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Towards an ecosystem-based approach of Guam's coral reefs: The human dimension

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ABSTRACT

Management of tropical reef ecosystems under pressure from terrestrial and extractive marine activities is not straightforward, especially when the interests of extractive and non-extractive marine resource sectors compete. Before implementing management actions, potential outcomes of alternative management strategies can be evaluated in order to avoid adverse or unintended consequences. In tropical reef ecosystems the continued existence of the cultural and recreational fishing activities and the economically important dive-based tourism and recreation industry rest on sustainably managed marine resources. Through a case study of Guam, an ecosystem model was linked with human behavior models for participation in fishing and diving to evaluate future socio-ecological impacts of different management options. Ecosystem indices for reef status and resilience, and extraction potential were identified to evaluate the performance of alternative management scenarios. These marine ecosystem indices link the natural system to human uses (fishing and dive-based tourism and recreation). Evaluating management scenarios indicate that applying a single management tool, such as input controls or marine preserves, without also managing the watershed, is suboptimal. Combining different management tools has negative near-term costs, particularly for the fishing sector, but these are likely to be outweighed by the long-term benefits obtained from greater species abundance. Adopting watershed management measures in addition to fishery regulations distributes the burden for improving the reef status across multiple sectors that contribute to reef pressures.

1. Introduction

Ecosystem-based management is increasingly advocated for marine fisheries around the world [1,2]. Typically, different management strategies could be implemented to achieve the management objectives specified in an ecosystem approach. Management strategy evaluation (MSE), which compares and contrasts outcomes across multiple management objectives, is a tool implicit to an ecosystem approach [3,4]. One MSE approach involves the development of integrated marine ecosystem models, which requires intimate knowledge of the biophysical as well as the socio-economic systems [5,6]. Integrated models can simulate the ecological, social, and economic consequences of different management approaches [7–9]. Changing human behavior is the main management lever, and thus a critical component of integrated ecosystem modeling [10]. However, human behavior models of non-commercial activities are seldom coupled to biophysical-economic models.

Typically, these integrated models depict economic behavioral drivers quantitatively through the use of metrics, such as profit maximization [11]. Yet these models fail to capture the significant, non-commercial element of the fishery system, where fish might be taken for cultural or traditional celebrations, household consumption or barter [5,12,13]. Moreover, this commercial focus on extraction ignores the significant economic importance of non-market and non-extractive uses of the marine ecosystem [14].

Both reef-fish fisheries and reef-related tourism and recreation

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are dependent on the condition of the reefs, which are presently under heavy pressure in many parts of the world [15,16]. Effective management of coral reef resources must consider continued existence of these valuable extractive and non-extractive resource uses as well as the health of the marine ecosystem upon which they depend [17]. In this study, a dynamic reef biophysical model is linked with human behavior models for the coral reef ecosystem of Guam. In Guam, tourism is one of the major contributing economic activities to Guam's gross domestic product [18] and reef-fish fishing is mainly conducted for social or cultural reasons [5]. Despite the importance of a healthy reef ecosystem, the status of Guam's marine resources has deteriorated over the past few decades [19,20]. Guam's reefs have been stressed by poorly executed coastal development and high sediment load from fallow land burning in southern upstream watersheds [20,21]. Inadequate sewage treatment systems and septic tanks have increased the nutrients and bacterial load in coastal waters [22,23]. Crown-of-thorns seastar predation outbreaks, which can be connected with high nutrient concentrations in the waters [24], have caused coral losses [20]. Fishing activities have caused a decline or loss of ecologically important fish species [25–27]. This combination of factors has led decision-makers to actively seek alternative management approaches and tools to guide them [28].

The socio-ecological model developed in this study has three main components: a quantitative ecological component and qualitative fishery and tourism human behavior components. Combined, these three components can be used to simulate anthropogenic impact scenarios and their ecological effects and *vice versa*. The management scenarios considered were developed in consultation with local resource managers from three agencies in Guam, and include removing existing marine preserves (MPs) and implement catch and/or size limits and reducing land-based sources of pollution through improved watershed management. While coral reef quality increases under some management scenarios, indicators that are important to the dive industry, such as the biomass of charismatic species, remain low. A management scenario that trades off some reduction in reef-fish landings against an increase in the ecological attributes that are favored by divers could be preferable.

2. Case study: Guam

Guam, which became an unincorporated territory of the United States in 1950, is the largest and southernmost island in the Mariana Archipelago of the western Pacific Ocean (between 13.2°N and 13.7°N and between 144.6°E and 145.0°E; Fig. 1). Guam in a volcanic island with an area of approximately 549 km^2 and a

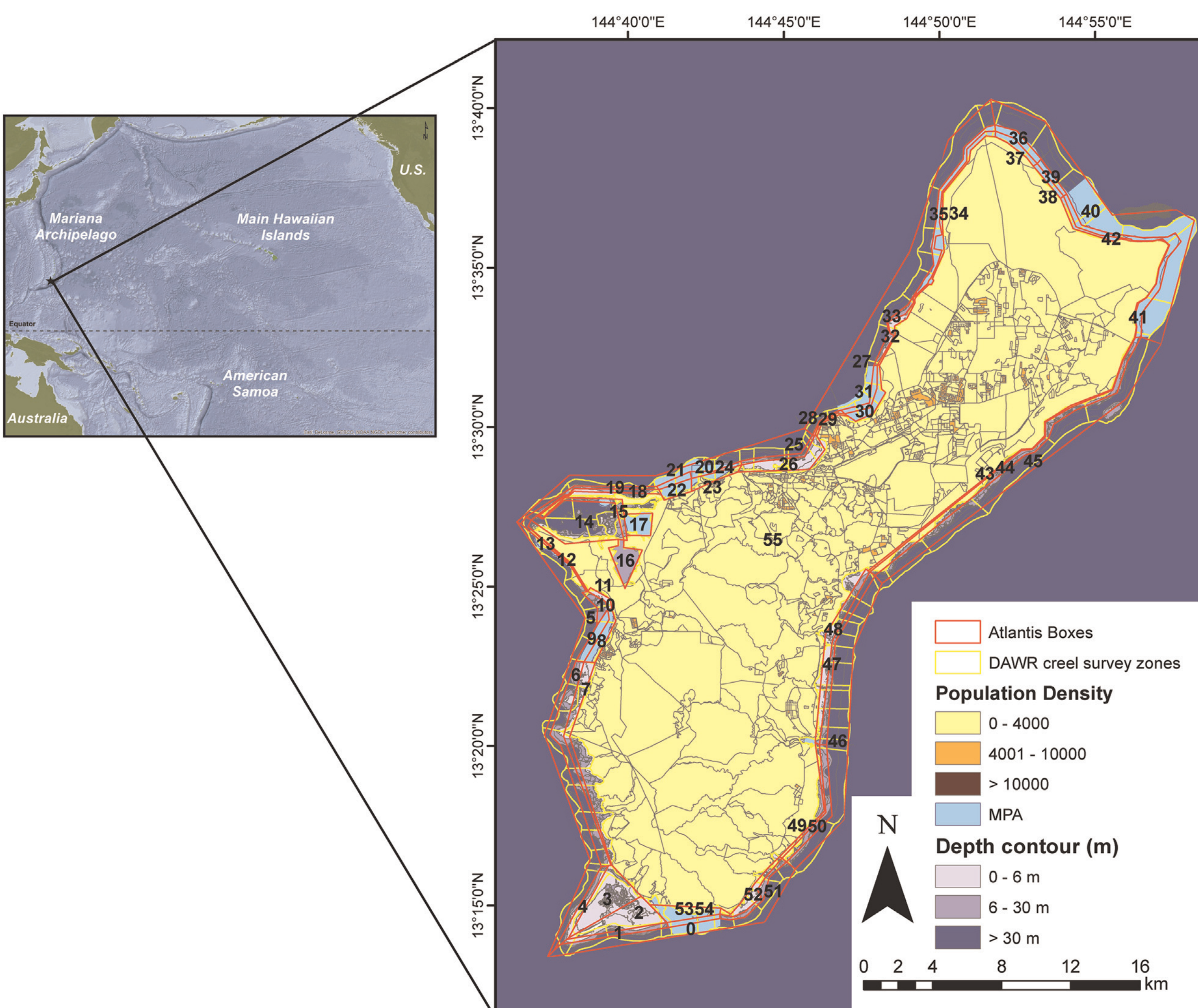

Fig. 1. Location of Guam in the western Pacific Ocean (inset map) and the spatial model (Atlantis boxes) of the Guam Atlantis Coral Reef Ecosystem model showing human population density, creel survey zones and the depth contours.

