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Original Article

Modelling the impacts of fish aggregating devices (FADs) and fish enhancing devices (FEDs) and their implications for managing small-scale fishery

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Fish aggregating devices (FADs) are deployed to aggregate fish over a limited area to improve fish catch. Fish enhancing devices (FEDs), which are FADs deployed in no-fishing areas, are fast gaining popularity as a fisheries management tool in the western Pacific. Yet, the impacts of utilizing FADs and FEDs are not yet well understood. In this work, we used a mean-field model to assess the effects of utilizing FADs and FEDs on stock biomass and catch. Our results indicate that using FADs enhances catch per boat when total fishing pressure is low, but can exacerbate fishery collapse when fishing effort is high. On the other hand, a FED-based system can increase the resistance of the fishery to collapse. A FED-based fishery may thus serve as pelagic marine protected areas and/or refugia. In a quota-based system, where fishing time is tied to catch quota, a phase transition occurs: both catch and biomass abruptly shift to low levels without warning. Deploying FADs to act as FEDs in a high quota fishery can prevent this phase transition resulting to a stabilizing effect.

Keywords: fisheries management tool, fishing strategy, fleet dynamics, ideal free distribution, optimal foraging, *payao*, sustainable fishery.

Introduction

Worm *et al.* (2009) and Hutchings *et al.* (2010) showed that there has been an easing of exploitation rate in some of the well-studied fisheries. However, this trend is not reflected in the fish stocks of the world's small unassessed fisheries (Costello *et al.*, 2012). In the Philippines, for instance, the high degree of poverty and high population density in coastal communities exacerbate exploitation of marine resources (White and Cruz-Trinidad, 1998; Green *et al.*, 2003). The continued dwindling of fish stock compels fishers to increase the use of more effective but destructive fishing methods (Patterson *et al.*, 2009), resulting to a further decline in catch and degradation of fisheries resources. In many areas, small-scale fishers face difficulties in exiting the fishery due to a lack of alternative options outside fisheries (Cabral and Aliño, 2011; Muallil *et al.*, 2011). Such fishers are already contented with a catch that will just compensate their travel cost (Salas *et al.*, 2004).

An intervention to enhance fisheries sustainability that is fast gaining popularity is the use of marine protected areas (MPAs). MPAs regulate fishing activities either by restricting access to an area or by regulating activities in an area. Based on the 2012 World Database on protected areas, there are 10 280 MPAs covering 2.3% of the world's ocean area (Spalding *et al.*, 2013). Majority of MPAs are coastal and nearshore. Only a few MPAs are in off-shelf waters due to an inherent difficulty in managing and enforcing them. In the Philippines, over 1600 locally managed MPAs are present (Horigue *et al.*, 2012).

Recently, coastal communities in cooperation with local governments in the Philippines, as well as in other countries with similar socio-economic conditions, have been deploying fish aggregating devices (FADs, locally known as *payaos*) to enhance the catch of fishers. FADs attract and aggregate free schooling tuna and small pelagics over a limited area, making fishing more successful. FADs are anchored or drifting floating objects such as logs, bamboo raft with assembled palm fronds, and artificial floating objects. Anchored FADs are usually used a few miles offshore (Dempster and Taquet, 2005). Drifting FADs are usually used in the high seas.

Anchored or moored FADs were first used in the Philippines before World War II to support small-scale fisheries (de Jesus, 1982). Today, anchored FADs are used throughout the western and central Pacific (Itano *et al.*, 2004). As cited by Holland *et al.* (1990), Kihara (1981) documented that commercial FADs just started in the Philippines in the early 1970s to attract yellowfin tuna. This happened right after the visit of the United Nation Food and Agriculture Organization in 1974 to test tuna fishing viability in the Philippines using experimental purse seining (Dickson and Natividad, 2000).

In the western and central Pacific, over half of the tuna are caught using purse-seine (Harley *et al.*, 2013). In the Philippines, 75% of the tuna are caught using purse-seine, ringnet, and handline (BFAR, NFRDI, and WCPFC, 2012) and majority of the catch are FAD-associated. Globally, 40% of the catch of tropical tuna comes from purse-seine fishing associated with floating objects that act as FADs (Dagorn *et al.*, 2012). Yet, the use of FADs has detrimental consequences. Signs of growth overfishing were already observed a decade after the first introduction of commercial FADs in the Philippines (Floyd and Pauly, 1984). Massive capture of fecund individuals or spawning stock results to recruitment overfishing (Fonteneau *et al.*, 2000). In the western and central Pacific, there is concern over the intense fishing of juvenile tuna stock in the Philippines and Indonesia as the area is known as a spawning ground and nursery of tuna (BFAR, NFRDI, and WCPFC, 2012; Cabral *et al.*, 2012, 2013a; Harley *et al.*, 2013). Many vulnerable and endangered marine animals are also threatened due to high levels of bycatch (e.g. Ménard *et al.*, 2000; Bromhead *et al.*, 2003; Lewison *et al.*, 2004; Molony, 2005; Wallace *et al.*, 2010). Yet, a recent review by Dagorn *et al.* (2012) suggests that FAD-associated bycatch is comparable or less than the bycatch for other gears and is primarily composed of non-threatened species. Dagorn *et al.* (2012) further argued that no substantial evidence exists to verify the negative impacts of FADs on the ecology of the fish.

An innovative fisheries management tool currently being explored in the Philippines and other countries in the western Pacific including Thailand, where it was reported to be first introduced (FRA-SEAFDEC, 2010), is the use of FADs as fish enhancing device (FEDs). Using FEDs still involves the deployment of FADs in the fishery but fishing is regulated, if not totally prohibited, in FADs coverage area. FEDs are also called "floating artificial reefs" and may contain additional structures other than the standard anchored FADs (FRA-SEAFDEC, 2010).

