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The economic efficiency of a time–area closure to protect spawning bluefin tuna

Paul R. Armsworth[1,2,*], Barbara A. Block[3], Josh Eagle[4,5] and Joan E. Roughgarden[2]

[1]*Department of Animal and Plant Sciences, University of Sheffield, Sheffield S10 2TN, UK;* [2]*Department of Biological Sciences, Stanford University, Stanford, CA 94305, USA;* [3]*Hopkins Marine Station, Stanford University, Pacific Grove, CA 93950, USA;* [4]*School of Law, University of South Carolina, 701 Main Street, Columbia, SC 29208, USA; and* [5]*Stanford Law School, Stanford University, Stanford, CA 94305, USA*

Summary

1. Spatial management measures, such as time–area closures, offer a widely advocated strategy for managing bycatch in fisheries and fisheries that impact particular life-history stages, like spawning. The effectiveness of proposed management strategies can be evaluated across different policy dimensions of which we focus on one – maximising total profit. We examine whether a time–area closure presents an economically efficient means to manage bycatches of Atlantic bluefin tuna *Thunnus thynnus* on their spawning ground in the Gulf of Mexico by longline fishermen targeting yellowfin tuna *T. albacares*.

2. We combine a behavioural representation of bluefin migration with population dynamic models for the two species and an economic representation of relevant fisheries and solve for optimal, equilibrial management strategies.

3. The models predict the western Atlantic bluefin population is close to open access harvesting conditions, and that rebuilding the bluefin population would increase overall economic revenues from the fisheries by 460%, regardless of the specific actions taken in the Gulf.

4. Time–area closures in the Gulf are predicted to be economically costly if there is little scope for recovery of the bluefin stock. However, the models predict such closures would offer limited economic benefits if there were a broader commitment to rebuild the bluefin population.

5. *Synthesis and applications*. Technological advances and improvements in our understanding of the life history of these and other species make increasingly precise spatial effort control possible in many fisheries. The case study illustrates when such management measures would maximise fisheries profits while accounting for population dynamics and differences in mortality from different fisheries. However, the case study also highlights that the more elementary policy challenge of preventing overfishing has still often to be overcome.

Key-words: bluefin tuna, economics, fisheries, Gulf of Mexico, longline, spatial management, *Thunnus albacares*, *Thunnus thynnus*, time–area closure, yellowfin tuna

Abbreviations: ICCAT, International Commission for the Conservation of Atlantic Tunas; MSY, maximum sustainable yield; MEY, maximum economic yield; NMFS, National Marine fisheries Service; SSB, spawning stock biomass.

Introduction

Current debates in fisheries science and policy focus on the design of spatially structured management strategies that account for the impact of fishing on multiple species (Pikitch *et al*. 2004; Babcock *et al*. 2005; Cook & Auster 2005; Fluharty 2005; Crowder *et al*. 2006; Kellner *et al*. 2007). For large pelagic species, spatial management of fishing effort, through measures such as time–area closures, can protect particular life-history stages or reduce bycatch of non-target species (Goodyear 1999; Hobday & Hartmann 2006; NMFS 2006; Grantham, Petersen & Possingham 2008; Game *et al*. 2009). As a case study in the use of these techniques, we evaluate the effectiveness of a time–area closure as a means for managing US tuna fisheries. As well as providing insights into the application

*Corresponding author. E-mail: p.armsworth@utk.edu

of time–area closures as a fishery management tool, the case study examines an applied ecology problem of immediate policy concern and develops new modelling approaches that account for individual movement patterns in population dynamic models of fisheries.

The effectiveness of fishery management policies should be examined across multiple policy dimensions. For example, management strategies can be evaluated based on their ecological impact using measures such as the effect of fishing on the age or sex structure of a population or on its spawning stock biomass (e.g. Armsworth 2001). Such measures also can be evaluated in terms of their distributional impacts on society, balancing distributional concerns both within and across generations. Here we focus on one dimension for evaluating fisheries management strategies that integrates ecological and economic factors. Specifically, we evaluate the economic efficiency of management strategies, but do so in a way that accounts for the population dynamics of the species involved and impact of different sources of fisheries mortality on the long-term status of stocks. An estimate of the maximum profit offered by a management strategy can provide a useful benchmark to policy-makers when evaluating alternative management options. With such an estimate, policy-makers can compare the cost to the public if an alternative policy is chosen, perhaps one designed to achieve conservation targets for stock rebuilding or to protect jobs in particular fishing communities.

We use profit maximisation as a criterion to evaluate time–area closures that are designed to manage incidental catches of bluefin tuna on pelagic longline gear. This case study in the use of time–area closures involves common challenges faced in fisheries management. Specifically, multiple species are often caught by fleets that target fish of different ages and stages. Also, future management plans commonly begin from a point of long-term overfishing and stock depletion.

The management of western Atlantic bluefin tuna, like that of other bluefin tuna stocks and species, is contentious (Safina 1998; Sissenwine *et al*. 1998; Polacheck 2002; Fromentin & Ravier 2005; Porch 2005; Kolody *et al*. 2008; Safina & Klinger 2008). Management is contentious, because the populations are in steep decline, catches are extremely valuable and the species' highly migratory life history exposes it to the fishing grounds of many fleets. Western Atlantic Bluefin tuna, *Thunnus thynnus* (Scombridae) – henceforth bluefin – undergo migrations of 1000s of km along the East Coast of North America as they move from high latitude foraging grounds to subtropical breeding grounds (Block *et al*. 2001, 2005). Some mature bluefin enter the Gulf of Mexico in late winter and spring to spawn (Block *et al*. 2001, 2005; Teo *et al*. 2007a,b). Pelagic longline fishermen in the Gulf catch bluefin incidentally while fishing for Atlantic yellowfin tuna, *T. albacares* – henceforth yellowfin.

The International Commission for the Conservation of Atlantic Tunas (ICCAT) coordinates Atlantic tuna management. The US National Marine Fisheries Service (NMFS) implements ICCAT recommendations within US waters and for US flagged vessels. ICCAT manages Atlantic bluefin as two distinct stocks, one in the western Atlantic that spawns in the Gulf of Mexico and is the focus of our study, and one in the eastern Atlantic that spawns in the Mediterranean Sea.