shoreline of about 187 km (129 km adjacent to coral reefs) [20]. The human population of Guam is estimated at 159,358 individuals [29]. Chamorros, the earliest inhabitants of Guam, comprise the largest ethnic group at 37.3% of the population [29], Filipinos make up 26.3%, followed by other Pacific Islanders (12.0%), whites (7.1%), and other Asians (6.0%). Nearly 10% of the population identify themselves as having two or more ethnicities [29].

Guam's Gross Domestic Product was $4.88 billion in 2013 [30], primarily based on tourism and the U.S. military. In 2013, Guam had approximately 1.3 million visitors of whom 70% were from Japan [31]. The tourism sector is estimated to contribute between 18% and 35% of local employment [5]. The U.S. military is the second largest contributor to Guam's economy; its economic importance has increased in the last few years, and is expected to continue to grow with the relocation of thousands of US Marines and their dependents [32].

2.1. Marine resource use in Guam

For Guam, fishing and diving are two important reef-based activities directly reliant on the status and ongoing sustainable use of Guam's coral reef ecosystems.

2.2. Diving in Guam

Guam residents as well as tourists participate in between 256,000 and 340,000 dives on Guam's reefs every year [18]. Thirteen legal dive outfitters operate on Guam and offer between one dive and up to four dives per day during peak seasons [31]. Additionally, there are anecdotal reports of some unregistered dive operators.

An estimated 6% of 1.34 million annual visitors go scuba diving while on Guam, and 3% of tourists visit Guam with scuba diving as the primary motivation for their trip [33, dive shop owner pers. comm. November 2014]. Although most tourists who visit Guam are from Japan, visitors from other Asian countries such as South Korea, Philippines, Taiwan, Hong Kong, Russia, and China have significantly increased in recent years [33]. This shift in the demographics of tourism is particularly relevant as the participation in dive trips varies by country of origin, with tourists from Hong Kong and Taiwan being far more likely to participate in scuba diving than tourists from Japan, the US, and Korea (Table 1).

2.3. Fishing on Guam

While diving is a popular non-extractive use of Guam's coral reef resources, reef fishing is an important extractive use of marine resources [18]. Guam's near-shore reef fishery is a multispecies and multi-gear fishery. Fishing occurs from boats and from shore involving trolling (mostly for pelagic fish), net fishing (e.g., cast net, gillnet, and surround net), and spearfishing (snorkel and scuba). Over the years gear methods have evolved and, new, more efficient catch methods used, some with detrimental impact. For instance, the relatively new practice of spearfishing on scuba has been linked to a decrease in large-size fishes leading to a targeting of smaller fish prior to reaching sexual maturity [25,34].

It is estimated that between 35% and 45% of Guam's households were involved in near-shore fishing [18]. Much of the fish caught on Guam is not traded in the market (and is not recorded in commercial statistics) but is instead eaten within the household or shared with family and friends. A 2005 survey of Guam households found that out of the fish consumed by households, nearly one-quarter (24%) was caught by the respondent or another member of the household, and an additional 14% was caught by a friend or extended family member [18]. The social obligation to share one's fish catch extends to all fishermen [35]. This cultural practice is particularly important among Guam's Chamorro residents, who often give a large proportion of their catch to family, friends, and the local community [36,37]. Some of the other social reasons to go fishing include spending time with family and friends, to provide fish for a particular event or to teach members of the younger generation traditional fishing practices. These practices have non-market value as they can underpin social networks and cultural ties throughout the Pacific Islands region [36].

Table 1
Breakdown of visitors by country [34] and the estimated number of people who went diving [18].

Country	Arrivals (FY2012)	Dive participation (2002) (%)	# Divers
Japan	901,683	5	45,084
Korea	164,821	2	3296
Hong Kong	8396	15	1259
Taiwan	49,851	14	6979
United States	50,967	8	4077

3. Methods

In this study a quantitative biophysical model of the coral reef ecosystems around Guam [38,39] was linked with qualitative behavior models of two reef-dependent sectors (coral reef fishing and dive tourism). The ecosystem model was based on the Atlantis framework and was developed in consultation with community experts (Appendix A) at workshops on Guam in November 2012 and June 2014. The aim of the Guam Atlantis model was to build a virtual coral reef ecosystem for managers and biologists to explore questions and provide a tool to undertake scenario analyses. The model integrates best available data from multiple disciplines, such as hydrology and marine biology, at multiple scales. Details can be found in Weijerman et al. [38] and Weijerman et al. [39].

Atlantis is a deterministic model spatially resolved in three dimensions that tracks nutrient flows through the main biological groups in the ecosystem. For Guam Atlantis two of four possible modules were parameterized [38]. The first is an ecological module that simulates primary ecological processes (consumption, production, waste production, migration, predation, recruitment, habitat dependency, and mortality). The reef-fish species were aggregated in functional groups based on their diet, life history characteristics, and functional role [38]. The second is a physical oceanographic module that represents the bathymetry, major currents, salinity, and temperature and is based on the Regional Ocean Modeling System framework developed for the Coral Triangle [40]. The third module simulates fisheries (or other human activities) and was simplified as a fixed fishing mortality per functional group based on historical catches from shore-based creel surveys conducted by the Guam Division of Aquatic and Wildlife Resources between 2010 and 2012 (DAWR). Due to a lack of data, this module did not include the effects of fishing gear on the benthic habitat and species (e.g., physical damage to corals, ghost net fishing, and damage resulting from fish lines). Finally, the fourth Atlantis module simulates the socio-economic dynamics, which typically represents commercial fisheries governed by economic rules, and was replaced by the fisher and diver behavior models, outlined below.

The recently developed Atlantis model can correctly simulate key dynamics in coral reef ecosystems around Guam [39]. These dynamics include ocean acidification [41], ocean warming [42], reef accretion and erosion [43], the relationship between the complexity of a reef ecosystem and its function to provide shelter for fish species [44,45], the effects of nutrient and sediment input on coral growth [46,47] and coral–algal dynamics (i.e., macroalgae can overgrow corals, outcompete corals in nutrient-enriched waters, prevent coral recruit settlement, and crustose-coralline algae and, to a lesser extent, turf algae facilitate coral recruitment [48–50]).

