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Achieving social and ecological goals of coastal management through integrated monitoring

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1 | INTRODUCTION

Successful resource management relies on an understanding of the complex relationships between social and natural systems and their governance (Berkes et al., 2016). Taken together these interacting systems have been described as part of a social-ecological system (SES). Here, natural system refers to the biological and physical (biophysical) system and is used interchangeably with ecological system or ecosystem. Social system is used to characterize the interactions within and among human communities and their institutions, particularly those related to resource governance. The SES framework was developed to explain the many complexities of these relationships, but also to characterize what contexts and processes could help improve the management of natural resources (Ostrom, 2009). More specifically, SES has been defined as 'a system that includes societal (human) and ecological (biophysical) subsystems in mutual interactions' (Harrington et al., 2010) or a system 'where social and ecological systems are mutually dependent' (Fidel, Kliskey, Alessa, & Sutton, 2014). Management is most successful when it maximizes the benefits that natural resources provide to people and human

stewardship of the environment. To date, limited evidence linking conservation and natural resource management interventions to human well-being exists (McKinnon et al., 2016). Monitoring must adapt to capture this complexity, and in particular, focus sharply on the interactions and interdependencies of natural and social systems.

In the sustainability sciences, when monitoring is part of adaptive management, the purpose is to track ecosystem change over time, assess management implementation, and evaluate how well objectives were achieved (Kendall & Moore, 2012). Natural resource managers have monitored the biophysical status of ecosystems for decades; however, monitoring social systems has not been as well defined nor have the links between biophysical and social systems been adequately addressed (Wongbusarakum & Heenan, 2018). While conceptual frameworks for SES have advanced (Ostrom, 2009), practical approaches are needed to examine human–environment interactions in different contexts and specific scales (Fleischman et al., 2014; Kittinger, Finkbeiner, Glazier, & Crowder, 2012). Integration of monitoring efforts may enhance the understanding of human-derived benefits from natural systems and improve natural resource management. However, successful

integration of these efforts requires additional capabilities and co-ordination to capture the complexities of interacting systems which operate at multiple scales (Fischer, 2018). It also requires scientists from different disciplinary backgrounds to be open to exploring new methods and willing to bridge disparate objectives, disciplinary epistemologies, and languages (Horlick-Jones & Sime, 2004).

Here, we discuss integrated monitoring (IM) as a coordinated long-term process in which scientists from multiple disciplines collect and analyse biophysical and social data to meet shared objectives of tracking, assessing and understanding changes over time in social and ecological systems and their interactions. Through merging datasets derived from varying methods, the goal of IM is to inform managers and policy makers about systemic changes and their linkages to achieving holistic natural resource management whilst promoting ecological health and human well-being. The limited number of guidelines and approaches for IM (e.g. Lindenmayer, Likens, Haywood, & Miezis, 2011; Wongbusarakum & Heenan, 2018) share common monitoring steps, including developing indicators relevant to management objectives, determining an appropriate sampling design, optimizing data collection methods, analysing and synthesizing datasets, and communicating results for adaptive management. We demonstrate how a causal model, a useful yet rarely implemented tool (Cheng et al., in review), can be applied to the monitoring process to illustrate plausible linkages among management strategies, changes in SESs, ecosystem services and human well-being.

We use Manell-Geus Habitat Focus Area (MGHFA) in Guam as a case study, to show practitioners how biophysical and social monitoring processes can be integrated into producing a holistic view of an SES. We built on IM approaches outlined in the literature to design a baseline assessment of the MGHFA and adjacent coastal community. We used the merged results from biophysical and socio-economic data to develop a management approach linking management strategies and changes in SESs, ecosystem services and human well-being. We also used the baseline data to revise indicators for long-term IM and demonstrate how IM can support the dual pronged coastal management objectives of restoring natural habitats and building community resilience. We discuss the practicalities of interdisciplinary collaboration in a real-world scenario and reflect on the successes and challenges posed when expanding traditional biophysical monitoring programmes to include human subjects and communities. Based on our experience of working with the stakeholders in MGHFA, we conclude with recommendations that could benefit future IM efforts in ecosystem management.

2 | APPLYING INTERGRATED MONITORING IN MANELL-GEUS

2.1 | Monitoring context

Located in southern Guam, the Manell-Geus Watershed with its adjacent reefs was selected as one of 10 Habitat Focus Areas across the US by the United States National Oceanic and Atmospheric Administration (NOAA) Habitat Blueprint Program. The MGHFA harbours endemic fauna in its streams (Camacho, Lindstrom, Moots, & Moran, 2016),

including coral reef, seagrass, mangrove habitats and the Achang Reef Flat Marine Preserve (Figure 1). Merizo village (population 1,800) lies within the MGHFA. Residents are primarily Chamorro, Guam's indigenous people who have strong cultural connections to the sea. The area supports cultural and subsistence harvests, as well as tourism. Over half of Merizo households harvest marine and freshwater resources, and 78% of them eat seafood (NMFS PIRO, in prep).

