LETTER

Optimizing for multiple species and multiple values: tradeoffs inherent in ecosystem-based fisheries management

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Abstract

Although a consensus in marine science is developing on the need to adopt ecosystem-based fishery management, few studies try to quantify the context-specific gains from implementing it. Using a multi-species bioeconomic model for a Caribbean reef community, we determine the optimal harvesting rates for predator and prey species and ask how this more comprehensive optimization differs from traditional single-species approaches. We also identify tradeoffs when the objective of the manager includes nonfishing values. We find that the optimal solution when accounting for nonfishing values can include temporary or permanent fishing moratoriums in contrast to continuous fishing at low levels when only fishing profits are considered. We also show that the greatest gains from ecosystem-based fishery management are not from improved estimation of the trophic coupling, but from reforming the social and economic management of individual fish stocks and by explicitly incorporating a broader set of values into management decisions.

Introduction

Ecosystem-based fishery management is promoted as a means of alleviating many of the escalating direct and indirect effects of fishing on targeted populations, trophic connectivity, essential habitats, and ecosystem functions (Gislason *et al.* 2000; Pauly *et al.* 2002; Browman & Stergiou 2004). Although the ecosystem-based approach that advocates for the consideration of multiple species and values has international and growing support (Pikitch *et al.* 2004; U.S. Commission on Ocean Policy 2004), many questions remain on the scope and achievability of its objectives relative to other management approaches (Browman & Stergiou 2004; Hilborn 2004; Levin *et al.* 2009). For example, a priori it is not immediately evident what the ecosystem effects of fishing are on fish populations, fishing effort, and economic returns, and how including additional sources of values (e.g., nonfishing values) into management objectives affects these metrics.

We address these questions by evaluating a range of management options along a continuum from open access to economically optimal management of multiple interacting species with fishing and nonfishing values (Figure 1). We ask: (1) Where are the largest economic and ecological gains in the progression from open access to single- and multi-species management and how does the strength of trophic coupling influence these gains? (2) How do standing stock, fishing effort, and economic returns qualitatively and quantitatively differ as the scope of management changes? and (3) How does the explicit incorporation of nonfishing values alter management recommendations?

While there have been many important general analyses of predator–prey systems that highlight the

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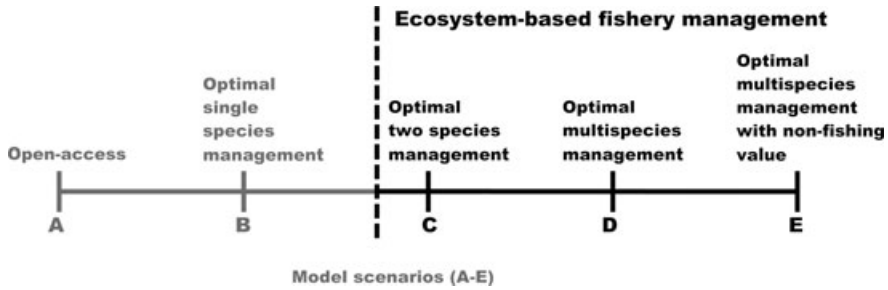

Figure 1 Continuum of ecosystem-based fisheries management options and model scenarios. Open-access fishing effort levels are determined by setting average fishing profits to zero in each period. In the case of single-species management, the manager optimally chooses the time path of fishing effort for one species by maximizing fishing returns and the fishing effort levels for the two other unmanaged species are at their open-access levels. When two species are optimally managed, the profits from both species are maximized over time with the other species operating under open access. The last two cases of optimal multi-species (three species) management are distinguished by whether the objective includes only fishing (profits) values.

qualitative implications of managing multiple species (see, e.g., Beddington & May 1980; Ragozin & Brown 1985; Matsuda & Abrams 2006), context-specific evaluations are the only way to provide insight into both qualitative and quantitative differences between variants of ecosystem-based fishery management and to assess the approach's benefits and costs relative to single-species management. To that end, we couple a parameterized ecological model for a coral reef ecosystem (Kellner *et al.* 2010) with an economic model of a manager who is optimally managing for each species or some combination of multiple species.