Understanding fishing dynamics is essential for effective fisheries management (Salas and Gaertner, 2004; Cabral *et al.*, 2010). Major fishing catastrophes have not been due to a lack of understanding of the environment or resources but the misunderstanding of fishing dynamics (Hilborn, 1985). Fishing behaviour and strategies have long been recognized as important components of fisheries management (Wilen, 1979; Charles, 1995) and in the development of appropriate policies (Salas *et al.*, 2004).

Optimal foraging strategy in fisheries is still an ongoing investigation (Cabral *et al.*, 2010; Poos *et al.*, 2010; Toft *et al.*, 2011). It was previously demonstrated that the flow of information among the vessels or agents is crucial in predicting fishery success (Little *et al.*, 2004; Cabral *et al.*, 2010). In a similar manner, the dynamics of fish aggregation is an important economic consideration. Harvesting in an area of large fish aggregation is economically ideal as less time and effort is needed for harvesting, yet spotting a large aggregation requires patience (Gatewood and Mace, 1990). On the other hand, one may harvest small patches of stock with more time and effort (Gatewood and Mace, 1990).

The ideal free distribution (IFD) theory predicts that the fishers will distribute themselves evenly among the resources (Fretwell and Lucas, 1970). IFD was initially used to predict the bird colonization of nesting sites and was later developed to describe the distribution of foragers in relation to the available resources (Fretwell and Lucas, 1970; Fretwell, 1972). IFD assumes that all foragers have complete knowledge of their environment and are free to move through all foraging sites without cost or restrictions (Houston and McNamara, 1988). Thus, IFD can only apply to a fishery system with substantial information flow across the fleet (Gillis, 2003).

Based on the concept of IFD, it is expected that the introduction of FADs will just increase the density of fishers in FADs. Here, we introduced a more flexible IFD by varying the fishers' preference towards FADs. We determined the catch and stock profile of the system as we varied three variables: number of boats, FADs density, and fishers' preference towards FADs. Another way to realize this intervention is by imposing levels of access through an external mechanism.

We aim to address the following questions: at what situation will the use of FADs improve the catch of small-scale fishery and ensure sustainability of fish stock? What is the effect of utilizing the not-yet-well-understood FEDs strategy? Answers to these questions can benefit fisheries managers in formulating appropriate policies, especially in the Philippines where variable fishing pressures exist and the use of FADs are widespread.

Method

Tuna can detect and orient themselves towards an FAD 10 km away (Girard *et al.*, 2004; Moreno *et al.*, 2007). To be most effective, FADs should then be no closer than 20 km from each other (Cayré, 1991; Marsac and Cayré, 1998). A single FAD therefore can have an effective area of 20 km by 20 km equivalent to a total effective area of $A_{\mathrm{FAD}} = 400\ \mathrm{km}^2$.

We considered a model fishery of area A (400 km × 400 km in this simulation) and total initial fish biomass S_0. Assuming that the FADs are spaced 20 km from each other, a maximum of 400 FADs can be deployed in the fishery (i.e., $A/A_{\mathrm{FAD}} = 400$) without overlap. The density of FADs deployed in the fishery, γ, can take any value from 0 to 1. A value of $\gamma = 0$ corresponds to a fishery with no FAD, and $\gamma = 1$ corresponds to a fishery with 400 FADs.

FADs modify the probability of finding a fish within their vicinity. It has been suggested that fishing in FAD areas increases the average catch by a factor of 2 (Fonteneau and Hallier, 1993), implying that FAD-area fish stock density is twice as much as free school stock density. In our model, we partitioned the total fish stock (S) into fish stock associated with FADs (S_{FADs}) and free school stock (S_{free}) such that the total stock in the fishery is given by $S = S_{\mathrm{FADs}} + S_{\mathrm{free}}$. With α being the ratio of the density of stock associated with FADs to the density of stock associated with free school, i.e. $\alpha = (S_{\mathrm{FADs}}/A_{FADs})/(S_{\mathrm{free}}/A_{\mathrm{free}})$, the fraction of FAD-associated fish biomass as a function of FAD density γ is:

$$S_{\mathrm{FADs}} = \frac{\alpha\gamma S}{1-\gamma+\alpha\gamma}, \tag{1}$$

and for free school is:

$$S_{\mathrm{free}} = \frac{S(1-\gamma)}{(1-\gamma+\alpha\gamma)} \tag{2}$$

(see appendix for the derivation). When $\gamma = 0$, all fish are free schooling. On the other hand, all fish are FAD-associated when $\gamma = 1$. For γ

between 0 and 1, Equations (1) and (2) ensure that the density of fish associated with FAD areas is α-times higher than in areas not influenced by FADs.

The local increase in the density of fish in FADs increases fishing success. Fonteneau *et al.* (2000), for example, suggest that the fishing success in targeting free school is 50% while FAD-associated harvesting is above 90%.

For N fishing boats, harvesting is done sequentially (one at a time). The catch of a boat fishing in an FAD is $C_{\mathrm{FADs}} = E\, S_{\mathrm{FADs}}/N_{\mathrm{FADs}}$, whereas the catch in free school is $C_{\mathrm{free}} = E\, S_{\mathrm{free}}/(400 - N_{\mathrm{FADs}})$, where $N_{\mathrm{FADs}} = 400\gamma$ is the number of FADs. The total catch per time-step is therefore $C_T = \sum_{i=1}^{N} (C_{\mathrm{FADs}} + C_{\mathrm{free}})$. Parameter E describes the fishing efficiency or gear efficiency (Hilborn and Walters, 1992) which describes the fish caught per fish available per boat and per unit time (Jul-Larsen *et al.*, 2003). S_{FADs} and S_{free} are updated whenever fishing is performed.

