proceed, are they depending on the composition of the sargassum itself, and what are the (un)beneficial environmental conditions for degradation, like light, oxygen, flushing speed?
3. How long do the decomposition processes of the residue, the sunken decomposing sargassum, take?
4. Is the oxygen concentration around the sunken sargassum a possible indicator of the rate of degradation of the sargassum?
5. What are the specific degradation products of sargassum per habitat type (coral, seagrass, mangrove, foreshore)?
6. What is the removal rate of the degradation products (nutrients, tannins, organic substances) from Lac Bay; this is again linked to the (natural) flushing rate of Lac Bay, and is it known?
7. What are the detrimental effects resulting from the degradation of sargassum on other parts of Lac Bay through the dispersal of nutrients and other degradation products?
8. What are the cumulative harmful effects of sargassum influx and its degradation on Lac Bay's ecosystems?
9. Are there positive effects of the *sargassum* influx on the Lac Bay ecosystems known?
10. At what load or density does the sargassum become critical; the so called critical load?
11. Which and in what quantities are harmful bacteria (or other micro-organisms) released during the decomposition of sargassum and what are the harmful effects of these on the coral reef?

12. What are the harmful effects of nutrients from sargassum degradation on the coral reef?

Questions concerning management measures for Lac Bay

13. How do you dispose of the cleaned sargassum and then process it in a safe way for the environment and human health?
14. How big, and what, is the damage of the various clean-up measures on the different ecosystems?
15. How do we ensure proper coordination for taking the right prevention and clean-up measures in a specific area?
16. Can we ensure an adequate monitoring program for the sargassum problems in the long term, for example in the new Bonaire National Marine Park Management Plan?
17. There is a grid of monitoring points in Lac Bay. In this way data from 2011 and beyond - from before and after the sargassum landings - can be compared. Which organization picks this up?
18. How do we ensure that proper regulation is put in place and enforced?
19. What is the perceived urgency of the sargassum problems among the residents of Bonaire?

Appendix C. Questionnaire send to the participants after the GBM sessions

A. The GMB model of Lac Bay represents a useful presentation of the issues at stake and captures the general relations and trends.
   1. strongly disagree
   2. disagree
   3. neutral
   4. agree
   5. strongly agree

   Please indicate your score by choosing one number:

B. Participants in the session were willing to listen to each other.
   1. 1 strongly disagree
   2. disagree
   3. neutral
   4. agree
   5. strongly agree

   Please indicate your score by choosing one number:

C. Participants in the session were willing to cooperate in a constructive manner.
   1. 1 strongly disagree
   2. disagree
   3. neutral
   4. agree
   5. strongly agree

   Please indicate your score by choosing one number:

D. For me the session was an useful experience.
   1. strongly disagree
   2. disagree
   3. neutral
   4. agree
   5. strongly agree

   Please indicate your score by choosing one number:

E. For me the session was a positive experience.
   1. strongly disagree
   2. disagree
   3. neutral
   4. agree
   5. strongly agree

   Please indicate your score by choosing one number:

If you have any further comments about the session, please write them here:

Data availability

No data was used for the research described in the article.

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