Intense demand for bluefin tuna began in the 1960s with the development of air freight and access to the Japanese fresh seafood market (Sissenwine *et al*. 1998; Fromentin & Powers 2005). Throughout the 1970s, bluefin catches in the western Atlantic averaged around 5000 mt, the majority of which were breeding aged fish taken by Japanese longliners in the Gulf of Mexico (Sissenwine *et al*. 1998). Directed fishing for bluefin on their Gulf of Mexico spawning ground was prohibited by ICCAT in 1982 (NMFS 2006). Between 1983 and 2007, western Atlantic bluefin catches averaged 2500 mt, with the US catching around 55–60% of this total (ICCAT 2009a). The western Atlantic bluefin spawning stock is estimated to have declined by 82% since 1970 (ICCAT 2009a). In the past five years, commercial fishermen in the US have been unable to catch their quota; in 2006, 2007 and 2008, they caught less than 25% of their quota. Adult bluefin remain extremely valuable, with the price of fish varying across the season and across fishing gears (Carroll, Anderson & Martinez-Garmendia 2001; Martinez-Garmendia & Anderson 2005).

The US lands approximately 4–6% of the 100 000–140 000 mt annual catch of Atlantic yellowfin tuna (ICCAT 2009b). A US longline fishery for yellowfin tuna developed in the Gulf of Mexico in the 1980s (Browder *et al*. 1991). Longlining catches multiple species (tunas, swordfish, billfishes, mahi mahi), but particular species are targeted with the gear configuration and adjustments of the depth, timing and location of sets. Yellowfin catches fetch a lower price than bluefin.

Adult bluefin are caught during the spawning season in the Gulf as a byproduct of fishing for yellowfin with longline gear. The question of how this fishery interaction should be managed has been a source of some debate. One management strategy would be to close areas within the Gulf to longlining during the bluefin spawning season (Block *et al*. 2005). 'Time–area closures' of this form are used elsewhere by NMFS to reduce bycatch. In 2006, NMFS published an extensive review that concluded such a closure was not justified in the Gulf (NMFS 2006). This conclusion was based on a range of ecological, social and economic considerations.

In any modelling study, researchers make assumptions and can only measure and account for so much. The modelling undertaken by NMFS to evaluate the costs and benefits of time–area closures in the Gulf is no exception. We explore the influence that some of the factors neglected in the NMFS study can have on the determination of whether a time–area closure would increase profits from tuna fisheries. In particular, we account for the latest information on the timing of bluefin entry and exit to the Gulf spawning grounds (Block *et al*. 2005; Teo *et al*. 2007a,b). To do this, we develop a behavioural model of fish migration decisions. We also explore the consequences of accounting for the population dynamics of the focal species, again something left out of the NMFS study. We do this by coupling the behavioural model of bluefin movements with population dynamic models of the species involved. To examine how population dynamics can influence recommendations about time–area closures, we

Table 1. Summary of policy evaluations regarding profitability of a time–area closure. In the status quo case in which historical overfishing continues, time–area closures always incur economic costs. In the rebuilding case, time–area closures are shown to increase profits from the fisheries across a range of parameters and scenarios. The maximum increase a time–area closure can offer is 2% of the value of expanded fisheries exploiting the rebuilt bluefin population

Parameter or scenario varied	% improvement from time–area closure	
	Status quo case	Rebuilding case
Area closed	None	0·4–2·0%
Effort displaced	None	0·8–2·0%
Bf catchability	None	1·8%
Bf maturity	None	0·4%
LL effort	None	0·9%
Bf productivity	None	0–0·1%
Bf mixing	None	0·7%

compare the effectiveness of time–area closures in two contrasting policy contexts, one (the *status quo case*) in which fishing pressure continues at historical levels and a hypothetical future scenario (the *rebuilding case*) in which fishing effort is tightly regulated and coordinated meaning some rebuilding of the bluefin stock would be possible. Finally, we assume that reductions of bluefin bycatches in the Gulf may be offset by increased catches at other times of year or in other bluefin fisheries in line with current legislation in the US. This assumption introduces the possibility that there may be economic benefits to the US from considering a time–area closure. To represent other fisheries, we use the largest of the bluefin fisheries, the commercial handgear fishery off New England. We also test the sensitivity of results to including additional US tuna fisheries.

We give a full exploration of the processes that underpin model predictions below. However, Table 1 summarises our main findings regarding the specific case study question for the Gulf. The models predict that a time–area closure is always costly if fishing by other fleets continues at historical levels, a finding that is unusually robust to variations in model parameters and assumptions. Time–area closures can increase profits if managing a rebuilt bluefin population, but the improvement that they offer is minor, especially when compared to the advantages of rebuilding itself.

Materials and methods

We outline the model structure here and provide more detail, including parameter estimates, in the Supporting Information (Additional Model Details). To determine whether time–area management in the Gulf of Mexico would increase profits, we need to examine the economic costs and benefits involved. Reducing pelagic longline effort around the bluefin spawning ground incurs direct costs in terms of forgone fishing opportunities for longliners. Any economic benefits would be felt as potential revenue increases from improvements in the status of the bluefin stock and increased catches at other times of year in the Gulf or in other bluefin fisheries. The basic model structure involves a two-stock (bluefin and yellowfin) two-fishery (Gulf longliners and commercial handgear) formulation.