We extend the bioeconomic literature in a number of directions. First, unlike previous studies that consider only open-access or optimal management (see, e.g., Wilen & Brown 1986; Ströbele & Wacker 1995; Supriatna & Possingham 1998; Fleming & Alexander 2003; Kar & Chaudhuri 2004), we consider a much broader range of governance and management options. Second, we expand the scope of values to include fishing and nonfishing values (see also Bulte & van Kooten 1999; Hoekstra & van den Bergh 2005). Finally, we consider a trophic system that includes a generalist predator, an element that is common to most marine communities, yet often omitted from bioeconomic analyses (Kar & Chaudhuri 2004).

Methods

We adopt the trophic model (Table 1) developed by Kellner *et al*. (2010) that successfully predicted patterns observed in field data from the Caribbean by Mumby *et al*. (2006; 2007a). This model of an archetypical Caribbean coral reef community includes two focal prey species (stoplight parrotfish *Sparisoma viride* and yellowtail snapper *Ocyurus chrysurus*) and a generalist predator (Nassau grouper *Epinephelus striatus*). Drawing upon empirically-based density estimates from community surveys in fished and reserve areas, Kellner *et al*. (2010) demonstrated that the three species can coexist at steady state across a range of harvesting levels and noted that trophic systems with generalist predators may be particularly sensitive to attack rates and additional prey availability (also see Closs *et al.* 1999).

This coral reef community exemplifies the types of fishing and nonfishing values that advocates of ecosystem-based fishery management argue should be incorporated into fisheries management decisions. Highly targeted species such as Nassau grouper are likely to have (nonfishing) value stemming from their contribution to biodiversity or their appealing presence as an ecotourism resource. Other species are valued for their ecosystem function; the stoplight parrotfish, for example, facilitates coral recruitment by feeding extensively on small macrophytes (e.g., *Dictyota* spp.) that preempt space for coral settlement and compete with established coral colonies (Box & Mumby 2007). Indeed, the maintenance of herbivory is a key element in managing the resilience of coral reefs (Hughes *et al.* 2003; Mumby *et al.* 2007b).

The goal of the fishery manager is to maximize the net present discounted value of the multi-species fishery by choosing the fishing effort in each period (see e.g., Clark 1990). The number of fished species where the manager has control of fishing effort and the values considered vary along the continuum (Figure 1). In the most general formulation, the objective function of the manager is

$$J = \max_{e_1(t), e_2(t), e_3(t)} \int_0^\infty e^{-\delta t} \left[\sum_{i=1}^{3} \pi_i(e_i(t), x_i(t)) + v_i(x_i(t)) \right] dt \tag{1}$$

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Table 1 Ecological model. Additional details and parameter values are provided in Appendix S1 and Kellner *et al.* (2010)

State equations

Parrotfish (prey):
$$\frac{dx_1}{dt} = \underbrace{\left[\left(\frac{m_1}{m_{1h} + x_1(t)}\right) - d_1\right]}_{density-dependent} x_1(t) - \underbrace{a_1 x_1(t) x_3(t)}_{\substack{predation\\mortality}} - \underbrace{q_1 e_1(t) x_1(t)}_{\substack{fish\\catch}}$$

Snapper (prey):
$$\frac{dx_2}{dt} = \underbrace{[r_2 - d_2 x_2(t)]}_{density-dependent} x_2(t) - \underbrace{a_2 x_2(t) x_3(t)}_{\substack{predation\\mortality}} - \underbrace{q_2 e_2(t) x_2(t)}_{\substack{fish\\catch}}$$

Grouper (predator):
$$\frac{dx_3}{dt} = \underbrace{\left[\varepsilon\left(a_1 x_1(t) + a_2 x_2(t) + a_Y Y\right)\left(1 - \frac{x_3(t)}{k_3}\right) - d_3\right]}_{density-dependent} x_3(t) - \underbrace{q_3 e_3(t) x_3(t)}_{\substack{fish\\catch}}$$

Parameters	Description
m_{1h}	Density of parrotfish where the recruitment rate is half its maximum
m_1	Maximum total recruitment rate
d_1	Parrotfish natural mortality rate
r_2	Snapper intrinsic rate of increase
d_2	Snapper density-dependent mortality rate
k_3	Grouper habitat carrying capacity
d_3	Grouper natural mortality rate
Y	Additional prey availability
a_1, a_2, a_3	Grouper predation rate on parrotfish, snapper, and additional prey
ε	Prey conversion efficiency
q_1, q_2, q_3	Parrotfish, snapper, and grouper catchability coefficient