The stock dynamics is given by a difference equation:

$$S(t+1) = S(t) + rS(t)\left(1 - \frac{S(t)}{K}\right) - C_T(t), \qquad (3)$$

where r is the growth rate of stock, K the carrying capacity, and $C_{\mathrm{T}}(t)$ the total catch of all the boats at time t.

On the average, the number of boats fishing in FADs at a given time is PN, where P is the probability of a fisher to fish in FADs (fishing bias), whereas $(1-P)N$ fishers pursue free school fish. Our analysis is focused on tracking the catch per boat and the standing stock biomass of the fishery as we vary the fishing bias towards FAD areas (P) and the density of FADs (γ).

The level of fishing pressure that will push the stock to a collapsed state may be used to describe the impact of various harvesting strategies (Cabral *et al.*, 2010, 2013b). A fishery is considered collapsed if the catch drops below 10% of the historical maximum (Worm *et al.*, 2006, 2009). Since the modelled fishery is well-known, collapsed fishery is defined as fish standing stock dropping below 10% of its carrying capacity (0.10 K). This removes the arbitrariness in defining the "collapsed state" which is sensitive to the exerted fishing effort. Resistance means the ability of the fishery to withstand fishing pressure without leading to a collapsed state.

Table 1 shows the parameters used in the model. In all our simulations, we considered an initial stock S_0 equal to the carrying capacity K. A sensitivity analysis shows that the model output is independent of initial stock (Figure 1). To ensure a steady state solution, all simulation results were taken after a sufficiently long time has elapsed ($t_{\mathrm{f}} = 500$).

Results

The first part of our analysis considers a fishery without a catch quota. Thereafter, we considered boats with a target level of harvest per fishing trip (constant-yield model).

Continuous fishing

Fishery dynamics as described by the catch per boat (Figure 2) and fish stock biomass (Figure 3) were tracked while varying FAD density (γ), probability of fishing at a FAD area (P), and number of boats (N). The baseline case of using the "regular fishing" method (i.e. no-FAD case: $\gamma = 0$ and purely targeting free school) is indicated by red dotted lines in Figures 2 and 3.

Deploying FADs and regulating fishing activity in FADs (a FED strategy) reduced the catchability of stock compared with regular

Table 1. Model parameters and their corresponding values.

Variable	Interpretation	Values used
A	Size of the model fishery $A = A_{\mathrm{FADs}} + A_{\mathrm{free}}$	160 000 km^2
A_{FADs}	Area associated with FADs (total area of influence of all FADs deployed)	Dependent on the density of FADs (γ) in the fishery
A_{FAD}	Effective aggregating area of a FAD or area associated with a single FAD	
A_{free}	Area associated with free school stock	Dependent on the density of FADs (γ) in the fishery
S_0	Total initial biomass of the fishery	1 000 000 kg
S_{FADs}	Fish biomass associated with FADs	Dynamic
S_{free}	Fish biomass associated with free school	Dynamic
$S(t)$	Biomass of the fishery at any given time, $S = S_{\mathrm{FADs}} + S_{\mathrm{free}}$	Dynamic
N	Number of boats	1–500
C_{FADs}	Catch of a boat associated with FADs	Dynamic
C_{free}	Catch of a boat associated with free school	Dynamic
$C_{\mathrm{T}}(t)$	Total catch of the entire fleet at a given time-step, $C_{\mathrm{T}} = \sum_{i=1}^{N} (C_{\mathrm{FADs}} + C_{\mathrm{free}})$	Dynamic
t_{f}	Terminal time of the simulation	500 time-steps
τ	Catch caps or catch threshold	500 kg and 1000 kg
E	Fishing efficiency or gear efficiency	0.001
r	Growth rate of stock	0.01, 0.1, 0.5
K	Carrying capacity of the stock	1 000 000 kg
P	Probability of a boat to fish in FAD areas or fishing bias to FADs	0 to 1
γ	Density of FADs in the fishery	0 to 1
N_{FADs}	Number of FADs, $N_{\mathrm{FADs}} = 400\gamma$	0–400
α	Ratio of the density of fish in FADs over free school	2 (Fonteneau and Hallier, 1993)

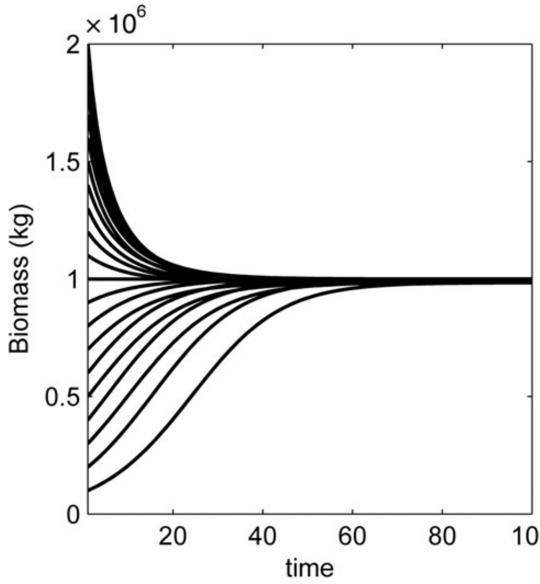

Figure 1. Output biomass for different initial biomass S_0 ($S_0 = 0.1$ to 2 K in increments of 0.1 K) for the case of $P = 0.5$, $\gamma = 0.5$, and no fishing boat. The resulting standing stock biomass (and hence catch output) is not sensitive to the initial biomass S_0. The same is true for other combinations of γ, P, and with non-zero fishing pressure.