Modeled output ecosystem metrics of Guam Atlantis were based on a 30-year simulation run and averaged over the last five years to account for interannual variation. Selected ecosystem metrics indicative of reef status and resilience [51–53] include: species abundance (measured as total reef-fish biomass), number of large fish (measured as the number of a slow growing species, represented by sharks, in the largest size class), and reef condition (measured as the ratio of calcifiers (corals and crustose-coralline algae) to non-calcifiers (turf and fleshy macroalgae)). Those metrics were augmented with two tourism-related metrics, abundance of charismatic species and reef-fish diversity (derived from species richness, i.e., the number of functional groups present, and the inverse of Pielou's Evenness: $J' = H'/H'_{max}$ where H' is the Shannon–Wiener diversity index), to link to the diver behavior model. For the link to the fishery behavior model two socio-economic metrics were added: landings of targeted fish species and landings of all species (including invertebrates; Fig. 2).

The qualitative human behavioral models leverage previously published information and expert knowledge from people who have worked with Guam's dive tourism sector or fishing sector (or both). The disciplinary background of the experts included anthropology, economics, resource science, sociology, and biological sciences. The two behavioral models focus on different aspects of the reef ecosystem; the tourism model focuses on reef condition while the fishery model focuses on the extraction of reef-fish species. For the tourism model, the selected ecosystem metrics are key to providing a high quality diving experience. For example, the presence or absence of charismatic species [54], such as the humphead wrasse, *Cheilinus undulatus*, and bumphead parrotfish, *Bolbometopon muricatum*; coral cover [55] (indicated by the ecosystem metric reef condition), species abundance [56], and water clarity [57] (implicitly included in reef condition, i.e., with high nutrients and/or sediments in the water column, clarity decreases and algal growth is favored over coral growth reducing the reef condition ratio).

For the fishery model, species abundance was selected, which is expected to influence reef-fish fishery participation. The fisheries relevant ecosystem metrics, landings of targeted fish species and total landings, were used to discuss consequences of changes in expected fisher behavior. A species was assumed to be a target species when its representation in the landings of a particular gear type was greater than 20% (DAWR shore-based creel survey data).

Quantitative change was projected in the selected ecosystem metrics to qualitatively explore six management scenarios (B–F) simulated using the Guam Atlantis model and compared to the status quo scenario (A) (Table 2).

As fisherman-specific catch data were not available, there were no current estimates of daily or weekly catches to set a hypothetical bag limit for scenarios Bi, Bii, D and E. Instead, for each functional group an annual allowable catch was set at 75% of the status quo landings at the end of a 30-year model run. This allowable catch was then divided by 52 to get a weekly bag limit. When this weekly limit was reached in the model run, fishing was stopped for the remainder of the week. For size limits, fishing of all

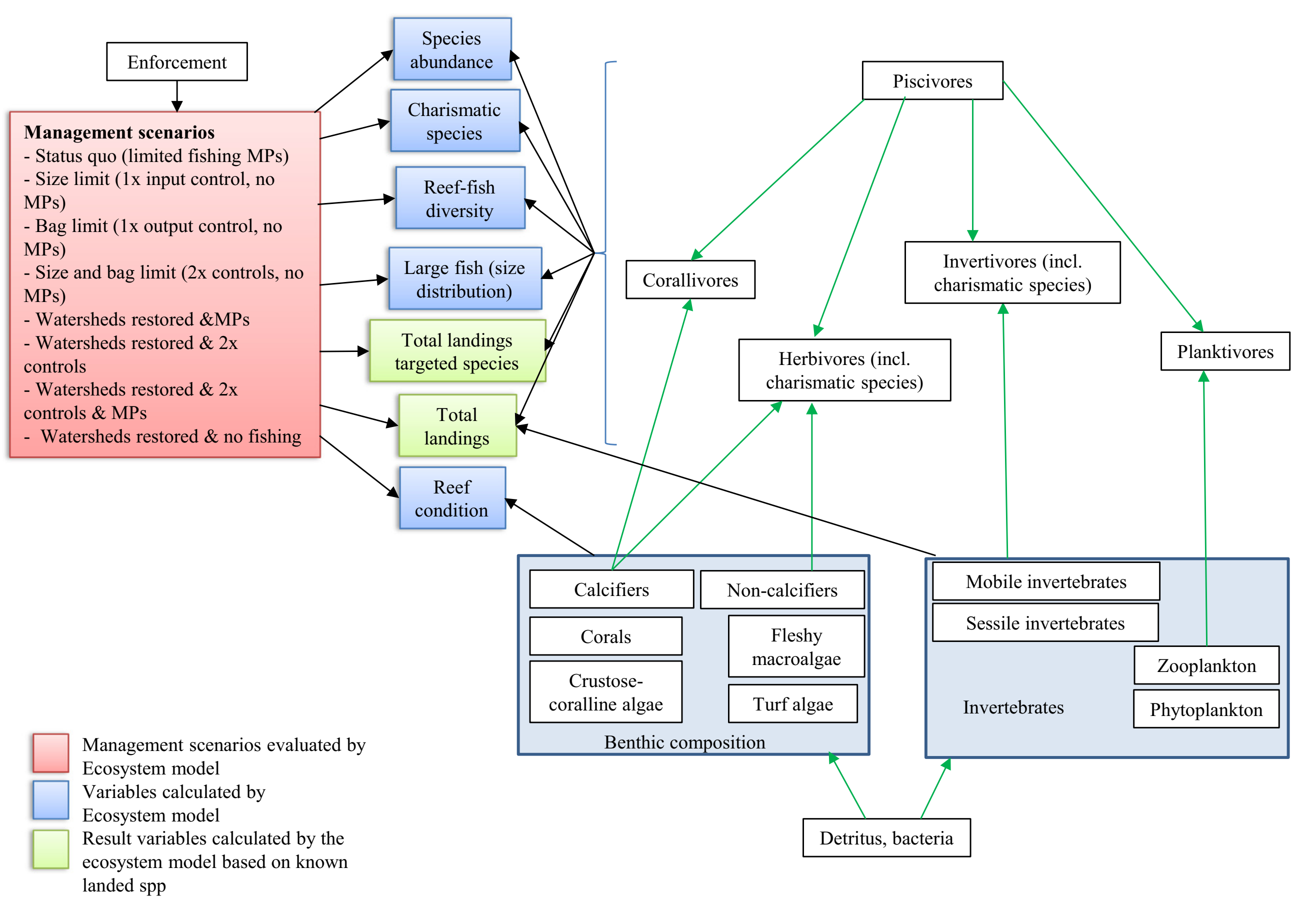

Fig. 2. Conceptual representation of the Guam Atlantis Coral Reef Ecosystem Model. Foodweb connections between (simplified) functional groups are shown by green arrows. Black arrows indicate the linkages between the ecological model and the ecosystem metrics.

Table 2
Details of simulated management scenarios. LBSP = land-based sources of pollution.

Scenario	Presence of marine preserves[1]	Existing levels of LBSP	Fishing effort compared to status quo (%)	Fishing of juvenile fish
A: Status Quo	Yes	Yes	100	Goatfish, rabbitfish, jacks
Bi: Bag and size limits	No	Yes	75	No
Bii: Bag limit	No	Yes	75	Goatfish, rabbit fish, jacks
Biii: Size limit	No	Yes	100	No
C: restored watersheds	Yes	No	100	Goatfish, rabbit fish, jacks
D: Bag and size limits, restored watersheds	No	No	75	No
E: Full regulations	Yes	No	75	No
F: No fishing, restored watersheds	Yes	No	0	No

[1] Preserves are no-take areas except for seasonal take of juveniles and limited hook and line fishing from shore.

fishes smaller than their size at maturity was stopped, including the seasonal runs on juvenile rabbitfish, goatfish and jacks.

For ease of interpretation and visualization, the 5-year mean values of the ecosystem metrics were normalized over all strategies resulting in values between zero (worst case) and one (best case).