Note: $x_i(t)$ is the density (stock level) of each species i in period t, and $e_i(t)$ is the fishing effort level for species i in period t. The identifier $i = 1$, 2, and 3 corresponds to the parrotfish, snapper, and grouper species, respectively.

where δ is the (societal) discount rate, x_i is the density (stock level) of each species i in period t, e_i is the effort level for each species i in period t, $\pi_i(e_i(t), x_i(t))$is the profit from fishing and $v_i(x_i(t))$ is the nonfishing value function for species i in each period t (van Kooten & Bulte 2000; Hoekstra & van den Bergh 2005). Explicitly incorporating fishing and nonfishing values into the manager's objective function provides a way to compare how nonfishing values alter the management recommendations.

The continuum of management scenarios illustrated in Figure 1 are mathematically derived in Appendix S2 and modeled as follows:

(1) Open access—Unmanaged system where all species are harvested at their open-access levels. Following Gordon (1954), we solve for the open-access steady-state effort levels by setting average profits $(\pi_i(e_i, x_i)/e_i)$ to zero.
(2) Single-species management—The manager optimally chooses the time path of fishing effort for one species by maximizing its fishing returns, while the two other unmanaged species are harvested at their open-access levels.
(3) Two-species management—The optimal time path of fishing effort for two species is solved for by optimizing the fishing returns for the two species, while the other unmanaged species is harvested at its open-access level. All two-species management combinations are explored (e.g., predator/prey, prey/prey).
(4) Multi-species management—The manager maximizes the fishing returns from the system by optimally choosing the time path of fishing effort for all three species.
(5) Multi-species management with nonfishing values—Scenarios A–D consider only the economic values from exploitation of the interacting fish stocks where $v_i(x_i) = 0$. In Scenario E, we rerun the multi-species analysis from Scenario D explicitly incorporating nonfishing values of one or more species.

The general nature of the manager's tradeoff is well known for simple predator–prey systems (see, e.g., Ragozin & Brown 1985; Flaaten 1989). For example, when deciding on the optimal catch of each prey species, the manager takes into account the marginal benefits and costs from predation and trophic reallocation into grouper. The marginal benefits are the economic returns

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the manager can receive by "waiting" for the prey to be consumed by grouper and harvesting the grouper. The marginal cost of this trophic reallocation is the lost economic returns from the prey had they been harvested prior to grouper predation. It is also important to note that the inclusion of a generalist predator may result in indirect interactions among the prey species (e.g., Holt 1977).

Estimating the incremental short- and long-run gains of moving along a multi-species management continuum has not been previously explored analytically, and it is not mathematically tractable to derive a full dynamic solution for complex predator–prey systems. We use numerical methods to explore the dynamic trajectory of all components starting from the open-access initial conditions (Appendix S2). We compare the net present value, which summarizes the value of the fishery during the transition to and including the steady state, when a species is managed individually (Scenario B) to the species contribution to total net present value when it is jointly managed (Scenarios C, D, or E). It is possible that the net present value of a prey species is lower when it is jointly managed relative to the case when it is the only species being optimally managed even though the total system-wide net present value is greater. Hence, we can distinguish between system-wide benefits of increasing the scope of management and tradeoffs at the individual species level.

Results

Steady-state solutions

To build intuition, we first examine the magnitude of potential gains and losses for Scenarios A–D at the steady state. Scenario E, which explicitly incorporates nonfishing values, is discussed separately below. We use unexploited and open-access conditions as benchmarks to compare model results.

As expected, optimization for either single- or multi-species management (Scenarios B–D) reduces steady-state fishing effort of the managed species from the open-access levels (Scenario A) by approximately 50% (Figure 2A, parrotfish 0.492 ± 0.007 SD, snapper 0.505 ± 0.003 SD, grouper 0.522 ± 0.008 SD) (see, however, Pinnegar *et al.* 2002; Micheli *et al.* 2004). However, surprisingly, when the number of species being managed is one, two, or three species, optimal steady-state effort varies only slightly (maximum 3.3% change). Overall, the greatest reductions in fishing effort are in the move from open-access to optimal single-species management.