The Guam Department of Agriculture (DoAg), the Guam Environmental Protection Agency, and the Guam Bureau of Statistics and Plans (BSP) are responsible for managing the coastal marine environment. Because Guam is a US territory, NOAA also has a role in managing marine and coastal resources. These agencies participate in the Guam Coral Reef Initiative (CRI), established in 1997, to address threats to coastal habitats, including land-based sources of pollution, unsustainable fishing practices and repeated coral bleaching (Burdick et al., 2008; Raymundo, Burdick, Lapacek, Miller, & Brown, 2017). Sedimentation linked to land use practices is a major cause for the degradation of Guam's southern reefs (Burdick et al., 2008). Upland disturbances by wildfires lead to erosion and runoff, increased stream flow, sediment transport and streambank erosion (Camacho et al., 2016). Increased frequency and severity of floods and sedimentation impacts both community safety and nearshore habitats (NMFS PIRO, in prep).

In 2010, the CRI initiated efforts to improve the condition of nearshore coral reef ecosystems by restoring upland areas thereby reducing sedimentation (Figure 2A). These efforts focused on the marine preserve, where the harvest of most fish species is prohibited (The Territory of Guam & NOAA Coral Reef Conservation Program, 2010). Limited public engagement in marine preserve management contributed to a lack of community support for watershed restoration. In response, BSP conducted a survey to elicit community conservation priorities and invited the community to participate in future planning efforts. The initial management model focused on biological targets, but was subsequently expanded to an ecosystem-based management (EBM) approach that included priority ecosystem services and desired human well-being outcomes (Figure 2B).

The modified approach aligned with the objectives of NOAA's Habitat Blueprint program (NOAA PIRO, 2017), which applies a national framework to improve habitat for fisheries, other marine life and coastal communities. In 2014, the MGHFA status was established with the goals: (a) improved coral reef ecosystem health; (b) improved community resilience to climate change impacts; and (c) enhanced community capacity to manage coastal resources. To achieve these outcomes, managers initiated an IM program to support evidence-based decision-making. The designation allowed managers to expand natural resource management activities to include human community resilience and refocus management efforts to systematically apply an SES framework.

2.2 | Implementing integrated monitoring

An interdisciplinary team was formed and included resource managers and aquatic, marine, terrestrial and social scientists from NOAA, CRI agencies, and the University of Guam. Together, they developed a monitoring strategy to assess the social and biophysical conditions of the
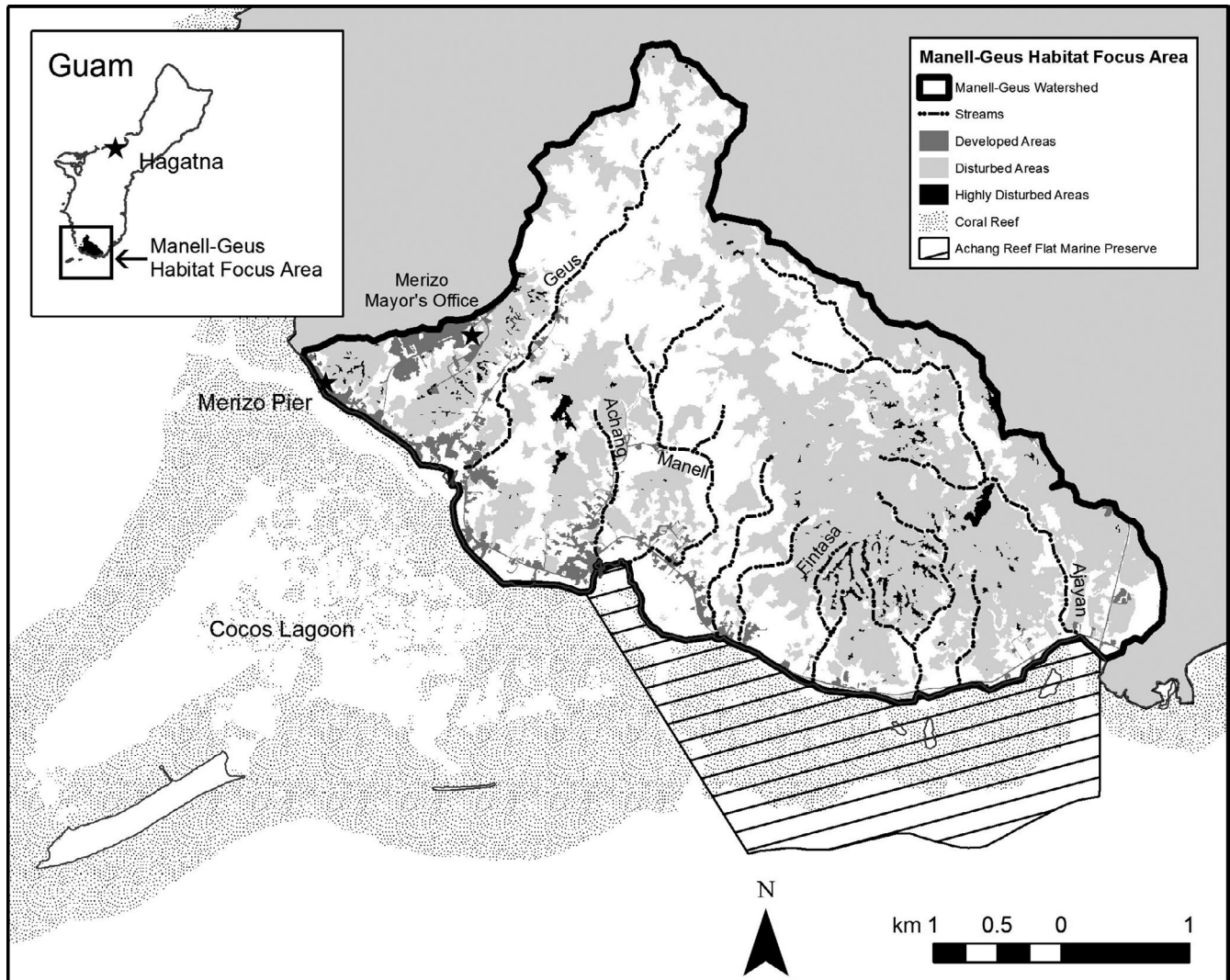
FIGURE 1 Manell-Geus Habitat Focus Area is located in southern Guam in Micronesia in the western Pacific (NMFS PIRO, in prep)