4. Results

The results comprise two main components: (1) a description of the theoretical dive tourism and reef fishing participation behavior models; and (2) a description of the changes in the ecosystem metrics as predicted by the Guam Atlantis ecosystem model for the different management scenarios. In the discussion these results are brought together by examining the socio-ecological implications of the different management approaches.

4.1. Dive behavior model

A qualitative model linking the ecological, economic, and social factors that influence participation in dive trips in Guam is shown in Fig. 3. A full description of nodes in the model is provided in Appendix B and a description of the relationship between nodes in Appendix C.

Guam's dive sector is heavily dependent on healthy coral reefs, and there is a clear connection between environmental attributes (i.e., the ecological indicators in the ecosystem model) and diver willingness to pay for diving on a reef [58]. Management can indirectly influence diver participation and the dive experience by changing the'quality' of the environment. For example, water clarity (turbidity), several areas around Guam have turbidity issues as a result of land-based pollution and changing water clarity could strongly influence the quality of the dive experience. However, it is acknowledged that other marine management not further explored here, can also influence the quality of a dive

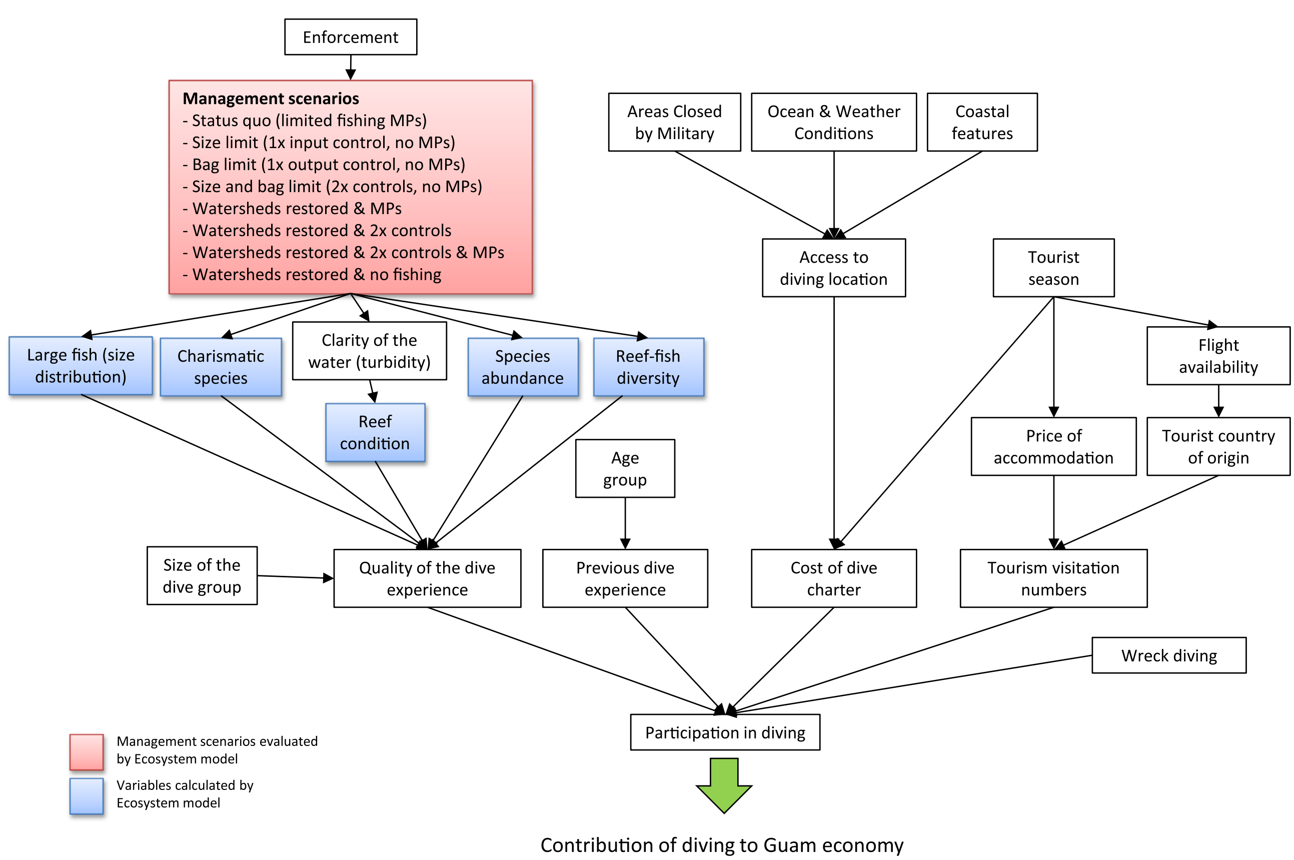

Fig. 3. Influence of different environmental and socioeconomic factors on participation in dive trips in Guam.

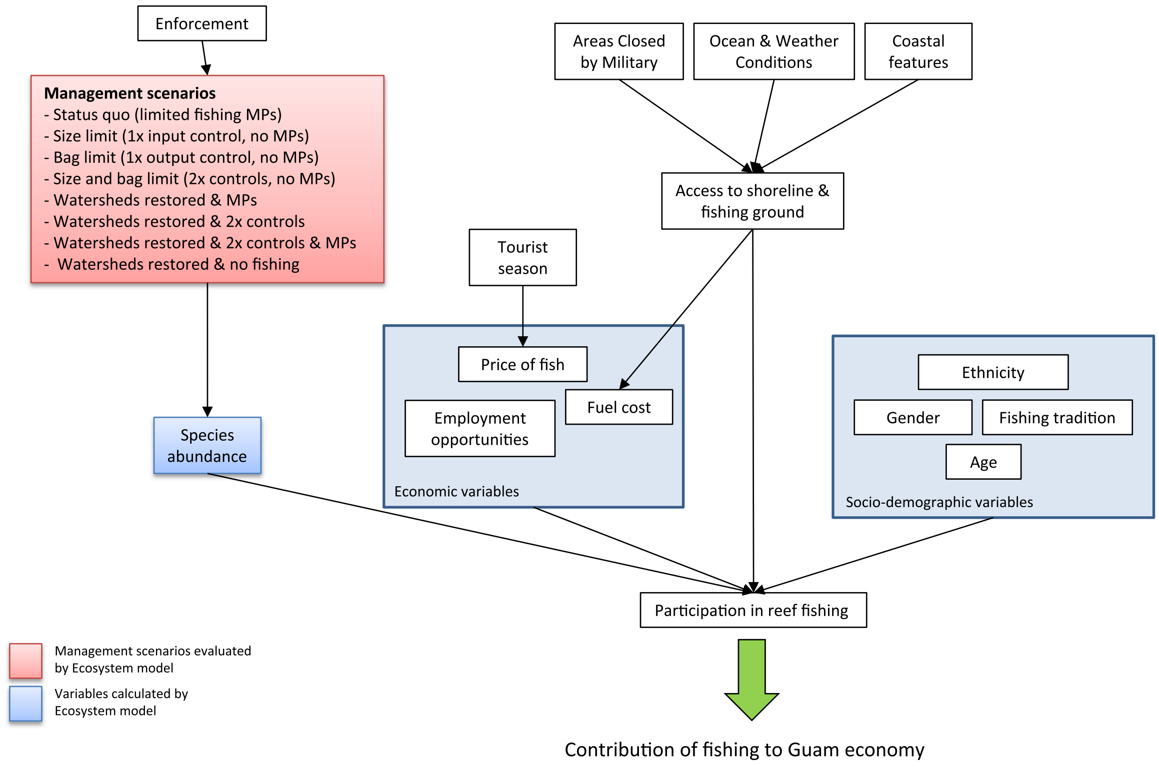

Fig. 4. Influence of species abundance, economic and socio-demographic variables and participation in reef fishing on Guam.

experience. These management approaches include, for instance, restricting diver behavior on the reef by placing limits on their autonomy [59], controlling access to marine protected areas [60,61] or avoiding inter-sector conflict by spatially limiting contact with fishers or fishing gear [62].