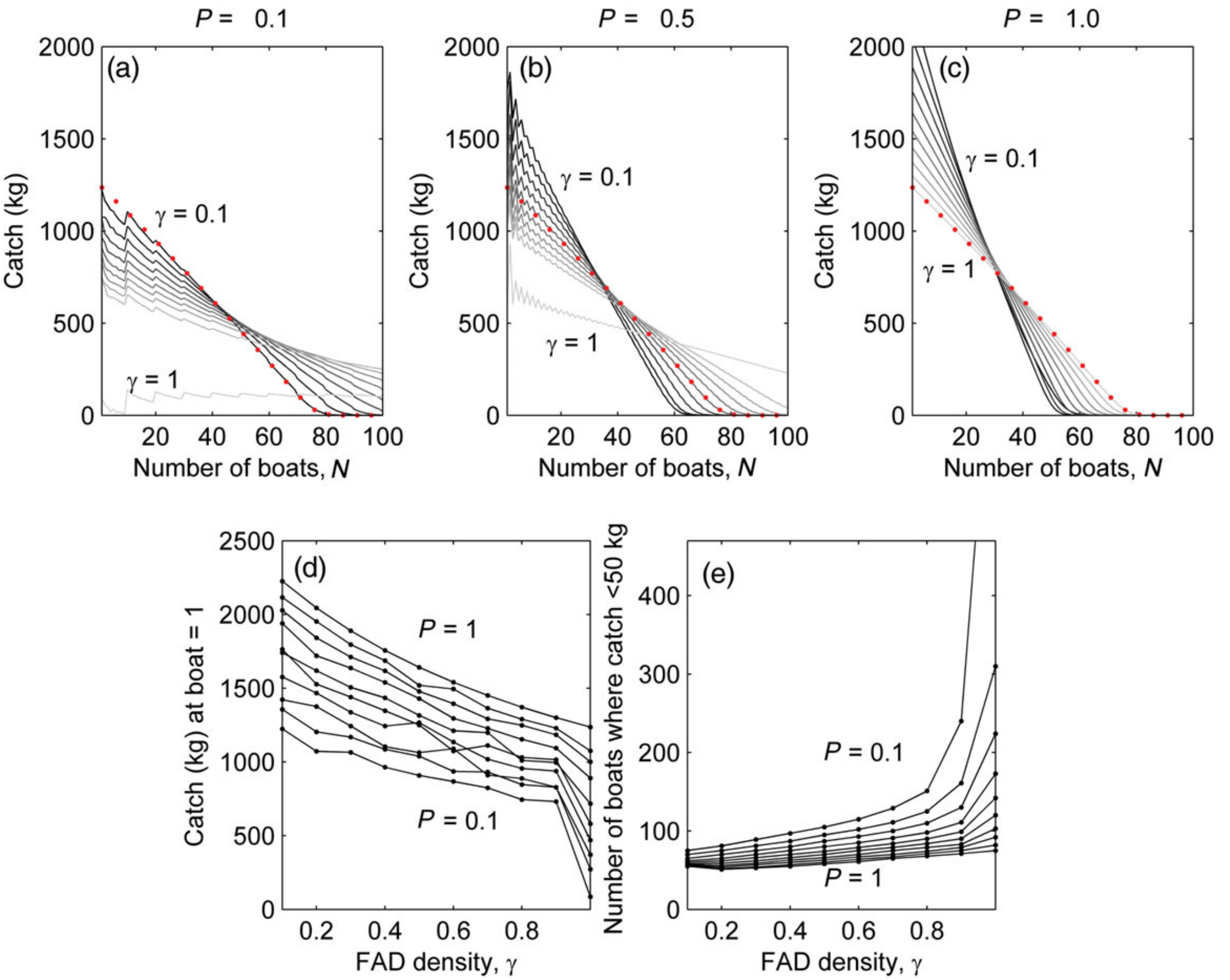

Figure 2. (a – c) Resulting catch per boat (kg) for varying probabilities of preference to fish in FAD areas ($P = 0.1$, 0.5, and 1) and variable FAD density ($\gamma = 0.1$ to 1 in increment of 0.1) at increasing number of boats. Dotted lines in (a) – (c) show trend for the no-FAD case ($\gamma = 0$, $P = 0$), (d) and (e) are the trend summaries of (a) – (c). (d) Catch at boat = 1 situation. (e) Number of boats where catch falls below 50 kg. Parameters used are presented in Table 1 with $r = 0.1$, evaluated using 100 model realizations.

fishing (e.g. $P = 0.1$ for variable γ, Figure 2a). Consequently, the rate of decline of stock slows down as the number of boats is increased (Figure 3a and d). As boats' fishing activity become highly associated with FADs (increasing P), catchability increases (Figure 2b and c). Compared with a strategy that involves alternating effort in targeting free schools and FAD-associated schools, concentrating fishing effort in FAD areas resulted to a higher catch per boat for a small number of boats (using boat = 1 to represent the small number of boats case, Figure 2d), but the rate of stock decline becomes faster as the number of boats is increased (Figure 3b–d). The concept behind FEDs is that FADs are deployed in the fishery but fishing is either not allowed or is heavily regulated in FAD areas (P close to zero). Low fishing preference to FADs (low P value) resulted to a highly resistant fishery (Figures 2 and 3). With more FADs deployed to function as FEDs (high γ, low P), more standing stock will spawn in the next cycle. Although a FED system does not enhance the catch at low fishing pressure, it will increase the resistance of the fishery at high fishing pressure especially when access is strictly enforced. This trend is generally not sensitive to the growth rate of stock except when the growth rate is very high (e.g. $r = 0.5$; Figure 4). For high growth rates, deploying a small number of FADs will not only increase the catch per boat at low fishing pressure but will also increase the resistance of the fishery at high fishing pressure.

Constant-yield fishing

When a boat targets a constant-yield per fishing trip, it may set (deploy) its fishing gears several times. A constant-yield strategy is common in the pelagic fleets and even in small-scale fisheries. We assume that the boats can engage in up to five fishing sets or gear deployments per trip, until its catch exceeds a constant-yield threshold (τ). Two constant-yield thresholds were tested ($\tau = 500$ kg and $\tau = 1000$ kg).