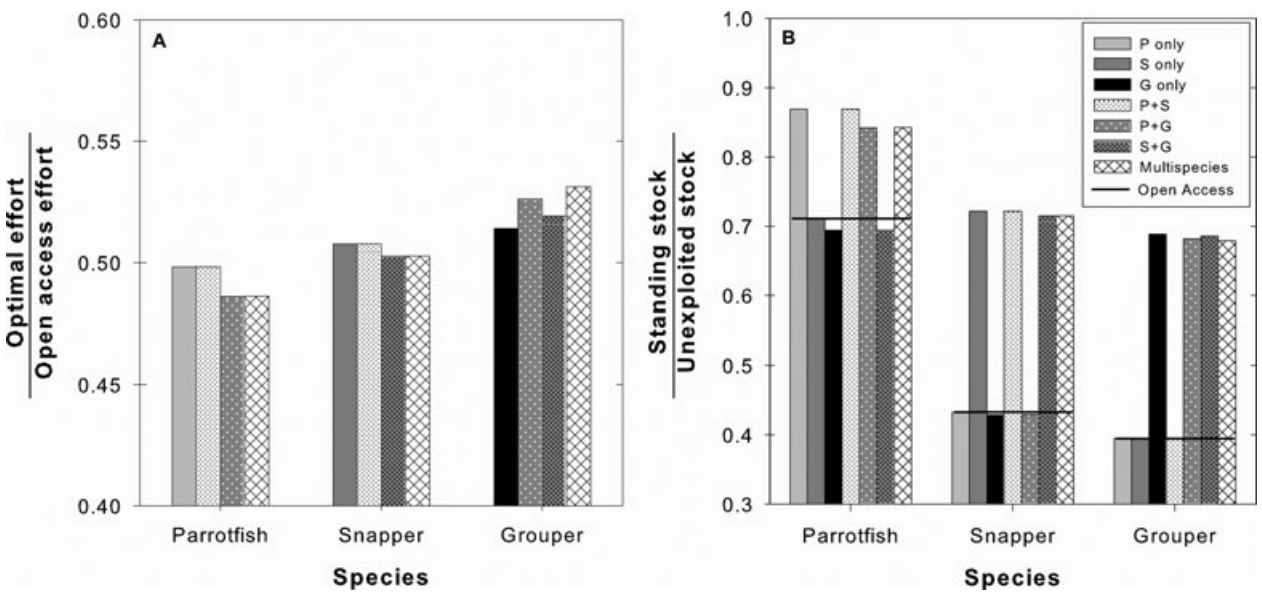

Figure 2 Steady-state optimal fishing effort and standing stock for the various management scenarios. Solid bars are single-species management for parrotfish, snapper, and grouper (Scenario B). Dotted bars are two-species management (Scenario C), and the multi-species bars represent a scenario where optimal effort is determined for all three species simultaneously (Scenario D). (A) Steady-state optimal fishing effort scaled to open-access effort levels (Scenario A). (B) Steady-state standing stock scaled to unexploited stock levels. (Note: to facilitate visual comparison, the y-axis for panel B starts at 0.3).

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In addition, the optimal fishing effort on each prey species is lower whenever it is managed with its predator, while the effort level on grouper is higher when managed with one or both of its prey species (Ströbele & Wacker 1995; Fleming & Alexander 2003). The greatest differences in the optimal fishing level occur when the prey is also managed with their shared predator (a likely result for communities with generalist predators). These results emphasize the potential advantage of multi-species approaches that account for food-web interactions.

Snapper and grouper standing stock (Figure 2B) showed a similar lack of sensitivity when moving from single- to multi-species management, where optimally managed populations were near 70% of the unexploited levels (Figure 2B, snapper 0.718 ± 0.004 SD, grouper 0.684 ± 0.004 SD). Parrotfish standing stock exhibited more variability in response to the management scenario, where standing stock ranged from 69.4 to 86.9% of unexploited levels, and like the snapper, its standing stock is only higher than the open-access level when it is an explicit part of the management scenario. This difference can be attributed to the higher turnover rate and lower catchability of parrotfish, which in turn means that it contributes proportionally more to the grouper's diet than snapper.

Optimizing fishing effort for only grouper is the scenario most detrimental to the parrotfish (compared to other harvesting scenarios that entail greater capture of the grouper and therefore less predation on the parrotfish). When only the predator is optimally managed, parrotfish densities can be driven lower than when all species are unmanaged under open access. This noteworthy result suggests that some prey species might be particularly vulnerable to explicit management of other species (especially their predators), which could lead to trophic cascades and other indirect food web effects if the prey themselves are not also managed.