The population dynamics for bluefin are given by a model of the form,

$$B_{t+1}^{1} = \frac{\alpha_b SSB_t^b}{\beta_b + SSB_t^b}, \quad B_{t+1}^{i+1} = s_t^i B_t^i \quad \text{for} \quad i \in \{2, ..., 9\}$$
$$B_{t+1}^{10_+} = s_t^9 B_t^9 + s_t^{10_+} B_t^{10_+}. \qquad \text{eqn 1}$$

Here, α_b and β_b are the Beverton–Holt parameters for the bluefin stock-recruitment relationship; B_t^i is the number of bluefin aged i at the start of year t and individuals aged 10 and over are grouped together in a single age class; s_t^i is the survival rate; and SSB_t^b is the spawning stock biomass. The relationship between bluefin spawning stock biomass and subsequent recruitment has long been a source of debate (reviewed in Sissenwine *et al.* 1998; Porch 2005). Later we test the sensitivity of model predictions to the possibility that our Beverton–Holt model over-estimates stock productivity. We assume initially that bluefin become sexually mature at age 8 and later test the sensitivity of the results to this assumption. Later, we also adapt eqn 1 to test the sensitivity of model predictions to different assumptions about mixing of bluefin tuna of Western and Eastern Atlantic origin on their North West Atlantic feeding grounds (Rooker *et al.* 2008). The population dynamics for yellowfin are given by a model with a similar structure to that in eqn 1 but one that tracks cohorts aged 0 to 5_+.

Fishery mortality rates for bluefin depend on an individual's exposure to the different fleets during its annual migration. We use a behavioural model to track bluefin population dynamics within a year based on results in Block *et al.* (2005) and Teo *et al.* (2007a). Let $\tau \in [0,1]$ represent time within a season and $B_t^i(\tau)$ and $Y_t^i(\tau)$ denote the numbers of bluefin and yellowfin aged i at the start of year t that are still alive at time τ. By definition, $s_t^i = B_t^i(1)/B_t^i(0)$ for $i = 1 - 10_+$. We assume that each sexually mature bluefin tuna of Western Atlantic origin enters the Gulf of Mexico once to spawn during the course of the year. The most detailed study to date of bluefin spawning migrations provides movement data on 28 individuals tagged with pop-up or archival tags that entered the Gulf of Mexico during the spawning season (Block *et al.* 2005; Teo *et al.* 2007a,b). All of these individuals displayed a single Gulf residency period in a spawning season and there was no evidence of Gulf exit and re-entry within the spawning season. We assume the date on which each individual enters the Gulf, τ_1, varies across the cohort. We assume the probability an adult bluefin enters the Gulf on a given date is independent of the entry decisions of other individuals and is independent across years. We assume this probability is given by the probability density function:

$$f_{\tau_1} = \begin{cases} \dfrac{6(\tau_1 - \tau_0)(\tau_T - \tau_1)}{(\tau_T - \tau_0)^3} & \text{if } \tau_1 \in [\tau_0, \tau_T] \\ 0 \quad \text{otherwise} \end{cases}. \qquad \text{eqn 2}$$

where τ_0 and τ_T are the first and last entry dates observed (Fig. 1a–c). After entering, we assume bluefin remain in the Gulf for a fixed period Δ before exiting and moving back onto their Atlantic feeding grounds. Therefore, the probability an individual bluefin is found in the Gulf at a given time τ is given by

$$p(\tau) = \text{Prob}[\tau_1 < \tau \leq \tau_1 + \Delta] \qquad \text{eqn 3}$$

(Fig. 1b). We assume an adult bluefin's spawning effort is distributed uniformly across its time in the Gulf.

Fishing strategies are differentiated in space and time with time–area management. To examine the usefulness of this strategy for managing bluefin bycatches, we allow the longline fishing year to be differentiated so that effort can be reduced around the time of

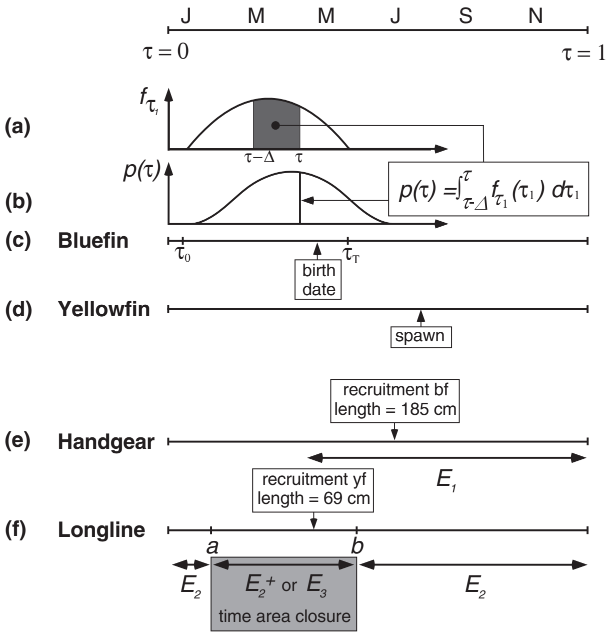

Fig. 1. Timing of events within a year. (a–c) The first date at which an adult bluefin might enter the Gulf of Mexico is denoted τ_0 and the final entry date by τ_T. (a) The timing of an individual's entry into the Gulf is determined by probability density function f_{τ_1}. (b) Because individuals are assumed only to remain in the Gulf for fixed period Δ, the probability an individual is in the Gulf at any given time $p(\tau)$ can be calculated by taking the area integral shown. (c) However, when calculating an individual's biomass, we assign all bluefin the same birth date. (d) Yellowfin are assumed to spawn later in the year than bluefin. (e) The handgear fishery opens in June and effort E_1 is then assumed to apply through to the end of the year. Bluefin aged 6 at the start of the calendar year recruit to the fishery in mid-July (by then aged 7). (f) The longline fishing year is differentiated into three time intervals [0,*a*],[*a*,*b*],[*b*,1]. The basic effort level E_2 applies on the first and last of these. But for a window of time surrounding bluefin spawning a reduced effort level E_3 can be applied around the bluefin spawning grounds and effort levels away from the spawning grounds may increase because of displaced effort.

bluefin spawning in an area encompassing the spawning grounds (Fig. 1f). The basic effort level for the Gulf longline fishery is E_2 (we use index 1 for the handgear fishery). We assumed that spawning bluefin occupy some fraction A of the Gulf longlining fishing grounds. Within this area, we assume a reduced effort level E_3 can be applied during time interval [*a*,*b*] which covers part of the time bluefin are in the Gulf. Parameter D describes the extent to which any surplus Gulf longlining effort can be displaced from the area where bluefin spawn and redistributed to other locations. The resulting effort level away from the bluefin spawning grounds is given by $E_2 + DA(E_2 - E_3)/(1 - A)$. In the analyses, we compared the full spectrum of possibilities including that the entire Gulf fishery would have to be shut to ensure bluefin were protected during spawning ($A = 1$) or that only a small fraction of the fishery would have to be shut ($A = 1/3$), and ranging from no redistribution of fishing effort being possible ($D = 0$) to a full redistribution of fishing effort ($D = 1$). In the main text, we show results for the simplest case where displaced effort does not incur additional fishing costs (e.g. for fuel). We test the sensitivity of including such costs in the Supporting Information (Scenario Sensitivity: Cost Scenarios).