With no FAD deployed (i.e. $P = 0$, $\gamma = 0$), a steep decline in stock and catch or kink towards collapsed state can be observed. For $\tau = 1000$ kg, this happens at 23 boats while for $\tau = 500$ kg at 46 boats (Figure 5). The steep decline can also be observed when using FADs. For high threshold (i.e. $\tau = 1000$ kg), the kink was replaced by a smooth response curve for the case where γ is high and P is low (i.e. $P = 0$, $\gamma = 0.75$; Figure 5). For low threshold (i.e. $\tau = 500$ kg), the removal of the kink was not observed yet the

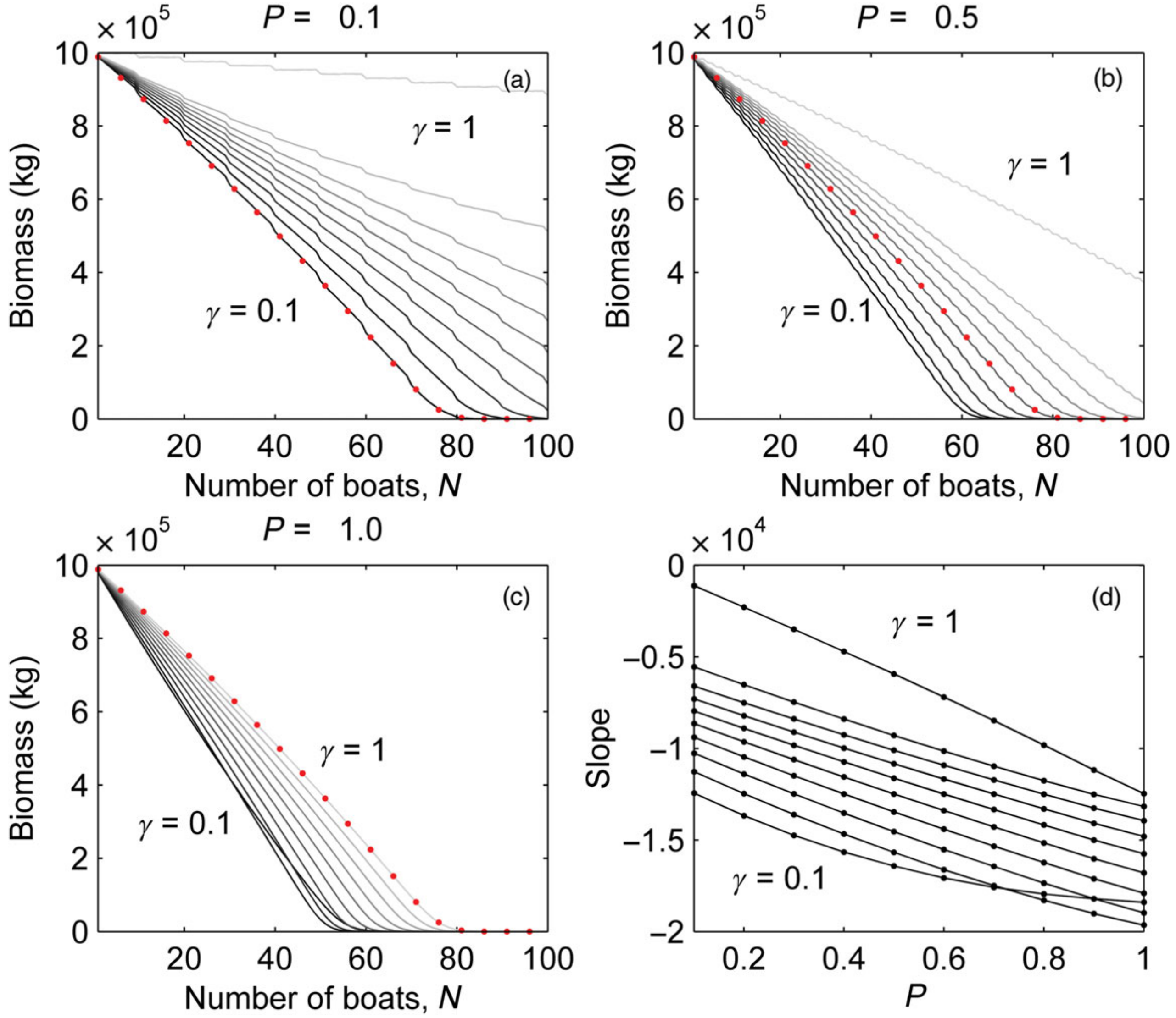

Figure 3. (a–c) Resulting total fish biomass for varying probabilities of preference to fish in FAD areas ($P = 0.1$, 0.5, and 1) and variable FAD density ($\gamma = 0.1$ to 1 in increment of 0.1) at increasing number of boats. The no-FAD case in dotted line ($\gamma = 0$, $P = 0$) is shown in (a)–(c) for reference. (d) Trend summary. Shown is the slope of the lines for variable P and γ. Slope of no-FAD case is -1.25×10^4 kg boat^{-1}. Parameters used are presented in Table 1 with $r = 0.1$, evaluated using 100 model realizations.

number of boats where the kink was observed increased to 46 (Figure 6). It appears that using FADs can exacerbate fishery collapse in a constant-yield fishing situation and is more apparent for a low-threshold case.

The number of fishing sets required in a FED-based strategy is generally higher than regular fishing. The increase in fishing sets is more pronounced at high fishing caps and lower fishing preference to FADs (high τ, low P value). For $\tau = 1000$ kg, the number of fishing sets can be as high as double, i.e. from about one fishing set to two fishing set at small number of boats (Figure 5). For $\tau = 500$ kg, the increase in fishing sets becomes apparent only after 25–35 fishing boats (Figure 6).