Dynamic solutions

The dynamic gains and losses in net present value for managing multiple species are small (0.4–4.2% change, Figures 3 and 5). Prey species indeed have lower net present value when managed with their predator. The greatest gain in net present value for grouper occurs when all three species are managed, but managing the predator and one of its prey (especially parrotfish with its higher growth rate) increases the predator's net present value.

We also investigated the hypothesis that the net present value of ecosystem-based fisheries management increases with the strength of trophic coupling. In our system, two factors that lead to stronger trophic coupling are (1) an increase in the attack rate and (2) the amount of additional prey available because grouper is a generalist predator. To examine the sensitivity of our results to these factors, we reran the single- and multi-species effort optimization scenarios for a ±50% range of attack rates (a_1, a_2) and additional prey availability (Y). Additional prey availability resulted in higher net present value for the grouper with little change in net present value corresponding to a change in attack rates (Figure 4). Overall, net present value of grouper was more sensitive to changes in prey availability than attack rates, while parrotfish and snapper were more sensitive to changes in the attack rate (Figure 4 and Appendix S3).

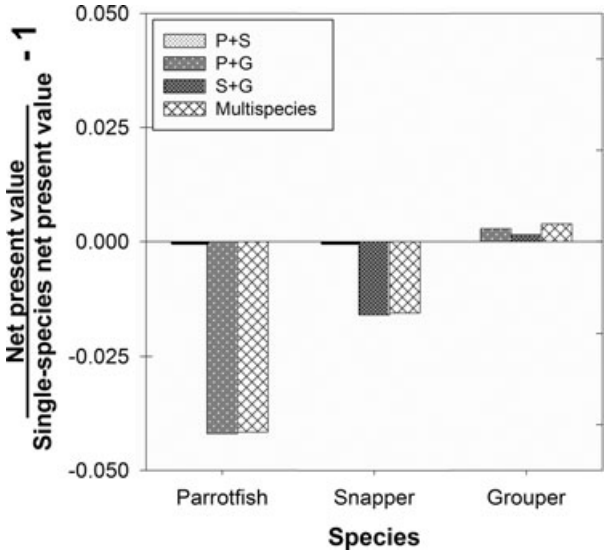

Figure 3 Net present value for the various ecosystem-based fisheries management options (Scenarios C and D) scaled to the single-species net present value (Scenario B). Values are zero or below for the two prey species (managed together and/or with their predator), and positive for the predator (grouper) indicating that managing all three species results in gains for the grouper and proportionally larger losses for the prey net present value. However, as this figure highlights, the overall quantitative gains in implementing multi-species management are limited for our study system.

Nonfishing value (Scenario E)

Parrotfish and grouper standing stock, optimal fishing effort, and net present value are all sensitive to the inclusion of nonfishing values, whereas snapper remained largely unaffected by the addition of nonfishing values of the other two species (Figures 5 and 6). Including broader values can lead to substantial shifts both in the short and long run. For example, incorporating a moderate value relative to a species market price might require that species-specific temporary moratoriums maximize