We contrast two alternative scenarios. In the status quo case, we assume that fisheries mortality from other fleets continues at historical levels and we only focus on changes to management in the Gulf longlining and handgear fisheries. This scenario is intended to examine whether a time–area closure would be economically efficient if management practices by other nations and fisheries remained unchanged. However, past management practices have led to the long-term decline and continued overfishing of the bluefin population. To understand how the broader policy context and the role of population dynamics influences the economic efficiency of a time–area closure, we compare this scenario with one that examines what could be achieved through stronger regulation and greater cooperation among fisheries active in exploiting the bluefin population. To explore this opposing policy extreme, we switch off fisheries mortality on bluefin from other fleets thereby bringing all fisheries mortality on bluefin under the regulator's control; this is sometimes called a sole owner assumption in fisheries bioeconomics (Clark 1990). We refer to this scenario as the rebuilding case, because it allows the regulator to implement rebuilding policies for the bluefin population that could not be achieved if other fisheries continued to fish at their historical levels.

The profit from each fishery in a given year $R_i(t)$ equals the value of landings minus the cost of fishing effort. For example,

$$R_2(t) = \gamma\left(\sum_{i=8}^{10_+}\int_0^1 p_{b2}p(\tau)q_{b2}^i\hat{E_2}(\tau)w_{bi}(\tau)B_t^i(\tau)\,\mathrm{d}\tau + \sum_{i=1}^{5_+}\int_{u_{y2}^i}^{5_+} p_{y2}q_{y2}^i\hat{E_2}(\tau)w_{yi}(\tau)Y_t^i(\tau)\,\mathrm{d}\tau - \int_0^1 c_2\hat{E_2}(\tau)\,\mathrm{d}\tau\right) \qquad \text{eqn 4}$$

for the longline fishery. We use subscripts b and y to indicate parameters specific to bluefin and yellowfin respectively. Here $[p_{b2},p_{y2}]$ are the prices per kilogram of bluefin and yellowfin caught in this fishery and c_2 is the per trip cost. Labour costs in the longline fishery are handled using a share-based system with γ indicating the vessel owner's share of net revenues. In the Supporting Information (Scenario Sensitivity: Cost Scenarios), we describe how results change if instead assuming fixed labour costs. Physiological growth functions $w_{bi}(\tau)$ and $w_{yi}(\tau)$ give the mass of an individual in the *i*th cohort of bluefin and yellowfin at time τ. To simplify the presentation of eqn 4 only, we provided the expression for R_2 for the special case where $A = 1$ and the entire longline fishery is affected by any reduction in effort levels around the time of bluefin spawning, and used $\hat{E_2}(\tau)$ to denote the time varying effort level in the Gulf longline fishery that accounts for any reduction in fishing during bluefin spawning time. However, the analyses examine the full model that allows parts of the Gulf fishing grounds to remain open and fishing effort to be displaced ($A < 1$ and $D > 0$).

We calculated optimal equilibrial strategies for the status quo and rebuilding cases. First, we maximised the annual combined net revenue from the fisheries ($R_1 + R_2$), termed maximum economic yield or MEY, by optimising across E_1 and E_2. We also found equilibrial strategies that maximised the overall yield in biomass for bluefin (termed maximum sustainable yield or MSY). The lower bound on effort in each fishery was zero. To focus attention on incidental catches of bluefin, we assumed that a significant expansion of the longline fishery is unlikely and required that $E_2 \leq 1500$ trips per year. Later we tested the sensitivity of the results to this assumption.

Next we allowed differentiation of the fishing year within the Gulf by varying a and b across a fixed grid and seeking to maximise revenue through the choice of effort level in the handgear fishery E_1, the basic longlining effort level in the Gulf E_2, and the reduced longlining effort level that applies around the bluefin spawning ground E_3. To do this, we required that the fishing intensity inside any time–area management unit was no larger than that outside it ($E_3 \leq E_2$). Finally, if this analysis indicated that breaking up the fishing year in the Gulf could increase profits, as was the case for the rebuilding scenario, we optimised across all of a, b, E_1, E_2 and E_3 simultaneously. It is important to note that we did not require $E_3 = 0$, but rather allowed this result to emerge from the optimisation. That is, we examined optimal time–area management and for the rebuilding scenario found that it involved a time–area closure.

To find management strategies that will maximise profits over the long-term, we first solved for equilibrial solutions of the underlying population dynamic models in eqn 1, and then used constrained optimisation routines in Matlab to maximise profit summed across these outcomes numerically.

Results

We first present the long-run management strategies that maximise sustainable profit from the fisheries with no time–area management for the status quo case and the rebuilding case. Then, we compare these with the equivalent quantities for a hypothetical situation where there are no incidental catches of bluefin on Gulf longlines. These comparisons suggest when and why time–area closures will decrease or increase profits. We test this, by maximising profits across the fisheries when allowing a local reduction of longlining effort around bluefin spawning. Time–area closures are economically costly in the status quo case, but they can increase profits in the rebuilding case (Table 1). For the rebuilding case only, we report the characteristics of a time–area closure designed to maximise profits. We then test the sensitivity of all of these results to parameter estimates and different scenarios regarding important management issues for the fisheries. Length constraints preclude us from also including analyses of the role of discounting and a calculation of the optimal approach paths taken to approach long-term management outcomes.