MGHFA to inform adaptive management (Figure 3). Indicators relevant to the MGHFA goals and the EBM model were identified (Table 1). The interdisciplinary team then evaluated existing data for the area. As these data could not fully inform management at the scale of the MGHFA, new baseline data were collected using a sampling design optimized for the watershed. The biophysical indicators were collected via habitat surveys and geospatial analysis, while social indicators were collected via household surveys, focus groups and key informant interviews.

2.3 | Using baseline results of integrated monitoring to adapt MGHFA management
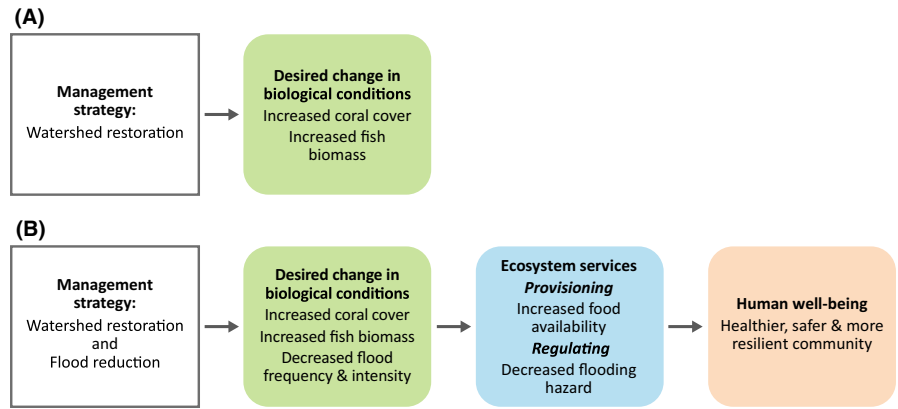
The team synthesized the baseline datasets to update the conceptual management model (Figure 4). This model illustrates the complex linkages among: EBM strategies, expected changes in social-ecological conditions resulting from management, expected changes in ecosystem services and long-term outcomes in human well-being. The updated model and baseline results informed the development of three strategies to address the three primary MGHFA goals: (a) an ecological strategy to