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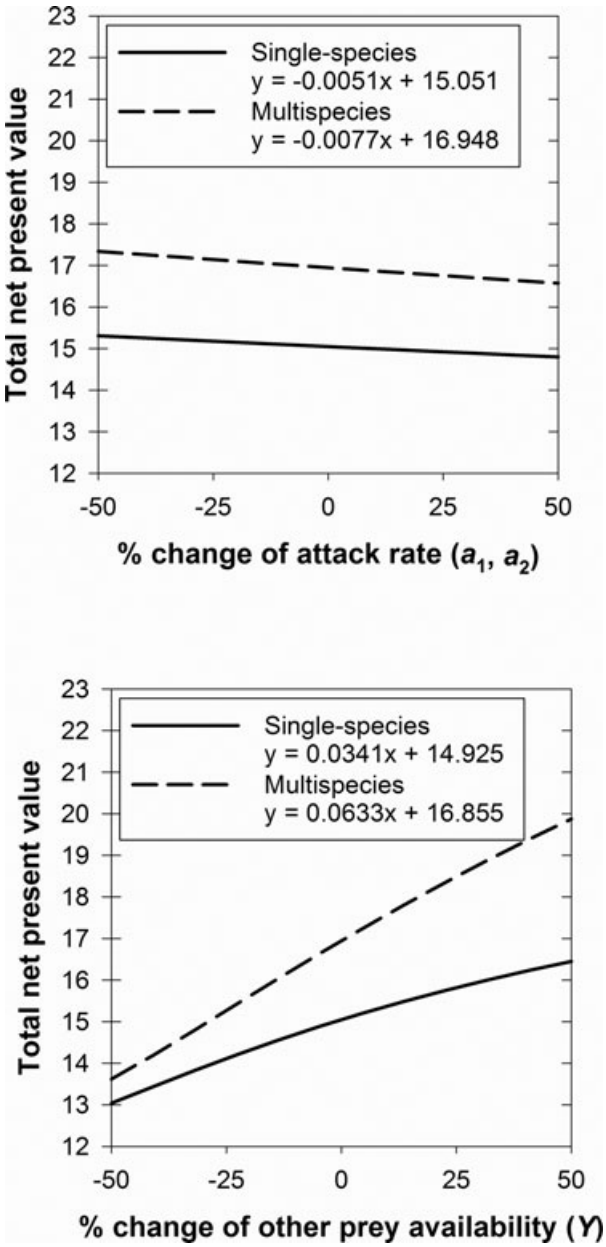

Figure 4 Sensitivity of total net present value to changes in the attack rate (top) and additional prey availability (bottom). Solid lines represent changes in total net present value, when species are managed individually and dotted lines represent sensitivity analyses when all three species are managed together (i.e., sum of the parts relative to the whole).

the economic returns from the system (Figure 5). Predictably, higher nonfishing values relative to market price can result in an economically efficient permanent closure of the fishery (Figure 6). These results stand in stark contrast to the solution we found when only fishing values were considered (fishing effort is positive for all t). Optimal dynamic management strategies, therefore, can change considerably when fishery managers consider a broader set of values (or stakeholders) when making management decisions. For example, with parrotfish, fishing effort decreases as its nonfishing value increases and eventually reaches a point where either a temporary or permanent moratorium is optimal (Figure 6).

Grouper patterns are slightly different. Like the parrotfish, higher grouper nonfishing values result in lower optimal harvesting levels, higher stock size, and lower net present value from fishing. A grouper nonfishing value that is 10% more than its price ($v_3 > 1.1p_3$) can achieve stock densities that are within 10% of unexploited stocks. Permanent moratoriums on grouper fishing result at higher levels compared to parrotfish permanent fishing moratoriums (Figure 6). We also find that prey should be fished at lower levels when v_3 is high relative to its price.

Maximizing top predator populations can require a reduction in harvesting of its prey but does not necessitate closure of the entire multi-species fishery. By using empirically-derived parameters, we in fact find that maximizing grouper standing stock might only require small reductions in harvesting of the lower trophic level when the lower trophic level is itself being optimally managed (Figure 6). When the manager considers the broader values associated with both grouper and parrotfish, the optimal level of fishing effort on both species decreases. Interestingly, the threshold level of v_3 for a permanent moratorium differs from when grouper is the only species where these values are explicitly considered (slightly higher). This captures the tradeoff between grouper's own value and its trophic interactions.

Permanent and temporary moratoriums may also arise with different values of costs (Appendix S2). Of course, with high enough operating costs, it would not pay to fish. Closures, however, might also be suboptimal if the social costs due, for example, from reductions in employment are explicitly taken into account in management decisions.

Discussion

Here, we carefully examined the role of ecosystem-based fisheries management by considering objectives and measurable benefits from moving along a management continuum in one consistent framework. This is especially relevant in our system, because more holistic management is often advocated for coral reef ecosystems, as they provide vital ecosystem services for both local and global communities (Moberg & Folke 1999) and are increasingly threatened by numerous anthropogenic and natural disturbances including climate change (Sala & Knowlton 2006).