EQUILIBRIAL TARGETS

Status quo case

When we assume mortality due to other fleets continues at historical levels, the maximum sustainable yield in biomass for bluefin from the longline and handgear fisheries combined is 504 mt dressed weight and is achieved with a bluefin spawning stock biomass of SSB = 7170 mt and an effort level in the handgear fishery of 53 700 trips year^{-1}.

In the status quo case, the maximum economic yield summed across the two fisheries occurs at a bluefin stock size more than two times larger than that maximising yield in bluefin biomass (column 2 in Table 2). At MEY, overall profit is dominated by the contribution from the Gulf longline fishery. In contrast, the commercial handgear fishery is only marginally profitable. Indeed, the bluefin spawning stock biomass corresponding to MEY is close to that giving open access conditions for the commercial handgear fishery, at which point positive rents are dissipated. Equilibrial open access conditions for the commercial handgear fishery occur with (SSB, Total Catch, Effort) = (13 900 mt, 229 mt, 9020 trips year^{-1}) when assuming the Gulf fishery continues at current effort levels. These open access conditions are computed by solving $R_1 = 0$ for E_1 in equilibrium. The commercial handgear fishery is only marginally profitable, because exogenous fishing mortality rates, which are assumed to be outside the control of the regulator, are already excessive.

Rebuilding case

Bluefin MSY from the two fisheries is much larger (bluefin MSY: (SSB, Catch, Effort) = (29 700 mt, 4160 mt, 110 000 trips year^{-1})) in the opposing policy scenario of very strong and coordinated regulatory control.

To facilitate comparisons between the rebuilding scenario and the status quo scenario, the contribution from the commercial handgear fishery in the rebuilding case should be rescaled by the fraction of the overall bluefin quota taken by vessels other than Gulf longliners that is caught in the handgear fishery. Recently, the commercial handgear fishery accounted for 24% of these catches. Rescaled values are given in parentheses in Table 2 when relevant. No rescaling is needed for comparisons within the rebuilding scenario.

The MEY summed across the two fisheries and including bluefin and yellowfin catches is achieved with a much larger spawning stock biomass and supports a larger commercial handgear fishery in the rebuilding case (column 4 in Table 2). Comparing the longline revenue plus 24% of the expanded handgear revenue in the rebuilding case to the MEY in the status quo scenario suggests that a rebuilt bluefin population would multiply annual revenue from these fisheries by a factor of 5·6. Furthermore, the contribution to overall revenues from the handgear fishery is now more than three times that from the longline fishery.

EFFECT OF INCIDENTAL CATCHES

To understand the consequences of incidental catches, we compared the MEY solution to a hypothetical scenario in which longlining in the Gulf results in no incidental catches of bluefin. To do this, we set the catchability of bluefin on Gulf longlines to zero (columns 3 and 5 in Table 2).

Status quo case

Overall revenues would decrease if there were no incidental catches in the status quo case. Revenues increase in the handgear fishery, but the increase is insufficient to offset the lost supplement to Gulf fishermen from incidental catches.

Rebuilding case

In contrast, incidental catches are economically costly when managing a rebuilt bluefin stock, as can be seen by comparing

	Status Quo		Rebuilding	
	MEY	MEY: no bf bycatch	MEY	MEY: no bf bycatch
Bf SSB (Th mt RW)	15·0	15·3	42·1	42·9
Bf HG Yield (mt DW)	69·5	123	3670 (865)	3840
Bf LL Yield (mt DW)	73·1	0	205	0
HG Effort (Th trips year^{-1})	3·6	6·3	69·5 (16·4)	71·5
LL Effort (Th trips year^{-1})	1·5	1·5	1·5	1·5
HG Profit (\$M year^{-1})	0·1	0·2	41·3 (9·7)	43·6
LL Profit (\$M year^{-1})	2·2	1·7	3·1	1·7
Total Profit (\$M year^{-1})	2·3	1·9	44·4 (12·8)	45·3

Table 2. Effect of incidental catches. Maximum economic yield (MEY) in status quo and rebuilding case (columns 2 and 4) and hypothetical MEY when there are no incidental catches (columns 3 and 5). Numbers in parentheses have been scaled by the current catch allocation of bluefin to the commercial handgear fishery

the overall MEY for the rebuilding scenario with the hypothetical case with no incidental catches. Therefore, management measures that reduce the incidental catch rate of bluefin on Gulf longlines will increase overall net revenues. The potential improvement such measures offer is bounded by the difference between the overall MEY with incidental catches (USD \$44·4 M) and the hypothetical MEY without them (USD \$45·3 M), and so cannot exceed more than 2% of the value provided by rebuilt bluefin fisheries.

TIME–AREA MANAGEMENT

Status quo case

Time–area management in the Gulf of Mexico provides one method for managing and reducing incidental catches of bluefin on pelagic longlines. No time–area management is optimal in the status quo case, because incidental catches increase overall profit. This finding is not sensitive to varying our assumptions about the distribution of bluefin in the Gulf, nor to what we assume about other key policy issues including: whether bluefin first mature at age 10 instead of 8; if the catchability of bluefin on Gulf longlines is significantly underestimated by logbook data; if the productivity of the bluefin stock is over-estimated by our choice of parameters; or if there is extensive mixing of bluefin tuna of Eastern Atlantic and Western Atlantic origin on their North West Atlantic feeding grounds.

Rebuilding case

Incidental catches are economically costly when managing a rebuilt bluefin stock and time–area management provides a possible means to reduce these costs. We first tested fixed windows of time for differentiating the Gulf fishing year, and found overall revenues increased when the fishing year was subdivided to recognise times when peak numbers of bluefin were present in the Gulf. We then computed economically efficient time–area management plans by simultaneously optimising net profits across possible dates for differentiating the Gulf fishing year, effort levels in each fishery, and effort levels for longlining inside the time–area management zone (Table 3). While we allowed for intermediate fishing intensities around the bluefin spawning grounds, optimal management plans typically involved closing this area to longlining altogether during the peak spawning period. The optimal timing for such closures encompassed the full period for which bluefin were in the Gulf only in special cases. More typically, optimal closures covered times when sufficiently many bluefin were present but not the tail ends of the spawning season (Table 3).