Discussion

The asymptotic dynamics of the population is independent of the initial population size, which suggests that our model is ergodic (Figure 1). The patterns/results of the simulations therefore reflect model dynamics and processes rather than initial population conditions.

In general, for continuous-harvest fishery, fishing in FADs that are sparingly deployed increases the catch per boat at low fishing pressure and a faster decline in stock at high fishing pressure (or number of boats). For a small number of boats, a low density of FADs with fishers having high fishing preference to FADs increases the catch per boat up to twofold compared with a fishery that does not use FADs. Deploying only a few FADs enables the fish stock to be more concentrated on FADs, thus harvesting in FADs resulted to high catch. On the other hand, saturating the fishery with FADs homogenizes the distribution of fish stock and effectively reduces the efficacy of FADs in aggregating fish. [As the density of FADs saturates the entire area (i.e. as γ approaches 1), the stock profile approaches the profile of the no-FAD case as expected. At $\gamma = 1$,

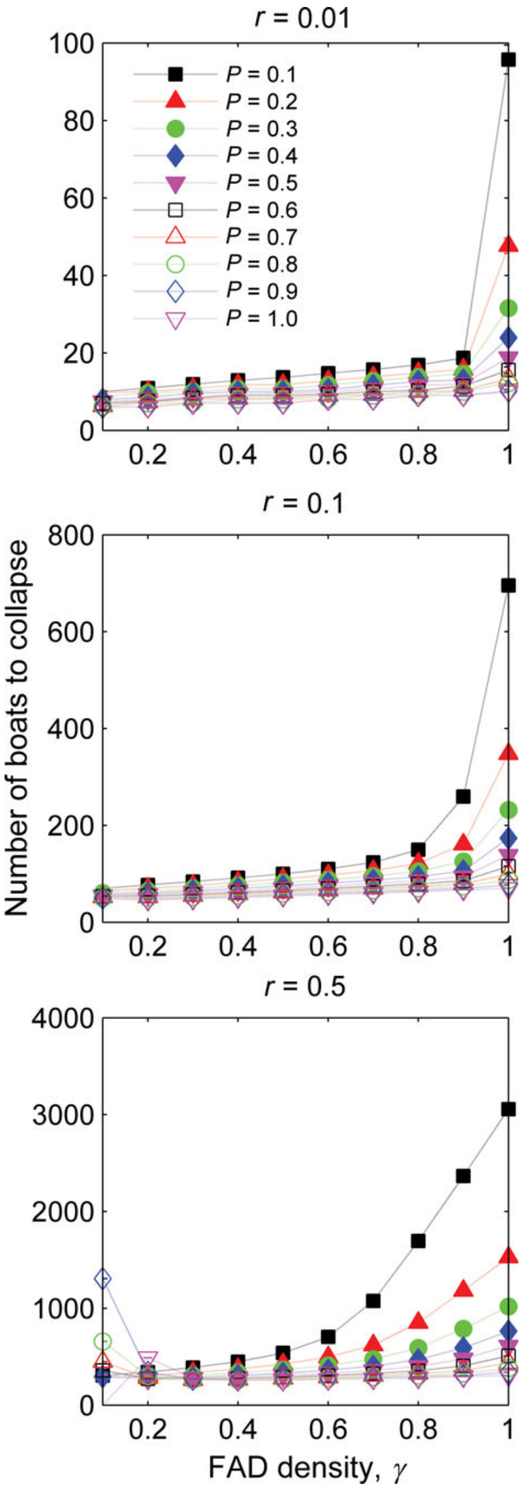

Figure 4. Minimum number of boats required to collapse the fishery for growth rate $r = 0.01$, $r = 0.1$, and $r = 0.5$.

the expression for S_{FADs} reduces to $S_{\mathrm{FADs}} = S$, independent of α and hence the density of fish will become homogeneous, the same as the no-FAD case situation.]

FED-based fishery operates on the notion of reducing the catchability of fish by limiting access to FAD areas. Deploying FADs and not fishing in these areas provide refuge to the stock. As a result, FEDs enhance the resistance of the fishery to increasing fishing pressure. The FADs, when coupled with access rights arrangements (a FED-based fishery), result to a management strategy akin to the effect of MPAs and marine managed areas: fishing areas are restricted yet catch remains sustainable due to spillover and reserve effects.

In nearly all simulations of a fishery driven by a constant-yield model, an abrupt stock collapse or kink is observed. The kinks are a signature of the constant-yield dynamics (Brauer and Sanchez, 1975; Murray, 2002). Deploying FADs at high densities with a low P value (a FED strategy) in a high-quota fishery leads to a stabilizing effect. The kinks and phase transitions are replaced by a smoothly and gradually decreasing stock profile (Figure 5).

The mechanism that explains the smoothening of kink at low P and high γ (a FED strategy) in a constant-yield model is the same as the continuous case: deploying many FADs and not fishing in these areas allows more stock to be protected. The FAD areas provide refuge for the stock and prevent the occurrence of overfishing. FED therefore can be a precautionary intervention for a constant-yield fishery system, especially when the catch threshold of fishers is high. Although a FED strategy may prevent a rapid collapse of fishery in a high-quota system, it may turn out to be costly for fishers as it requires a greater number of fishing sets.

Describing the dynamics of fish stock by tracking only two aggregate values (FAD-associated and free-schooling biomass) implies acceptance of a mean-field model. We argue that the high variance in the movement of fish together with the small area of the modelled fishery supports the homogenous fish stock (mean-field model) assumption (Bonabeau *et al.*, 1999). For example, tunas have a swimming speed of around 0.6–2.1 $\mathrm{m\ s^{-1}}$ (Cayré, 1991) or a potential daily covered distance of 52–181 km. [Multiplying speed by 24 h derives this range of values. Cayré (1991) found that for the yellowfin tuna, the average sustained speed is 1.44 $\mathrm{m\ s^{-1}}$, which translates to a potential coverage distance of 124 $\mathrm{km\ d^{-1}}$.] We expect that our assumption will fail in a large fishery area such as at a regional scale (e.g. western and central Pacific Ocean), where natural aggregations can be observed.