restore coastal environments; (b) a social strategy to involve the community in threat reduction and improve resource stewardship; and (c) a hybrid ecological and social strategy to reduce flooding and improve community safety and resiliency. These goals and strategies mutually support one another. After identifying target social-ecological conditions, the team included links between biophysical and social changes within the management model. Improvements in social-ecological conditions are expected to affect ecosystem services and human well-being outcomes, which in turn should inform adjustments to management strategies and activities. The changes in ecosystem services and human well-being are also expected to affect social-ecological conditions, including changes in human pressure on resources and stewardship. The next section details strategies for each of the three project goals.
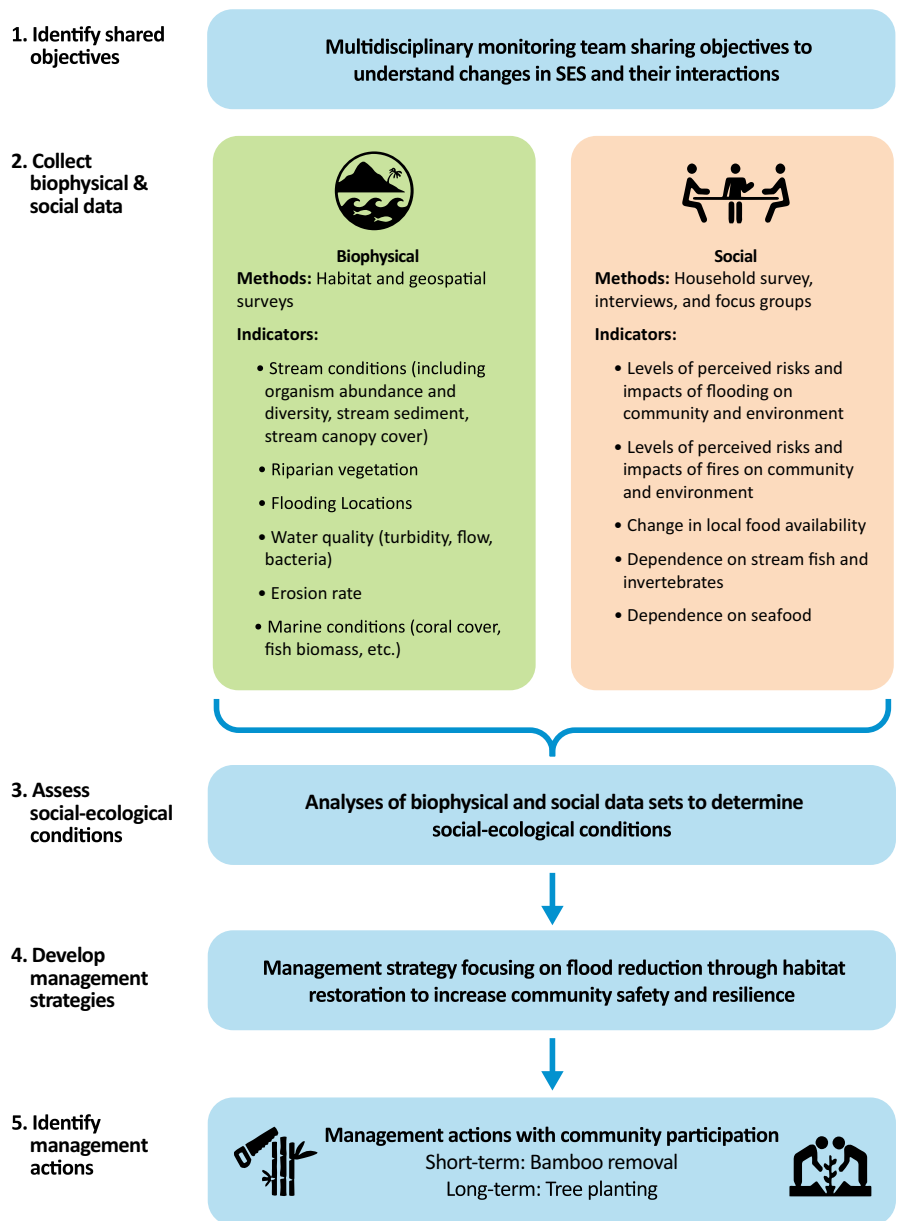
2.3.1 | Improved reef ecosystem health goal: Watershed restoration strategy

The MGHFA ecological strategy is to reduce erosion, flooding and sedimentation, which have been linked with a decline in reef health

FIGURE 2 Evolving management approaches used in Manell-Geus. Initial management focused on biophysical outcomes (A). Over time, this was modified (B) to include ecosystem services and human well-being

(A)

Management strategy: Watershed restoration → Desired change in biological conditions: Increased coral cover, Increased fish biomass

(B)

Management strategy: Watershed restoration and Flood reduction → Desired change in biological conditions: Increased coral cover, Increased fish biomass, Decreased flood frequency & intensity → Ecosystem services: *Provisioning* Increased food availability, *Regulating* Decreased flooding hazard → Human well-being: Healthier, safer & more resilient community

FIGURE 3 Integrated monitoring process as applied to the hybrid ecological and social strategy for flood reduction and community safety

1. Identify shared objectives

Multidisciplinary monitoring team sharing objectives to understand changes in SES and their interactions

2. Collect biophysical & social data

Biophysical
Methods: Habitat and geospatial surveys

Indicators:

- Stream conditions (including organism abundance and diversity, stream sediment, stream canopy cover)
- Riparian vegetation
- Flooding Locations
- Water quality (turbidity, flow, bacteria)
- Erosion rate
- Marine conditions (coral cover, fish biomass, etc.)