CHARACTERISTICS OF AN OPTIMAL TIME–AREA CLOSURE IN THE REBUILDING CASE

For the rebuilding case only, we examined the sensitivity of optimal time–area closures to the fraction of the longline fishing grounds that would need to be closed to encompass the area occupied by spawning bluefin (measured by parameter A) as well as to differing assumptions about the displacement of longline fishing effort (measured by parameter $D \in [0,1]$). In all circumstances, time–area closures were part of the economically optimal management strategy (Table 3). Combined revenues increase the smaller is the area of the Gulf that needs to be closed to protect spawning bluefin and the more readily longlining effort can be displaced outside this area, because the cost in forgone fishing opportunities for Gulf longliners is reduced (but see Supporting Information: Scenario Sensitivity: Cost Scenarios). These same conditions favour optimal time–area closures that cover a greater proportion of the time bluefin are present in the Gulf.

We examined how five bluefin management issues influenced the optimal time–area management strategy for the rebuilding case (Table 4). First, we explored the possibility that incidental catch rates of bluefin are higher than one would estimate based on self-reported logbook returns. Increasing the vulnerability of bluefin to Gulf longlines decreases overall net revenue and lengthens optimal time–area closures. Then, we explored the implications if bluefin matured at age 10 instead of age 8. This time, overall revenues diminished, reflecting the reduced productivity of the bluefin stock, but the efficiency and timing of the closure was unaffected. Next, we examined the possibility that effort in the Gulf longline fishery could expand significantly from current levels. This change also had no effect on the timing or efficiency of the closure. We also explored the possibility that the bluefin population might not be as productive as our basic parameter estimates suggest. Provided our

Table 3. Characteristics of the optimal time–area closure in the rebuilding scenario as we vary the proportion of the Gulf longline fishery that would need to be closed to encompass the bluefin spawning grounds, area A, and the proportion of fishing effort that can be displaced outside that area, D. No time–area closure is optimal in the status quo case

Area	$A = 1/3$				$A = 2/3$				$A = 1$
Displacement	D=0	1/3	2/3	1	D=0	1/3	2/3	1	N/A
Closure start a	01/18	01/18	01/09	01/01	01/26	01/18	01/18	01/01	02/26
Closure end b	06/21	06/21	06/30	07/09	06/01	06/21	06/21	07/09	05/17
HG effort (Th trips year^{-1})	71·8	71·5	71·5	71·5	71·4	71·5	71·5	71·5	70·8
LL effort (Th trips year^{-1})	1·5	1·5	1·5	1·5	1·5	1·5	1·5	1·5	1·5
LL time–area effort	0	0	0	0	0	0	0	0	0
Bf yield HG (mt DW)	3850	3840	3840	3840	3830	3840	3840	3840	3790
Bf yield LL (mt DW)	3·1	3·1	0·5	0	16·5	3·1	3·1	0	64.0
Yf yield LL (mt DW)	1320	1400	1470	1550	1180	1250	1400	1550	1200
HG profit ($M year^{-1})	43·6	43·6	43·6	43·6	43·4	43·6	43·6	43·6	42·9
LL profit ($M year^{-1})	1·4	1·5	1·6	1·7	1·3	1·3	1·5	1·7	1·7
Total profit ($M year^{-1})	45·0	45·1	45·2	45·3	44·7	44·9	45·1	45·3	44·6

basic parameter estimates did not greatly over-estimate stock productivity, a time–area closure continued to be efficient. However, if the productivity of the bluefin stock is reduced sufficiently, the trade-off between forgone longlining revenues and increased bluefin productivity eventually reverses and a time–area closure is no longer efficient. Finally, we tested how model predictions changed under different assumptions about mixing of bluefin tuna of Eastern and Western Atlantic origin on their North West Atlantic feeding grounds (Rooker *et al.* 2008). A time–area closure remains part of the optimal management strategy in the rebuilding case even when assuming that there is extensive mixing currently but that the ongoing stock collapse in the East Atlantic population will greatly reduce future in-migration of Eastern origin fish to the North-West Atlantic.

PARAMETER SENSITIVITY

We tested the sensitivity of our findings further by considering small perturbations to all parameter estimates. We tested the sensitivity of the optimal strategy to each parameter individually and to errors in all parameters at once. Our key findings regarding optimal time–area management, namely that restrictions of fishing effort in the Gulf are not warranted economically in the status quo case but would be economically optimal in the rebuilding case, are unusually robust to small perturbations to parameters (Supporting Information: Parameter Sensitivity). Other predictions of the models, such as those concerning how large a handgear fishery is economically desirable, can show more sensitivity to parameter uncertainty (Supporting Information: Parameter Sensitivity, Supporting Table 2).

Table 4. Effect of five policy scenarios (logbooks underestimate incidental catches, bluefin mature at age 10, longline fishery can expand from present day size, bluefin stock productivity overestimated in the base case models, and there is extensive mixing of bluefin tuna of Western Atlantic and Eastern Atlantic origin on the North West Atlantic feeding grounds) on optimal time–area closures for the rebuilding scenario shown for the situation where $A = 1$ and the whole longline fishery must be shut to protect spawning bluefin. No time–area closure is optimal in the status quo case

	Basic rebuilding	High catchability	Mature at 10	Increased LL effort	$(\hat{\alpha}, \hat{\beta}) = 0{\cdot}85(\alpha, \beta)$	$(\hat{\alpha}, \hat{\beta}) = 0{\cdot}75(\alpha, \beta)$	Mixing E. Atl. collapse
Time–area closure (yr)							
Start date a	02/26	01/18	02/26	02/26	04/05	–	02/18
End date b	05/17	06/21	05/13	05/13	05/13	–	05/21
Effort (trips year^{-1})							
Handgear	70 800	71 400	68 100	70 200	65 200	60 500	77 500
LL normal	1500	1500	1500	3000	1500	1500	1500
LL time–area	0	0	0	0	0	–	0
Harvest (mt)							
Bf Handgear (DW)	3790	3840	3360	3730	3080	2610	3970
Bf LL (DW)	64·0	8·7	82·3	138	124	168	60·7
Yf	1200	860	1210	2410	1390	1550	1150
Profit (USD $M)							
Handgear	42·9	43·5	36·4	42·1	32·6	26·0	43·9
Longline	1·7	0·9	1·8	3·4	2·4	2·9	1·6
Total	44·6	44·4	38·2	45·5	35·0	28·8	45·5