In reef fisheries, natural aggregations can exist even in small areas (e.g. fisheries of few kilometres in size). Spawning aggregations of reef fish are specific to certain locations (Sadovy and Domeier, 2005). Some fish that are dependent on the associated habitat in their life stages (ontogenetic habitat shift) tend to aggregate by age and size (Mamauag *et al.*, 2009). Some fish are also know to segregate by sexes (e.g. females of the grouper *Epinephelus guttatus* can be found in shallow inshore reefs while males aggregate in the offshore and deeper region and both sexes meet only during spawning season; Shapiro *et al.*, 1993). Selectively fishing these natural aggregations can impact the sustainability of stock (Zhou *et al.*, 2010).

Our mean field model neglects seasonal variation in stock (e.g. Beets, 1989), although such variation cannot affect the result of the model if taken on the average. We also assumed that restructuring of population and aggregation are instantaneous and that all FADs are identical and therefore contain the same density of fish. Boats are also fishing in a sequential manner. Although there will be a variation of catch per boat per time-step, the result were taken as the average catch of boats per time-step. The mean field assumption of the stock prevents the occurrence of having fishers that consistently have a high catch due to their extensive knowledge of the fishing site.

In the near shore areas, the use of FADs improves fishing success (Buckley, 1986; Friedlander *et al.*, 1994) and can be a tool to divert

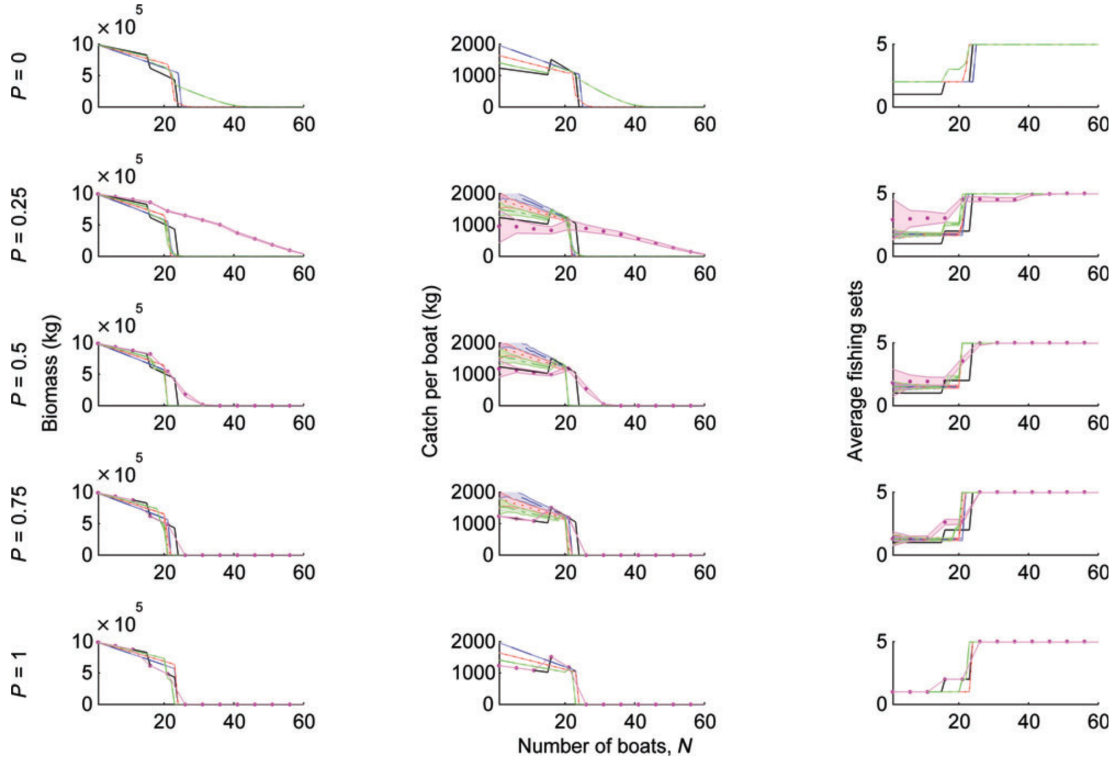

Figure 5. Biomass, catch per boat, and average fishing sets for variable fishing preference to FADs P, fishing cap of $\tau = 1000$ kg, and variable FAD density [$\gamma = 0$ (black, solid line), 0.25 (blue, dashed line), 0.5 (red, hyphen line), 0.75 (green, dashed hyphen line), 1 (magenta, circled line)] at increasing number of boats.