Dive participation can be influenced by many other economic and social factors, some of which are outside the direct scope of influence of resource managers, such as tourist visitation numbers. Tourist visitation numbers and country of origin are of particular interest, as some tourists are more likely to go diving than others.

4.2. *Reef fishing participation model*

Similar to the diving model, a qualitative model describing the socio-demographic, economic, and ecological factors influencing participation in Guam's reef fishery was developed (Fig. 4 and Appendices D and E).

Strategies for managing marine resource extraction and coral reef health can influence participation in reef fishing by affecting the abundance of exploited and non-exploited species, and by affecting where and when fishing can occur, what species (and sizes) can be taken, and the type of gear that can be used. Management scenarios introducing bag and size limits restrict the number and size of fish catch, which can influence how and where fishers choose to fish [63,64]. Management of adjacent watersheds can decrease sedimentation and increase water quality, improving near-shore coral reef ecosystems that could lead to higher species abundance for reef fishing.

Spatial management of marine areas, such as marine preserves, can affect access to shoreline and nearshore fishing grounds [65]. Access to fishing grounds is also affected by environmental variables, including coastal features, such as cliffs [5], and adverse ocean and weather conditions and by military exercises [66].

Ethnicity [5], gender, age [13] and whether one's family has been traditionally engaged in fishing are socio-demographic variables that play a role in determining participation in reef fishing. Economic variables that affect a fisher's decision to go reef fishing include the price of fish, which is partially determined by whether it is high tourist season, opportunities for employment, and the cost of fuel [13].

4.3. *Changes in ecological indicators as a result of management*

Performance of scenarios that include restored watersheds outcompeted the other scenarios in terms of better reef condition and species evenness (Fig. 5). The full regulation and no fishing and

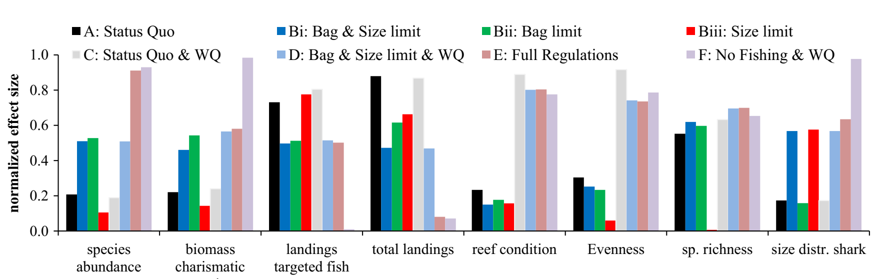

Fig. 5. Effect size based on normalized values of ecosystem metrics at the end of a 30-year simulation to allow comparisons of alternative management scenarios. Modeled scenarios are explained in "2 Methods" section.

Table 3
Relative effect size of ecosystem metrics at the end of a 30-year simulation of the various management scenarios to the Status Quo scenario. Values are means of the last five years of simulations. Overall effect size is the mean of the normalized ecosystem metric values as represented in Fig. 5.

	Status quo A	Bag and size limits Bi	Bag limit Bii	Size limit Biii	Water-shed Rest. C	Bag and size and watersh rest. D	Full reg. E	No fishing and watershed rest. F
Total reef-fish biomass	1	1.12	1.13	0.94	0.99	1.12	1.31	1.33
Biomass iconic species	1	2.50	2.97	0.34	1.14	3.09	3.18	7.56
Landings targeted groups	1	0.79	0.80	1.05	1.08	0.80	0.79	0.0
Total landings	1	0.53	0.67	0.71	0.98	0.52	0.02	0.0
Reef condition	1	0.96	0.98	0.97	1.24	1.19	1.19	1.18
Evenness	1	1.00	1.00	0.98	1.04	1.02	1.02	1.03
Sp. richness	1	1.00	1.00	0.98	1.00	1.00	1.00	1.00
Size distribution sharks	1	12.32	0.37	12.54	1.00	12.32	14.10	31.01
Overall effect size	*0.41*	*0.44*	*0.42*	*0.31*	*0.59*	*0.61*	*0.62*	*0.65*

restored watershed scenarios had a positive effect on the species abundance, but performed worst of all scenarios with regard to total landings (Fig. 5).

Compared to the status quo scenario (scenario A), removing marine preserves while imposing bag and size limits (scenario Bi) resulted in a 12% increase in species abundance and in 2.5 times the biomass of charismatic species (Table 3). However, fish landings were 79% of the status quo landings and total landings (including invertebrates) dropped to 53% of the status quo landings.

5. Discussion

Effective management of tropical reef ecosystems under pressure from terrestrial and extractive marine activities is not straightforward, especially with potentially competing reef-based activities. The shift towards ecosystem-based fisheries management (EBFM) demands quantitative tools to support policy and management decisions. Ecosystem modeling and management strategy evaluation (MSE) are widely used in single species management testing and are becoming increasingly used in support of EBFM [67]. For EBFM evaluation, ecological models are coupled with socio-economic models to uncover societal linkages [2,10]. Evaluation of the potential effect of different management approaches prior to implementation through modeling will reduce the chance of adverse or unexpected ecological or socio-economic outcomes in the future and likely improve performance and compliance [9].

While the focus of this work was on a case study in Guam, the non-commercial reef-fish fishery and economic importance of diving also apply to many other tropical islands and coast lines making this approach generally applicable. EBFM that specifically includes the human dimension has gained traction among scientists, politicians and resource managers in the last decade [2,68]. However, only a few models have attempted to couple biophysical and socio-economic dynamics for coral reef ecosystems [69–71]. Human dimension-centered models have examined different coral reef ecosystem states and the links to socio-economic conditions and fishing participation [68], as well as the effects of gear types on the overall reef condition [72]. Hence, the approach presented in this study is novel as it includes the entire ecosystem from plankton to humans and could be a valuable tool for EBFM.

Diminishing catches affecting the fishing sector have prompted a discussion on ways in which improved fishing and water quality outcomes may be achieved for Guam [28, J. Cameron, POC Guam Coral Reef Conservation Program, pers. comm. July 2014]. With the approach outlined in this case study, key human behavior models were linked with a biogeophysical model to gain insight into the ecosystem metrics that link the two systems and evaluation of the consequences of management for socio-ecological effects in both the fishing and diving sector. The impacts of the management scenarios were quantified by means of ecosystem indices that could be meaningfully interpreted (although in a qualitative manner) in the context of the main marine activities in Guam.

5.1. Trade-offs between marine sectors

At the heart of EBFM are the complex trade-offs between objectives; these trade-offs can be between ecological and socio-economic objectives (as in this study), but competing uses can also require trade-offs to be made between different socio-economic objectives. It is clear that both Guam's dive industry and reef fishing activities are inherently reliant on healthy coral reef ecosystems. The number of ecological indicators that the dive sector aims to maximize are more numerous (four in total) than the fishing sector, where species abundance (total reef fish biomass) is the only direct link to participation in reef fishing. In evaluating these trade-offs, that should be taken into account.