Social
Methods: Household survey, interviews, and focus groups

Indicators:

- Levels of perceived risks and impacts of flooding on community and environment
- Levels of perceived risks and impacts of fires on community and environment
- Change in local food availability
- Dependence on stream fish and invertebrates
- Dependence on seafood

3. Assess social-ecological conditions

Analyses of biophysical and social data sets to determine social-ecological conditions

4. Develop management strategies

Management strategy focusing on flood reduction through habitat restoration to increase community safety and resilience

5. Identify management actions

Management actions with community participation
Short-term: Bamboo removal
Long-term: Tree planting

(Burdick et al., 2008). In 2015, DoAg initiated reforestation projects in target sub-watersheds to reduce erosion. As reforestation takes over a decade to attain full effect, NOAA and BSP also implemented shorter-term measures, such as installing vegetative buffers and fibre rolls (NMFS PIRO, 2017). The expected improvements in water quality associated with reduced sedimentation should translate into

TABLE 1 Indicators for Manell-Geus Habitat Focus Area (MGHFA) integrating monitoring. Each indicator measures the current status of an aspect of the system at a specific point in time. Indicators align with the management strategies and goals for the MGHFA

Strategies	Goals	Type of change	Ecosystem services[a]	ndicators
Watershed restoration	Improved reef ecosystem health	Biophysical	Supporting	Coral cover[b]
				Benthic cover
				Coral diversity
				Coral health
			Provisioning	Fish biomass[b]
				Fish diversity
				Macroinvertebrate density
				Macroinvertebrate diversity
			Regulating	Water quality (turbidity, flow, bacteria)
				Land cover
				Erosion rate
		Social	Provisioning	Change in local food availability from MGHFA
				Dependence on seafood from MGHFA
				Dependence on stream fish and invertebrates from MGHFA
				Local livelihoods
				Perceived conditions and changes of natural resources in MGHFA[b]
			Cultural	Cultural and traditional use and connection with reef
Flood reduction	Improved community resilience to climate change impacts	Biophysical	Provisioning	Stream organism abundance/diversity
			Regulating	Riparian vegetation
				Stream canopy cover
				Stream sediment
		Social	Regulating	Perceived risks and impacts of flooding[b]
				Perceived risks and impacts of fire
				Perceived community safety
				Change in perception of climate threats to the community
Community engagement	Enhanced community capacity to manage resources	Social	N/A	Stakeholder participation in resource stewardship activities[b]
				Attitudes and compliance with resource use rules and regulations[b]
				Perceived reduction of threats to coastal and marine resources
				Demographics

[a]Ecosystem services categories based on Millennium Ecosystem Assessment 2005.
[b]These indicators also track management performance.

ecosystem service benefits related to provisioning (local sea food), cultural (aesthetics and recreation) and regulating (safety from floods) services.

2.3.2 | Improved community resilience goal: Flood reduction strategy

The flood reduction strategy is based on the initial baseline assessment which indicated that invasive bamboo (*Bambusa vulgaris*) exacerbates streambank erosion and flooding downstream, impacting both freshwater and marine fish habitat (Camacho et al., 2016). Flooding was also identified as a community concern, with over 50% of households being affected between 2011 and 2016 (NMFS PIRO, in prep). This information prompted a hybrid social-ecological flood reduction strategy to increase community safety and achieve long-term resilience (Figure 3). Invasive bamboo removal and restoration of native stream bank vegetation are expected to reduce flood risk, as well as stream sedimentation and associated run-off onto reefs. Based on a pilot bamboo removal project that reduced flooding after rainfall (NMFS PIRO, 2017), larger scale removal was implemented in 2018.

FIGURE 4 A revised Manell-Geus Habitat Focus Area (MGHFA) management model illustrating the connected nature of the EBM strategy for the watershed and the primary goals of the MGHFA
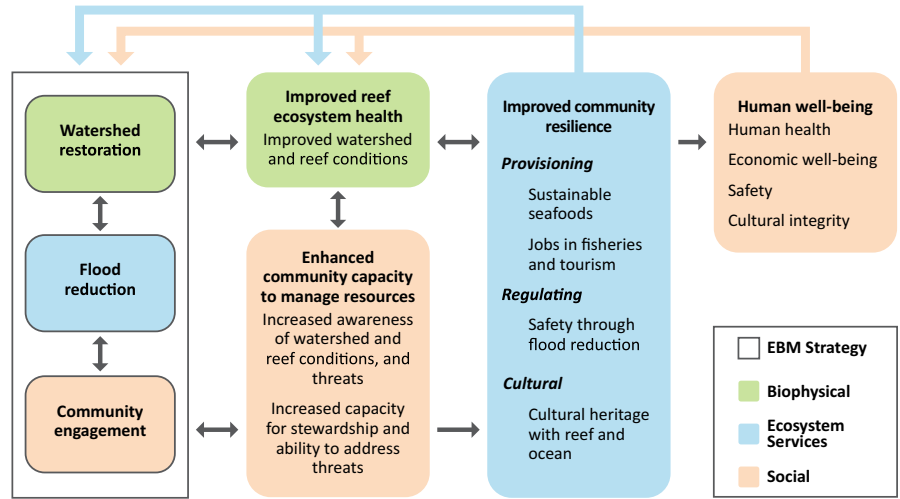
2.3.3 | Engaged community capacity goal: Social preparation strategy