Discussion

Conflicts arise in fisheries management because of the nonselective nature of many fishing gears, which result in catches of multiple species rather than a targeted catch. Recent technological advances and improvements in our understanding of species' life histories offer possible management solutions for these conflicts. Data from electronic tags have enabled us to delineate the particular times and places where stocks overlap and to identify where and when life stages such as spawning occur (Block *et al.* 2001, 2005). Also, Vessel Monitoring Systems, which are compulsory on US pelagic longlining vessels in the Atlantic, enable fishery managers to monitor where and when fishing is occurring. We present a case study that explores when and how spatial management measures made possible by these advances, such as time–area closures, can be deployed to maximise profits from fisheries. The case study examines the incidental catch of spawning bluefin tuna in the Gulf of Mexico by pelagic longline fishermen, who are primarily targeting yellowfin tuna.

We compare the economic benefits and costs of time–area closures in two different policy contexts. In the status quo case, the decision on whether to use a time–area closure is taken while assuming other nations will not change their existing fishery management policies. The rebuilding case provides the contrasting policy scenario in which there is strong, coordinated management of effort across the fisheries to rebuild the bluefin population. The two contrasting policy contexts themselves can be compared independently of any decisions regarding the specific Gulf management issue. For example, the relevant comparison for MEY is between values in column 2 of Table 2 and the bracketed values in column 4. Our basic results before examining time–area management suggest that the current status of the western Atlantic bluefin tuna stock is close to what would be expected under open access conditions. The handgear fishery is predicted to be at best marginally profitable in our status quo case in which other, mostly non-US, fleets continue to fish at their historical levels. This result is in accordance with the inability of US fishermen to catch their quota allocation in recent years. At the same time, these basic results also make clear the potential profitability of rebuilding the bluefin population, which we predict would increase overall revenues from the fisheries by 460%. The extent to which this profit can be realised of course is a question of whether the requisite strong and coordinated management could be achieved and how large would be the administrative costs of the multinational negotiations that this would demand. ICCAT was created in order to deliver this type of coordinated, multilateral management and has agreed rebuilding targets for the bluefin stock, but, thus far, has failed to set sufficiently conservative quotas and policies to achieve rebuilding.

In the Gulf, the specific recommendation about time–area management depends on the policy context examined. A time–area closure would be economically costly in the status quo case where the Gulf management decision is taken in isolation. In contrast, a time–area closure increases long-term profits in the rebuilding case. The maximum increase in value that a time–area closure can offer is approximately \$0·9 M per year.

It is worth comparing these results with the economic analyses of a Gulf time–area closure conducted by NMFS (2006). NMFS first estimated the likely change in catches with a closure based on the current distribution of catch per unit effort. No consideration was given to how species' population dynamics might respond to management actions, and as such, NMFS predictions will only apply over the short-term. NMFS multiplied the predicted changes in catch in biomass by ex-vessel prices and summed the totals across species to arrive at an overall cost estimate for different closure designs. NMFS then repeated this exercise under different assumptions regarding how longline fishing effort might be redistributed following a closure. The NMFS analysis ignores fishing costs, which can be substantial. Net revenues are much lower than the gross revenue estimates relied upon by NMFS. The NMFS analysis also ignores any economic benefits of time–area closures that might be realised either through growth of the stock or through improved conditions for other US fisheries. Because of these missing factors, our models predict that NMFS over-estimate the costs of time–area closures by a factor of 3·5–6·1. This prediction is based on comparing the net revenue when a closure is imposed in the status quo case in our model with NMFS estimates of costs of foregone catches of bluefin and yellowfin; the variation reflects different assumptions made by NMFS about prices and effort redistribution. Despite NMFS having substantially over-estimated the costs of a time–area closure, the overall outcome of the NMFS analysis agrees with the findings of our models. Over the short-term, we also find that time–area closures to protect spawning bluefin are likely to incur an economic cost. However, we find that time–area closures could offer limited economic benefits over the long-term as part of a larger commitment to rebuild the western Atlantic bluefin stock.

Model assumptions

Obviously, our model results depend upon the question we examined, assumptions we made and parameter estimates we used. For our study question, we evaluated time–area closures based on a criterion of maximising summed profits across fisheries. Other criteria for evaluating the policy are also considered in the decision-making process. For example, our capacity to manage the spatial distribution of fishing effort brings equity concerns into sharper focus. While our analyses highlight circumstances in which a time–area closure in the Gulf would be profit maximising for US fisheries in aggregate, either policy choice (closure or no closure) has distributional impacts on the fishing communities involved. With the current management regime (no closure), US fisheries outside the Gulf lose out, because a portion of the US bluefin quota is expended on incidental catches on Gulf longlines. Alternatively, if a closure were to be implemented Gulf fishermen would lose out, because of the lost bluefin catches and opportunity costs in forgone fishing opportunities for yellowfin. The distributional impacts of a Gulf closure warrant sensitive discussion, because participants in the Gulf longline fishery do not appear well integrated into coastal communities or fishery management meetings (NMFS 2006). These communities were also heavily impacted by Hurricanes Katrina and Rita in 2005 (NMFS 2006).

In this paper, we focused on long-term equilibrial outcomes and static optimisation and ignored the role of time preference (discounting). Our long-run predictions largely continue to determine the results when incorporating discounting and the time taken for the bluefin population to recover in the rebuilding case (P.R. Armsworth *et al*., unpublished results). However, if discount rates are large enough and the opportunity costs for Gulf fishermen in foregone fishing opportunities are big enough, time–area closure may no longer offer benefits even in the rebuilding case.