For the tourism and recreation sectors, divers on Guam are important to Guam's economy and have demonstrated a willingness to make financial contributions towards marine management [58]. While the dive model presented here does not allow for backwards interactions, it is important to note that given Guam's reliance on tourism, the ecological attributes that indicate coral reef quality may influence other factors, such as, tourist visitation rates. Guam is a very popular diving location due to its high biodiversity and a change in the perception of Guam as a lower quality dive location could have a negative effect on the tourism industry.

From the standpoint of the diving industry, a management scenario where there is no fishing and no land-based source pollution provides optimal results with the highest values for ecological indicators. However, this scenario eliminates all reef-fish fishing which may be impractical and infeasible politically in addition to not being economically optimal as commercial fishing also contributes to the local economy, albeit a smaller amount than tourism. Importantly, the absence of fishing would counter the traditional use and identity of Guam's residents. Even though it is not easy to express the value of cultural fishing in monetary terms, the maintenance of cultural activities has important links to cultural identity and a healthy community and society [37].

5.2. Interpreting alternative management scenarios

Alternative fisheries management scenarios will result in different ecological outcomes. Input and output controls, such as size and bag limits, will limit reef fishing by restricting the size and number of fishes that can be taken [63,64]. Based on the ecosystem metrics for the management scenario, it is clear that imposing a simple input restriction (size limits) without any additional management measures will not improve the ecological outcomes for the reef; in fact, it may prove to worsen outcomes compared to the status quo, as fishing effort stays the same (so fishers will catch more larger individuals to make up the forgone catches of smaller fishes). Combined input and output controls in the form of size and bag limits or bag limits on their own will only marginally improve the ecological outcomes for the reefs' status compared to the status quo. In practice, input management tools are relatively easy to implement [73] and could mean a fast change in reef fishing behavior, but the net result on overall participation in fishing activities, compliance behavior, and location choice is uncertain. For example, under size limits, fishers may choose to avoid areas where they know there are higher numbers of small fish, which in turn may lead to localized depletion in areas with larger fish. Similarly, fishers may choose to fish closer to shore to reduce fuel cost if there are bag limits – again causing localized effects. When areas are improving ecologically under the restored watershed management, fishers may choose to direct their effort to those areas. In other words, a transfer of effort as a consequence of the management scenarios is possible, which makes it difficult to determine with certainty the total effect of controls on fishing participation.

The ecological metrics indicate that watershed restoration is an important contributor to a healthy marine ecosystem. However, watershed restoration on its own is not adequate to address the problems facing Guam's reefs and, in addition, may not achieve enough to provide the coral reef quality desired by the dive industry. While coral reef quality increases under the status quo and improved watershed scenario, total fish species biomass and the biomass of charismatic species remain low. Given the importance of these indicators for divers, selecting an alternative management scenario that allows for some reduction in fishery landings to be traded off against an increase in the ecological attributes that are favored by divers may be preferable to managers looking to balance the needs of both sectors.

Surprisingly, the scenarios with full regulations including size and bag limits and watershed restoration with retention of existing MPs (scenario E) and without the MPs (Scenario D) achieve similar ecological outcomes. The main difference is in the total reef fish biomass that is 17% higher when existing MPs are retained, most likely because fish can grow larger in MPs [26]. Removing MPs would increase shoreline and nearshore access to areas currently closed to fishers. It is likely that fishers will begin fishing in some of the areas that were common fishing grounds prior to being closed to fishing when MPs were established [65]. Fishers may also choose to fish with different gear and target different reef fish with the opening of MPs. The net result of reef-fishing participation in scenarios where MPs are opened cannot be determined. However, the potential for interactions between divers and fishers if MPs were opened may be concerning, as divers in other locations have expressed a preference to avoid such interactions [62].

Results show that there is little point in trying to manage the reef ecosystem and those who use it without also managing the watershed. Over a 30-year timeframe, the three management approaches with the most positive ecological impact all include restored watersheds. Three out of four ecosystem metrics important to the dive sector will improve if size and bag limits are imposed, the watershed is managed, and existing marine preserves are maintained. In the short term there will be some negative impacts particularly on the fishing sector as a consequence of size and bag limits, but the long-term benefits for fishers and divers obtained from greater species abundance are likely to outweigh these short term costs. Adopting watershed measures in addition to input and output controls distributes the burden for improving the reef status across multiple entities responsible for reef pressures.

6. Next steps

Despite the difficulties in predicting the overall behavioral changes of fishers and divers under the different scenarios, the conceptual behavioral models (combined with the ecosystem model) provide a starting point for discussions with stakeholders. Effective resource management of coral reef ecosystems is highly dependent on effective involvement of local communities [74]. The qualitative model of human behavioral drivers for reef fishing does not currently include probability distributions to enable a quantitative analysis. However, the behavioral models can be transformed into Bayesian Networks (BN), which would enable quantitative analyses of management approaches and the effects on the probability of participation in the dive and fishing sectors in Guam [17,75]. Even though the probability density function for a number of the variables was known, the conditional probabilities and relationships between mostly the social and cultural variables needs to be confirmed and tested by the local Guam community. Setting and testing the underlying probability distribution assumptions is an important component of developing a BN especially to promote local community ownership of the BN and modeling results.

7. Conclusion

Linking an ecological ecosystem model with socially and economically important human behavior gives us a better understanding of changes in ecological performance due to management of human-use activities. An integrated ecosystem model for Guam's fringing reef ecosystem enabled us to simulate alternative management scenarios and assess the performance criteria on both dive participation and participation in reef-fisheries. When the objectives for reef ecosystems encompass conservation and extraction goals, an integrated ecosystem model can make the trade-offs between different uses explicit. This allows managers to weigh the various performance measures and objectively consider the trade-offs between resource users and determine a 'best management solution'. From this study it is clear that the optimal management solution for the reef ecosystem in Guam (and the dive tourism and fishing sector) is to combine input and output controls, but most importantly, to restore the watershed and to thus reduce land-based ecological impacts.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2015.09.028.

References

[1] K. Sainsbury, U.R. Sumaila, Incorporating ecosystem objectives into management of sustainable marine fisheries, including 'Best Practice' reference points and use of marine protected areas, in: M. Sinclair, G. Valdimarson (Eds.),