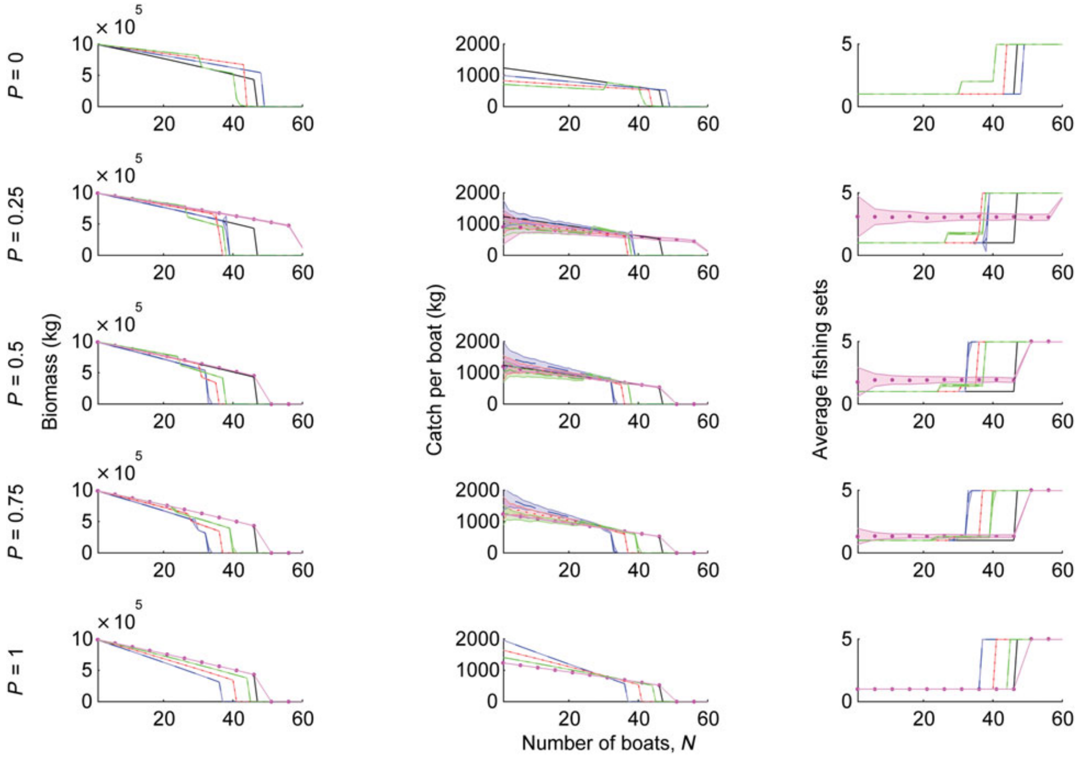

Figure 6. Biomass, catch per boat, and average fishing sets for variable fishing preference to FADs P, fishing cap of $\tau = 500$ kg, and variable FAD density [$\gamma = 0$ (black, solid line), 0.25 (black, dashed line), 0.5 (black, hyphen line), 0.75 (black, dashed hyphen line), 1 (black, circled line)] at increasing number of boats.

fishing pressure away from overfished fishery (Bohnsack and Sutherland, 1985; Lokani *et al.*, 2013). The management challenge is how to encourage the fishing community to be compliant with access rules to FADs. Utilizing FADs with strict control on access and use creates a good balance between the community benefits and a resistant stock. Deploying anchored FADs away from the ecologically important marine habitat and areas with proper enforcement mechanisms can benefit the community.

A common problem in the use of MPAs is the mismatch of fish and habitat protection. In some cases, key habitats are protected yet the range of protection is not enough to afford protection for highly mobile species, which often require large and continuous MPAs. FADs deployed in key protected habitats (FED-based fishery system) are akin to a system of MPAs with increased protection for highly mobile species. FADs in a FED-system act as both a habitat (e.g. an extension of a degraded habitat) and a stock enhancement device (Beets, 1989; Aliño, 2002).

In general, a FED-based system can be used as a management tool for a fishery with high fishing pressure. Fishing pressure is relaxed due to a reduction in fish catchability, which consequently increases the resistance of the fishery to high fishing pressure (Hannesson, 2005). Fish catchability reduction as a means to increase resistance to fishing pressure has also been numerically demonstrated in a spatial-based model of fishing strategies (Cabral *et al.*, 2010). The strategy of following the best performing boat in terms of yields (Cartesian strategy) results to a fishing pattern scenario that has a patchy spatial pattern (Cabral *et al.*, 2010). Similar to FADs, enforcement and compliance are necessary to afford the benefits derived from a FED-based fishery. With poor enforcement and compliance, a FED-based fishery can easily transform into a FAD-based fishery and may only accelerate fish stock decline. Anecdotal accounts from some of the sites in the Philippines where FED-based fisheries exist showed that catch generally increases when they implement a FED-based fishery.

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Appendix

Derivation of the stock associated with FADs and free school for a variable number of FADs

The density of stock associated with FADs is higher by a factor α than the free school stock for any density of FADs. Hence,

$$\alpha = \frac{S_{\mathrm{FADs}}/A_{\mathrm{FADs}}}{S_{\mathrm{free}}/A_{\mathrm{free}}}, \tag{A1}$$

where S_{FADs} and S_{free} are the stock associated with FADs and free schools and A_{FADs} and A_{free} are the areas associated with FADs and free schools, respectively.

Solving for S_{FADs}, we have

$$S_{\mathrm{FADs}} = \frac{\alpha S_{\mathrm{free}} A_{\mathrm{FADs}}}{A_{\mathrm{free}}}. \tag{A2}$$

Note that $A_{\mathrm{FADs}} = \gamma A$, $A_{\mathrm{free}} = (1-\gamma)A$, and $S_{\mathrm{free}} = S - S_{\mathrm{FADs}}$, where γ is the density of FADs, S the total standing stock fish biomass, and A the total area of the fishery that follows the relation $A = A_{\mathrm{FADs}} + A_{\mathrm{free}}$. Inserting these equations to Equation (A2), we have

$$S_{\mathrm{FADs}} = \frac{\alpha\gamma(S - S_{\mathrm{FADs}})}{(1-\gamma)}. \tag{A3}$$

Solving for S_{FADs},

$$S_{\mathrm{FADs}} = \frac{\alpha\gamma S}{1-\gamma+\alpha\gamma}. \tag{A4}$$

Now, for the fraction of stock associated with free schools, we express Equation (A2) in terms of S_{free}, i.e.

$$S_{\mathrm{free}} = \frac{S_{\mathrm{FADs}}(1-\gamma)}{\alpha\gamma}. \tag{A5}$$

Substituting Equation (A4) to Equation (A5), we have,

$$S_{\mathrm{free}} = \frac{S(1-\gamma)}{1-\gamma+\alpha\gamma}. \tag{A6}$$

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