Habitat restoration success depends on community support. In turn, support requires an engaged community that understands the threats facing the ecosystem and the management efforts planned to address those issues. Coral cover has declined on Guam's reefs in recent decades, including a 60% reduction between 2003 and 2014 (NMFS PIFSC, 2019). However, nearly half of the household survey respondents perceived coral condition to be good and even improved over time (NMFS PIRO, in prep). This contrast between biologically measured and socially perceived ecosystem status could be indicative of decreased interaction with resources, and education and outreach gap, or shifting baseline syndrome. The shifting baseline syndrome refers to sliding standards for ecosystem health due to a lack of experience of the past and understanding of relevant historical condition (Levin et al., 2009). To address these concerns, managers developed a social strategy to engage the community and activities to foster support for management and increase the

**FIGURE 5** Community members in Manell-Geus Habitat Focus Area forest restoration efforts

knowledge of community members concerning sustainable use of the ecosystem. MGHFA efforts include experiential outreach activities (Figure 5) such as watershed hikes and snorkelling tours, capacity-building events such as native plant propagation and responsible burning workshops, expansion of citizen science programmes and service learning opportunities for local youth in restoration and monitoring projects (NMFS PIRO, 2017).

2.3.4 | Adaptive management process

The integration of social and biophysical indicators in ecosystem monitoring informed adaptive management processes and improved management strategies and actions. Figure 6 illustrates how IM was expanded and incorporated into the management process over time. The site was selected based on biophysical indicators of low coral cover and presence of highly erodible areas. The initial management strategy focused on watershed restoration (Figure 6, Cycle 1). Social assessments indicated that flooding was a concern for the community and the management strategy was expanded to incorporate flood reduction in watershed restoration efforts (Figure 6, Cycle 2). Biophysical assessments were conducted to assess flooding risk and causes, and social monitoring was introduced. After the MGHFA designation, the team created the IM programme to assess the biophysical and social indicators described above. That information was used to develop the SES model and further expand the management strategies (Figure 6, Cycle 3) to increase community engagement and develop targeted approaches to reduce flooding. At this stage, bamboo removal, increased reforestation and inclusion of native plants in restoration efforts were added to the management strategies. Based on recent monitoring assessments and project performance, future strategies (Figure 6, Future cycle) will likely include reef restoration to address recent declines in coral cover due to coral bleaching events, increased attention on fire prevention strategies and mangrove restoration to address vulnerabilities to sea level rise identified in community assessments.
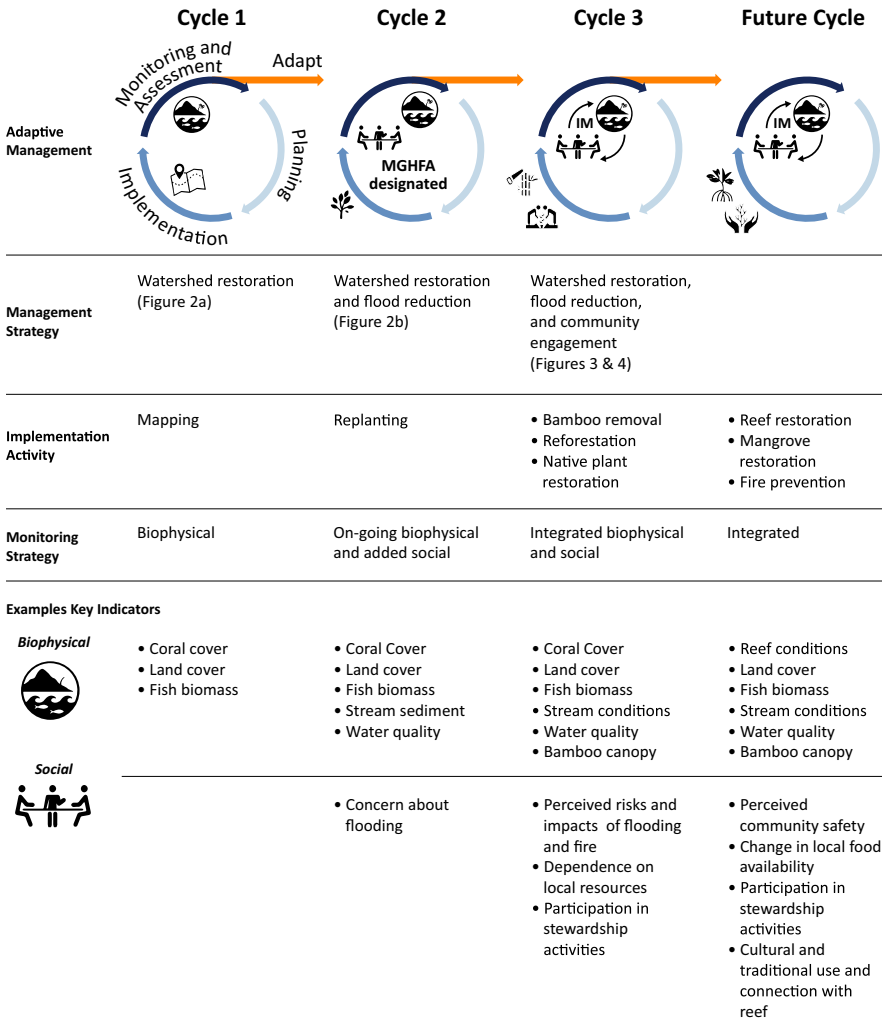
FIGURE 6 The evolution of the adaptive management process in the Manell-Geus Habitat Focus Area (MGHFA). Integrated monitoring played a key role in expanding the management strategies and informing adjustments to the management plan over time