Responsible Fisheries in the Marine Ecosystem, FAO, 2003, pp. 343–361.
[2] E. Pikitch, E. Santora, A. Babcock, A. Bakun, R. Bonfil, D.O. Conover, et al., Ecosystem-based fishery management, Science 305 (2004) 346–347.
[3] A. Smith, Management strategy evaluation: the light on the hill, Popul. Dyn. Fish. Manag. (1994) 249–253.
[4] K.J. Sainsbury, A.E. Punt, A.D. Smith, Design of operational management strategies for achieving fishery ecosystem objectives, ICES J. Mar. Sci.: J. Conseil 57 (2000) 731–741.
[5] S. Allen, P. Bartram, Guam as a fishing community. Admin Rep H-08-01. Pacific Islands Fis. Sci. Cent., NMFS, NOAA, Honolulu HI 96822-2396, Pac. Islands Fish. Sci. Cent. (2008) 55.
[6] S.H. Yee, J.F. Carriger, P. Bradley, W.S. Fisher, B. Dyson, Developing scientific information to support decisions for sustainable coral reef ecosystem services, Ecol. Econ. (2014).
[7] A. Smith, K. Sainsbury, R. Stevens, Implementing effective fisheries-management systems–management strategy evaluation and the Australian partnership approach, ICES J. Mar. Sci.: J. Conseil 56 (1999) 967–979.
[8] A.D.M. Smith, E.J. Fulton, A.J. Hobday, D.C. Smith, P. Shoulder, Scientific tools to support the practical implementation of ecosystem-based fisheries management, ICES J. Mar. Sci.: J. Conseil 64 (2007) 633–639.
[9] E.A. Fulton, A.D.M. Smith, D.C. Smith, P. Johnson, An integrated approach is needed for Ecosystem Based Fisheries Management: Insights from ecosystem-level management strategy evaluation, PLoS ONE 9 (2014) e84242.
[10] E.A. Fulton, A.D. Smith, D.C. Smith, I.E. van Putten, Human behaviour: the key source of uncertainty in fisheries management, Fish Fish. 12 (2011) 2–17.
[11] I.E. van Putten, S. Kulmala, O. Thébaud, N. Dowling, K.G. Hamon, T. Hutton, et al., Theories and behavioural drivers underlying fleet dynamics models, Fish Fish. 13 (2012) 216–235.
[12] A. Everson, A.M. Friedlander, Catch, effort, and yields for coral reef fisheries in Kane 'ohe Bay, O 'ahu and Hanalei Bay, Kaua 'i: comparisons between a large urban and a small rural embayment, Status Hawaii's Coast. Fish. New Millen. (2004) 110–131.
[13] J. Hospital, S. Beavers, Economic and social characteristics of Guam's small boat fisheries. Honolulu: Pacific Islands Fish. Sci. Cent., Natl. Mar. Fish. Serv., NOAA; 2012. p. 60p+Appendices.
[14] R.K. Craig, Coral reefs, fishing, and tourism: tensions in US ocean law and policy reform, Stanf. Environ. Law J. 27 (2008) 3–41.
[15] R.E. Brainard, C. Birkeland, C.M. Eakin, P. McElhany, M.W. Miller, M. Patterson, et al. Status review report of 82 candidate coral species petitioned under the U. S. Endangered Species Act. US Dep Commer, NOAA Tech, Memo, NOAA-TM-NMFS-PIFSC-27. Honolulu, HI2011. p. 530.
[16] L. Burke, K. Reytar, M. Spalding, A. Perry, Reefs at risk revisited. Reefs at Risk, World Resources Institute, Washington, DC (2011), p. 114.
[17] É.E. Plagányi, I. van Putten, T. Hutton, R.A. Deng, D. Dennis, S. Pascoe, et al., Integrating indigenous livelihood and lifestyle objectives in managing a natural resource, Proc. Natl. Acad. Sci. 110 (2013) 3639–3644.
[18] P. Van Beukering, W. Haider, M. Longland, H. Cesar, J. Sablan, S. Shjegstad, et al., The economic value of Guam's coral reefs, Univ. Guam Mar. Lab. Tech. Rep. 116 (2007) 102.
[19] I.D. Williams, J.K. Baum, A. Heenan, K.M. Hanson, M.O. Nadon, R.E. Brainard, Human, oceanographic and habitat drivers of central and western Pacific coral reef fish assemblages, PLoS ONE 10 (2015) e0120516.
[20] D. Burdick, V. Brown, J. Asher, M. Caballes, M. Gawel, L. Goldman, et al. Status of coral reef ecosystems of Guam Guam: Bureau of Statistics and Plans, Guam Coastal Management Program; 2008. p. iv+76pp.
[21] E. Wolanski, R.H. Richmond, G. Davis, V. Bonito, Water and fine sediment dynamics in transient river plumes in a small, reef-fringed bay, Guam, Estuar. Coast. Shelf Sci. 56 (2003) 1029–1040.
[22] E.P.A. Guam, Integrated Report Barrigada, Guam: Water Programs Division; 2010.
[23] L.J. Raymundo, K. Kim, J. Redding, R.J. Miller, K. Pinkerton, D. Baker, Links between deteriorating coral health and sewage pollution of guam reef flats. University of Guam Marine Laboratory Technical Report No. 131; 2011. p. 24.
[24] G. De'ath, K.E. Fabricius, H. Sweatman, M. Puotinen, The 27–year decline of coral cover on the Great Barrier Reef and its causes, Proc. Natl. Acad. Sci. 109 (2012) 17995–17999.
[25] P. Houk, K. Rhodes, J. Cuetos-Bueno, S. Lindfield, V. Fread, J. McIlwain, Commercial coral-reef fisheries across Micronesia: a need for improving management, Coral Reefs 31 (2012) 13–26.
[26] B.M. Taylor, J.L. McIlwain, A.M. Kerr, Marine reserves and reproductive biomass: a case study of a heavily targeted reef fish, PLoS ONE 7 (2012) e39599.
[27] S. Bejarano, Y. Golbuu, T. Sapolu, P.J. Mumby, Ecological risk and the exploitation of herbivorous reef fish across Micronesia, Mar. Ecol. Prog. Ser. 482 (2013) 197–215.
[28] M. Weijerman, V. Brown, A summary of the Guam Coral Reef Ecosystem Model workshop and discussions in Guam, November 14–20, 2012 Admin. Rep. H-13-3: Pacific Islands Fisheries Science Center, NMFS, NOAA ; 2013, p. 14.
[29] U.S. Census Bureau, American Factfinder; 2014.
[30] Bureau of Economic Analysis, The Bureau of Economic Analysis releases 2013 estimates of Gross Domestic Product for Guam; 2014.
[31] Guam Visitors Bureau, Visitor arrivals in 2013 even better than 2012; 2014.
[32] M. Ruane, Guam's Economy: Potentially Better than 2012; 2013.
[33] Guam Visitors Bureau, Wedding, Dive, and Waterpark: Guam's Growing Industries. Annual report; 2013, p. 2013.
[34] S.J. Lindfield, J.L. McIlwain, E.S. Harvey, Depth refuge and the impacts of SCUBA spearfishing on coral reef fishes, PLoS ONE 9 (2014) e92628.
[35] J. Amesbury, R. Hunter-Anderson, Review of archaeological and historical data concerning reef fishing in the US flag islands of Micronesia: Guam and Northern Mariana Islands Prepared for the Western Pacific Regional Fishery Management Council, Honolulu: Micronesian Archaeological Research Services, Guam; 2003, p. 147.
[36] T.K. Pinhey, D.H. Rubinstein, S.M. Vaughn, Fishing and fiestas in Guam: an exploratory note on the reinforcement of cultural traditions, Pac. Stud. 29 (2006) 74–82.
[37] D. Kotowicz, L. Richmond, Traditional Fishing Patterns in the Marianas Trench Marine National Monument Honolulu: Pacific Islands Fish. Sci. Cent., Natl. Mar. Fish. Serv., NOAA; 2013, p. 54.
[38] M. Weijerman, C. KaplanI, E.A. Fulton, R. Gorton, S. Grafeld, R. Brainard, Design and parameterization of a coral reef ecosystem model for Guam. U.S. Dep. Commer., NOAA Tech. Memo., NOAA-TM-NMFS-PIFSC-43; 2014. p. 133+Appendices.
[39] M. Weijerman, E.A. Fulton, C. KaplanI, B. Gorton, R. Leemans, W.M. Mooij, et al., An integrated coral reef ecosystem model to support resource management under a changing climate, PLoS ONE (2015) (in preparation).
[40] F.S. Castruccio, E.N. Curchitser, J.A. Kleypas, A model for quantifying oceanic transport and mesoscale variability in the Coral Triangle of the Indonesian/Philippines Archipelago, J. Geophys. Res.: Oceans 118 (2013) 6123–6144.
[41] J.A. Kleypas, R.A. Feely, V.J. Fabry, C. Langdon, C.L. Sabine, L.L. Robbins, Impacts of ocean acidification on coral reefs and other marine calcifiers: A guide for future research. Report of a workshop held 18–20 April 2005, St Petersburg, FL, sponsored by NSF, NOAA, and the US Geological Survey Report of a workshop held 18–20 April 2005, St. Petersburg, FL, sponsored by NSF, NOAA, and the US Geological Survey; 2006, p. 88.
[42] P.L. Jokiel, S.L. Coles, Response of Hawaiian and other Indo-Pacific reef corals to elevated temperature, Coral Reefs 8 (1990) 155–162.
[43] C.M. Eakin, A tale of two Enso Events: carbonate budgets and the influence of two warming disturbances and intervening variability, Uva Island, Panama, Bull. Mar. Sci. 69 (2001) 171–186.
[44] Y.M. Bozec, L. Alvarez-Filip, P.J. Mumby, The dynamics of architectural complexity on coral reefs under climate change, Glob. Change Biol. (2014).
[45] N. Graham, K. Nash, The importance of structural complexity in coral reef ecosystems, Coral Reefs (2013) 1–12.
[46] B.E. Lapointe, Nutrient thresholds for bottom-up control of macroalgal blooms and coral reefs, Limnol. Oceanogr. 44 (1997) 1586–1592.
[47] E. Wolanski, R.H. Richmond, L. McCook, A model of the effects of land-based, human activities on the health of coral reefs in the Great Barrier Reef and in Fouha Bay, Guam, Micronesia, J. Mar. Syst. 46 (2004) 133–144.
[48] M.L. Baskett, A.K. Salomon, Recruitment facilitation can drive alternative states on temperate reefs, Ecology 91 (2010) 1763–1773.
[49] A. Marshell, P.J. Mumby, Revisiting the functional roles of the surgeonfish *Acanthurus nigrofuscus* and *Ctenochaetus striatus*, Coral Reefs 31 (2012) 1093–1101.
[50] M.M. Nugues, R.P.M. Bak, Differential competitive abilities between Caribbean coral species and a brown alga: a year of experiments and a long-term perspective, Mar. Ecol. Prog. Ser. 315 (2006) 75–86.
[51] J. Bascompte, C.J. Melián, E. Sala, Interaction strength combinations and the overfishing of a marine food web, Proc. Natl. Acad. Sci. USA 102 (2005) 5443–5447.
[52] D.R. Bellwood, A.S. Hoey, T.P. Hughes, Human activity selectively impacts the ecosystem roles of parrotfishes on coral reefs, Proc. R. Soc. B: Biol. Sci. (2011).
[53] M. Weijerman, E.A. Fulton, F.A. Parrish, Comparison of coral reef ecosystems along a fishing pressure gradient, PLoS ONE 8 (2013) e63797.
[54] M. Rudd, M.H. Tupper, The Impact of Nassau Grouper Size and Abundance on Scuba Diver Site Selection and MPA Economics, Coast. Manag. 3 (2002) 133–151.
[55] N. Barker, C. Roberts, Scuba diver behaviour and the management of diving impacts on coral reefs, Biol. Conserv. 120 (2004) 4814–489.
[56] I.D. Williams, Polunin NVC. Differences between protected and unprotected reefs of the western Caribbean in attributes preferred by dive tourists, Environ. Conserv. 27 (2000) 382–391.
[57] J. Wielgus, N.E. Chadwick-Furman, N. Zeitouni, M. Shechter, Effects of coral reef attribute damage on recreational welfare, Mar. Resour. Econ. 18 (2003) 225–238.
[58] S.L. Grafeld, K.L.L. Oleson, M. Barnes-Mauthe, C. Chan-Halbrendt, M. Peng, M. Weijerman, Divers' Willingness to Pay for Improved Coral Reef Conditions in Guam: An Untapped Source of Funding for Management and Conservation? (September 23, 2015). Available at SSRN: 〈http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2664405〉; 2015.
[59] M.G. Sorice, C.-O. Oh, R.B. Ditton, Managing scuba divers to meet ecological goals for coral reef conservation, Ambio: A J. Hum. Environ. 36 (2007) 316–322.
[60] J. Asafu-Adjaye, S. Tapsuwan, A contingent valuation study of scuba diving benefits: case study in Mu Ko Similan Marine National Park, Thailand, Tour. Manag. 29 (2008) 1122–1130.
[61] G.R. Parsons, S.M. Thur, Valuing changes in the quality of coral reef ecosystems: a stated preference study of SCUBA diving in the Bonaire National Marine Park, Environ. Resour. Econ. 40 (2008) 593–608.
[62] D.A. Gill, P.W. Schuhmann, H.A. Oxenford, Recreational diver preferences for reef fish attributes: economic implications of future change, Ecol. Econ. 111 (2015) 48–57.
[63] S.A. Berkeley, M.A. Hixon, R.J. Larson, M.S. Love, Fisheries sustainability via protection of age structure and spatial distribution of fish populations,