Focusing on the case of zero discounting considered here, a dynamic version of the models predicts that the optimal timing for implementing a time–area closure in the rebuilding case depends on the cost in terms of forgone fishing opportunities for Gulf longliners as determined by the area that must be closed to encompass the bluefin spawning grounds (A) and what is assumed about effort displacement (D). When these costs are small (A small and D large), then a time–area closure should be implemented immediately. However, if these costs are larger (large A and small D), then a time–area closure may only increase profits once sufficient rebuilding of the bluefin population has already taken place (P.R. Armsworth *et al*., unpublished results). The optimal rebuilding trajectory with a time–area closure only provides greater annual profits after 14–30 years than the optimal rebuilding trajectory in which Gulf longlining is assumed to continue at current effort levels, this variation in the profit schedule also being determined by parameters A and D.

Of our model assumptions, arguably the most important concerns the extent to which the fisheries can be regulated. We assumed effort levels in US fisheries can be controlled. To understand how assumptions about the broader policy context affect the outcome of any evaluation of time–area closures we compared two very different regulatory scenarios, one in which historical overfishing continues unchecked (status quo case) and one in which effort is tightly regulated in a bid to rebuild the bluefin population.

A second, important assumption is that we assume that if time–area management leads to a reduction in bluefin mortality in the Gulf, bluefin catches on Gulf longlines outside of the relevant time period and bluefin catches in other fisheries could increase to compensate. This outcome seems particularly likely in light of existing US legislation, under which NMFS are prohibited from setting lower overall quotas than those assigned by ICCAT. Instead, NMFS role is one of allocating the available quota between competing fishing interests. To account for other fisheries, we modelled the largest of the bluefin fisheries, the commercial handgear fishery off New England, which accounts for 50% of commercial catches in the US, explicitly. We then aggregated the impact of all other fisheries into exogenous sources of age-specific fishing mortality that we assumed were outside the regulator's control in the rebuilding case. Our results reflect differences in the ecological and economic characteristics of the longline and handgear fisheries, including the different ages of fish caught, the different prices for bluefin, and different trip costs involved in each fishery. If we had resolved the detail of additional bluefin fisheries more fully in the models, our results potentially could have been different. To test this possibility, we re-ran the basic MEY models for the status quo and rebuilding case while also modelling historically the next largest commercial US bluefin fishery (Atlantic purse seiners) explicitly. Our main conclusions that a time–area closure would be economically costly in the status quo case but would offer a small economic improvement (0·4% of the total value of the fisheries in the situation least favourable to a time–area closure ($A = 1$)) in the rebuilding case remained unchanged (Supporting Information: Scenario Sensitivity: Aggregation of Fisheries).

The parameter estimates are intended to be representative not definitive. Available data are less detailed for yellowfin than bluefin, and more data on the private costs of fishing would be particularly helpful. We provide detailed sensitivity analyses of the effects of all parameter estimates individually and in concert in the Supporting Information (Parameter Sensitivity). We also considered the implications of five scenarios of particular interest in bluefin management, reestimating all parameter values to account for the relevant scenario.

At the end of the day, however, one model can only do so much and assumptions have to be made. In the context of MEY approaches to fisheries management, this means that some benefits and costs will not be resolved as finely as they might and others may be left out altogether. In the Supporting Information (Scenario Sensitivity: Cost Scenarios), we test the sensitivity of model predictions to different assumptions about labour costs and increases in variable costs of fishing if time–area closures are implemented. However, we have not forecast future changes in prices and costs with the changing economic and policy climate (e.g. future fuel prices). We have also not yet accounted for capital adjustment costs, but we do not expect these to be large because recent effort levels in the overcapitalised handgear fishery already exceed those recommended in the more optimistic rebuilding case. One could take a position that MEY calculations are only useful if all possible benefits and costs are included. However, such a position is at odds with current practice in fisheries science and policy. For example, NMFS used an evaluation of some of the benefits and costs involved when ruling on a time–area closure in the Gulf. We have tested the effects of a number of the factors that the NMFS evaluation left out. Perhaps, the most useful way to interpret the type of MEY analyses that we have presented is as revealing the different directions in which previously neglected factors are pulling as well as providing an estimate of their relative magnitude and importance in determining the outcome of the policy evaluation process.

Conclusion

Technological advances and our improved understanding of the life history of target species have made increasingly precise fisheries management possible (Hobday & Hartmann 2006). In many developed fisheries, we are now well positioned to regulate both the species that are targeted and the life stages that are affected by fishing. However, these advances often have not been matched by the political will to regulate the fisheries in question. We have examined under what conditions a time–area closure to protect spawning bluefin tuna would increase fisheries profits. Importantly, even when a time–area closure is optimal, the overall economic improvement it provides over the best management action without such a closure is much smaller than the more elementary difference between allowing the stock to rebuild and allowing overfishing to continue. Indeed, while we have adopted an optimisation frame for our analyses, a simpler open access vision may well provide a more accurate description of the outcome of past management of the bluefin fisheries.

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Supporting Information

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

Additional Model Details provides more detail of the model formulation

Parameter Estimates details all base case parameter estimates in the model and how these were obtained

Sensitivity Analysis: Scenario Sensitivity provides more detail for the scenarios modelled in Table 4

Sensitivity Analysis: Scenario Sensitivity: Cost Scenarios details additional scenario sensitivity tests that consider costly effort displacement and changes to labour costs

Sensitivity Analysis: Scenario Sensitivity: Aggregation of Fisheries details additional sensitivity tests that optimise across effort levels in an additional fishery (US purse seiners)

Parameter Sensitivity: Individual Parameters details sensitivities and elasticities of different model predictions (optimal effort levels, SSB levels, catch levels and net revenues) to individual parameters

Parameter Sensitivity: All Parameters describes sensitivity tests that examine how predictions regarding the optimality of a time–area closure are affected by simultaneous perturbations to all parameters

Table S1. Biomass growth parameters

Table S2. Five largest elasticities to perturbations to model parameters for a range of model predictions