	Cycle 1	Cycle 2	Cycle 3	Future Cycle
Management Strategy	Watershed restoration (Figure 2a)	Watershed restoration and flood reduction (Figure 2b)	Watershed restoration, flood reduction, and community engagement (Figures 3 & 4)	
Implementation Activity	Mapping	Replanting	• Bamboo removal • Reforestation • Native plant restoration	• Reef restoration • Mangrove restoration • Fire prevention
Monitoring Strategy	Biophysical	On-going biophysical and added social	Integrated biophysical and social	Integrated
Examples Key Indicators				
Biophysical	• Coral cover • Land cover • Fish biomass	• Coral Cover • Land cover • Fish biomass • Stream sediment • Water quality	• Coral Cover • Land cover • Fish biomass • Stream conditions • Water quality • Bamboo canopy	• Reef conditions • Land cover • Fish biomass • Stream conditions • Water quality • Bamboo canopy
Social		• Concern about flooding	• Perceived risks and impacts of flooding and fire • Dependence on local resources • Participation in stewardship activities	• Perceived community safety • Change in local food availability • Participation in stewardship activities • Cultural and traditional use and connection with reef

3 | SUCCESSES

We integrated social and biophysical indicators in ecosystem monitoring. This allowed for comparisons of community relationships and perceptions of local resources with associated biophysical assessments. The approach also considered how changes in social and ecological systems could influence each other, and enabled a more holistic view of the MGHFA. Such knowledge is critical to inform and improve adaptive management strategies that address biophysical and social conditions, while minimizing negative human well-being outcomes. Further, community support for management activities increased when community priorities, such as safety from floods, were identified and incorporated into management strategies and actions. For example, initially the MGHFA had a fisheries objective to increase herbivorous fish biomass through voluntary harvest restrictions. However, biophysical data revealed that non-herbivorous fish contain higher levels of contaminants due to the incomplete remediation of a former military site (Hartwell, Apeti, Pait, Mason, & Robinson, 2017). It would have been unsafe, unfair and likely unsuccessful to have a fisheries objective that asked fishers to switch to higher risk fish

to protect herbivores. This objective was dropped and the project team is now working with the local and federal governments to mitigate the contamination.

The Manell-Geus example also demonstrated how natural and social sciences can be integrated to strengthen monitoring and better inform management decisions. Qualitative data from interviews and group discussions raised issues unobtainable from quantitative methods or biophysical data alone. For instance, focus group discussions revealed the tremendous negative psychological impact of flood events that was not captured in the flood statistics.

Our case study demonstrates that IM can be implemented with limited funding and resources. Managers were hesitant to invest resources in monitoring instead of implementation activities. However, through an iterative process, the team identified indicators that were informative, cost effective and repeatable. All indicators in Table 1 will be monitored every 5 years. Key indicators, such as benthic cover, coral health and fire and flood impacts will be monitored more frequently to inform adaptive management. To do this, the team partnered with existing biophysical monitoring efforts, including citizen science programmes, and is using qualitative and semi-quantitative data to monitor social indicators.

4 | CHALLENGES

Relying on existing data may minimize costs, however, finding data at appropriate temporal and spatial scales to guide management decisions can be problematic. For example, a national-level effort has monitored Guam's coral reefs since 2003 (NOAA Coral Program, 2014), but at an island ecosystem scale, rendering the data unsuitable for assessing localized trends at the scale of the MGHFA. Additional funding allowed data to be gathered at a finer spatial scale using the national-level methodology. These data collected within the HFA can be compared against island-wide trends.