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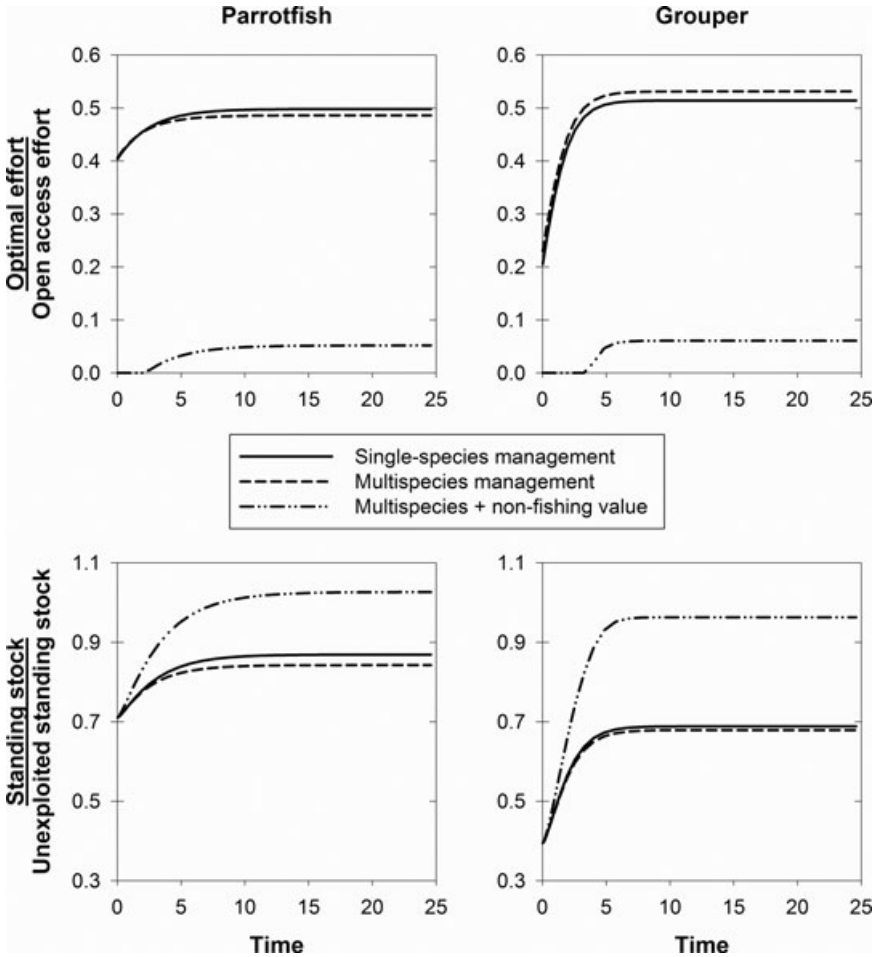

Figure 5 Patterns of optimal fishing effort levels (top row) and standing stock (bottom row) for multi-species options without (Scenarios B and D) and with nonfishing value (Scenario E, $v_i = 1.45p_i$). Optimal fishing effort levels are scaled to the steady-state open-access effort levels and standing stock levels are scaled to the steady-state open-access stock levels. Optimization scenarios that include nonfishing values of parrotfish or grouper impose temporary harvesting moratoriums ($e_i^*(t) \leq 10e^{-5} \cong 0$ for some t) as populations recover from open-access levels. All analyses successfully approximated steady-state levels within 25 time steps.

By using a model calibrated to empirical data, we compare qualitatively and quantitatively the conservation and economic tradeoffs across multiple management scenarios. Moving from single- to multi-species management generally resulted in small changes (<5%) in effort levels and standing stock, while including nonfishing values led to much more substantial shifts both in the short and long run. For example, we found that the optimal solution in the presence of multiple objectives can include temporary or permanent fishing moratoriums on a species in contrast to continuous fishing at low levels, when only fishing profits are considered. Of course, the effect of nonfishing values on optimal management recommendations depends on their magnitude, which is an empirical question (see Holland *et al.* 2010 for more information on how to measure nonfishing values).

Overall, we find that evaluating the potential advantages of ecosystem-based fisheries management in a system-specific context indicates that the differences across the various management scenarios might not be as large as one might predict and/or desire from either a conservation or economic standpoint. Furthermore, the greatest gains in standing stock levels, in reductions in fishing effort, and in net present value are not from improved estimation of the strength of trophic coupling, but from improving management and by expanding its objectives.