Fisheries 29 (2004) 23–32.
[64] C. Birkeland, P.K. Dayton, The importance in fishery management of leaving the big ones, Trends Ecol. Evol. 20 (2005) 356–358.
[65] M.B. Mascia, C. Claus, R. Naidoo, Impacts of marine protected areas on fishing communities, Conserv. Biol. 24 (2010) 1424–1429.
[66] D.M. Kotowicz, S. Allen, Guam Fishing community profile update-2013 Update; 2015.
[67] E.A. Fulton, J.S. Link, I.C. Kaplan, M. Savina-Rolland, P. Johnson, C. Ainsworth, et al., Lessons in modelling and management of marine ecosystems: the Atlantis experience, Fish Fish. 12 (2011) 171–188.
[68] J.E. Cinner, T.R. McClanahan, T.M. Daw, N.A.J. Graham, J. Maina, S.K. Wilson, et al., Linking social and ecological systems to sustain coral reef fisheries, Curr. Biol. 19 (2009) 206–212.
[69] J. Shafer, Agent-Based Simulation of a Recreational Coral Reef Fishery: Linking Ecological and Social Dynamics, University of Hawaii, Honolulu, 2007.
[70] N. Gribble, GBR-prawn: modelling ecosystem impacts of changes in fisheries management of the commercial prawn (shrimp) trawl fishery in the far northern Great Barrier Reef, Fish. Res. 65 (2003) 493–506.
[71] J. Melbourne-Thomas, C.R. Johnson, P. Perez, J. Eustache, E.A. Fulton, D. Cleland, Coupling biophysical and socioeconomic models for coral reef systems in Quintana Roo, Mexican Caribbean, Ecol. Soc. 16 (2011) 23.
[72] T.R. McClanahan, J.E. Cinner, A framework for adaptive gear and ecosystem-based management in the artisanal coral reef fishery of Papua New Guinea, Aquat. Conserv.: Mar. Freshw. Ecosyst. 18 (2008) 493–507.
[73] T.J. Emery, B.S. Green, C. Gardner, J. Tisdell, Are input controls required in individual transferable quota fisheries to address ecosystem based fisheries management objectives? Mar. Policy 36 (2012) 122–131.
[74] J.E. Cinner, T.R. McClanahan, M.A. MacNeil, N.A. Graham, T.M. Daw, A. Mukminin, et al., Comanagement of coral reef social-ecological systems, Proc. Natl. Acad. Sci. 109 (2012) 5219–5222.
[75] I. van Putten, A. Lalancette, P. Bayliss, D. Dennis, T. Hutton, A. Norman-López, et al., A Bayesian model of factors influencing indigenous participation in the Torres Strait tropical rocklobster fishery, Mar. Policy 37 (2013) 96–105.