Epistemological differences between the natural and social sciences can challenge interdisciplinary teams. We managed these differences by adopting a stance of mutual respect and trust among team members and recognizing that all team members had different disciplinary expertise to offer. Furthermore, there was collective expectation that everyone would work beyond their disciplinary perspective to understand the complex interlinked SES. Navigating these differences can be difficult. For example, social monitoring took longer to complete than biophysical monitoring due to ethical protocols used in studies with human subjects and required approval by relevant organizations. Additionally, social data collection relied on trust between the community and the team.

Engaging scientists of different disciplines in a collaborative effort requires regular, effective interaction. In Manell-Geus, sustaining adequate communication was particularly challenging as the team lacked a dedicated coordinator and was spread across multiple time zones. Initial meetings to establish indicators and monitoring protocols were well attended, but coordination declined as the project entered its time-consuming implementation phase.

5 | RECOMMENDATIONS FOR FUTURE INTEGRATED MONITORING

Adaptive EBM is complex and should be informed by integrated approaches to monitoring and management. We recommend the following:

1. Establish policies and institutional support to sustain multidisciplinary expertise and coordination long-term. Availability of dedicated funding and resources for site specific IM programs are fundamental.
2. Engage players early in the planning process, particularly during the development of a conceptual systems model, to ensure monitoring objectives align across multiple interest groups and scientific disciplines. This streamlines subsequent decisions, such as prioritizing SES indicators and selecting strategies and target audiences for communication efforts.
3. A dedicated coordinator is recommended to facilitate communication within the multidisciplinary team, establish regular meetings, and guide a cohesive IM process. The importance of effective facilitation cannot be underestimated. Authentic integration requires more than bringing scientists from multiple disciplines into one room. Regular team meetings promote cross-disciplinary dialogue, underscore the value of diverse data streams, allow experts to examine and leverage differences in monitoring approaches and discuss conflicts.
4. Biophysical and social data with different sampling designs and from multiple data collecting methods create opportunity for result triangulation, and generation of more complete knowledge and implications for adaptive management. In ecological monitoring, each sampling unit should have equal probability of being selected, such that maximum generalizable inference can be made at the whole population and ecosystem scale. In our case, biological data indicated that coral was in poor condition and had declined over the last decade. In social monitoring, both purposive sampling design for key informant interviews and census household survey were used. The purposive sampling design screened key community members who had intimate knowledge of the coral conditions. Their in-depth local ecological knowledge and evaluation of the reefs and marine resources confirmed the biological monitoring results and revealed likely causes of the decline. On the other hand, the community households, overall, viewed conditions of coral and some other marine resources as neutral. This highlighted the gaps of marine resource knowledge among the general population and informed management decision to increase the knowledge of community members concerning the resource condition and sustainable use of the ecosystem.
5. System learning and adaptation are crucial, and the IM process and SES conceptual models should be adjusted based on insights from each assessment. This can result in adjustments to team composition, conceptual models, monitoring questions and indicators, sampling design, data collecting methods, data analysis and interpretation or communication of results. Evaluating different sets of results and synthesizing overall conclusions is essential to developing a more comprehensive understanding of social–ecological relationships.
6. Teams should evaluate appropriate monitoring timescales as changes in biophysical conditions, ecosystem services, and human well-being are seldom simultaneous. Implementation plans that secure the technical and human resources needed for iterative monitoring of a range of indicators can inform adaptive management. As some impacts could be sudden and have severe impacts on both ecological and social systems (e.g. wildfire during drought or mass coral bleaching), it is important to balance a long-term monitoring plan against the flexibility to address unexpected short-term needs.

6 | CONCLUSIONS

In the MGHFA, the integration of social and biophysical monitoring for EBM started with engaging the Merizo community to identify their priorities for management. For the community, the social and ecological systems are inherently interdependent. Their resilience to climate change impacts is closely tied to improved coastal habitats and optimal governance practices, in which their own capacity and participation are

critical for coastal resource management success. IM was employed as a tool for supporting management and to improve understanding of SES in the specific context and at a scale relevant to the MGHFA. It involved a multidisciplinary team that shared monitoring objectives to incorporate metrics tracking social and biophysical conditions. The team worked with coastal resource managers and stakeholders to link observed changes in each system with each other, with ecological targets, and with human well-being objectives. The key purpose, and also a challenge, of IM is to describe how social indicators may respond to changes in biophysical conditions over time, while simultaneously understanding how biophysical indicators are affected by social changes.

IM begins with different sets of disciplinary data, but the most meaningful analyses start once these data are brought together to complement each other, identify and/or fill knowledge or action gaps. This process leads to a better understanding of the complex relationships among the SES, as well as more comprehensive management that considers human communities and ecosystem interactions in their objectives. The MGHFA illustrates how IM allowed managers to shift from conventional biological targets to accounting for the complex connections, multiple pathways and multiple objectives of a SES. This approach has allowed managers to prioritize activities that benefit both ecological and social objectives in the MGHFA, and can serve as a model to support EBM in other contexts.

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DATA AVAILABILITY STATEMENT

Data have not been archived because this article does not contain data.

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