Although we consider several features common to any ecosystem-based fisheries management analysis—trophic interactions, generalist predators, fishing and nonfishing values—there are other potentially important factors that should be explored in future research. For

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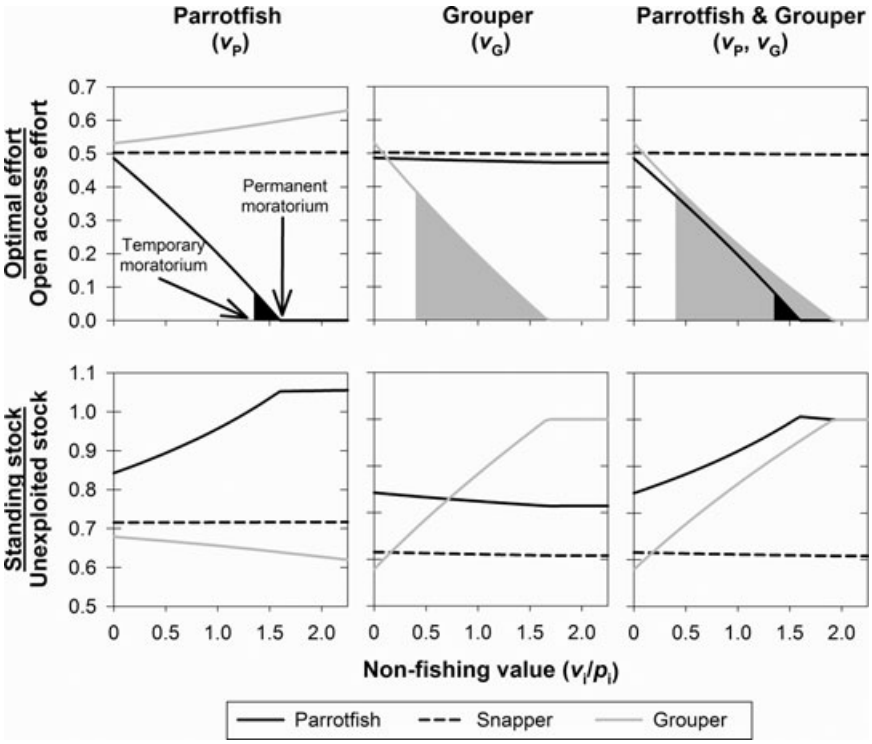

Figure 6 Changes in optimal fishing effort levels and standing stock with increasing nonfishing value, v_i/p_i (x-axis), of parrotfish (left column), grouper (middle column), and both species (right column). The figure captures both the fishing effort dynamics (shaded areas) and the steady-state effort levels and fishing densities (lines). Shaded areas represent the nonfishing values where species-specific temporary moratoriums are imposed by the dynamic optimization of Equation (1). The duration of the temporary moratoriums (occurring when $e_i^*(t) \leq 10^{-5} \cong 0$ for some initial period) increases as the threshold of the permanent moratoriums is approached from below. The steady-state fishing effort level for the species is also decreasing toward zero. For all cases, permanent moratoriums on fishing will arise when nonfishing values are very high.

example, we consider only two trophic levels, but communities are comprised of complex food webs that include multiple species (Bascompte *et al.* 2005) that have multiple sources of value embedded in changing environmental conditions. Parrotfish is also subject to bycatch in traps for grouper (Matos-Caraballo 2005), which we can model by assuming that fishing effort on grouper results in incidental mortality on parrotfish. On the economic side, in some smaller, more remote settlements, the responsiveness of fish prices to catch levels could have ramifications that ripple through the food web. Future modeling efforts would benefit by expanding this analysis to incorporate these and other features, such as management costs and tradeoffs for various stakeholders (see e.g., Imperial 1999).

In many parts of the world, there are efforts underway on reforming fishery management institutions with the goal of implementing ecosystem-based fisheries management (Zhou *et al.* 2010). In 2009, for example, the U.S. government set out to simultaneously increase the number of catch share programs (NOAA 2010) and adopt an ecosystem-based approach in U.S. waters (CEQ 2010). Although extrapolating our results to non-coral reef systems is premature, we find support for prioritizing investments in reforming the social and economic management of fish stocks (e.g., catch shares). Our study also showed that it is essential to identify and quantify the suite of ecosystem services and values from these ecosystems (Kareiva *et al.* 2007) and it is critical to include these broader values into management decisions.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Biological and economic parameter estimates based on the Caribbean.

Appendix S2. Model details and solution techniques.

Appendix S3. Sensitivity of total net present value to changes in the attack rate and additional prey availability.

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