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The role of discounting and dynamics in determining the economic efficiency of time-area closures for managing fishery bycatch

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Abstract Time-area closures are commonly used to manage fisheries bycatch and involve temporarily closing an area of the ocean to particular fishing gears. We examine conditions in which implementing a time-area closure would increase the economic value of fisheries, focusing on a case study application in the Gulf of Mexico. Pelagic longline fishermen catch the highly valued Atlantic bluefin tuna (*Thunnus thynnus*, Scombridae) on their Gulf of Mexico spawning grounds while fishing for Atlantic yellowfin tuna (*Thunnus albacares*). We analyze a multispecies, multifishery bioeconomic model that includes information on migratory patterns from electronic tagged bluefin tuna. We use dynamic optimization to identify management strategies that would maximize the net present value of tuna fisheries, allowing for discounting of future benefits and costs relative to the present. If past fishing mortality rates continue in Atlantic bluefin tuna fisheries, implementing a time-area closure in the Gulf of Mexico incurs economic costs. However, the net present value of the fisheries is increased by implementing a time-area closure as part of a broader commitment to rebuild the heavily depleted bluefin population, provided the discount rate and the costs of such a closure in forgone fishing opportunities are not too large. The increase in economic value offered by a time-area closure is small relative to the overall economic value of rebuilding itself and it may be economically optimal only to implement a closure once sufficient rebuilding has already taken place.

Keywords Fisheries · Economics · Time-area closure · Longline · Bluefin tuna · Yellowfin tuna · *Thunnus thynnus* · *Thunnus albacares* · Gulf of Mexico · Discounting · Marine protected area

Introduction

Fisheries management increasingly involves spatially structured management strategies often facilitated by the use of Vessel Monitoring Systems. For neritic species with sedentary life stages, spatial management can take the form of permanent closures or zoning restrictions (Palumbi 2004; Fernandes et al. 2005; Crowder et al. 2006; Halpern et al. 2008). However, temporary measures, such as time-area closures,

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are often preferred for more mobile pelagic species (Hobday and Hartmann 2006; Grantham et al. 2008; Game et al. 2009). With a time-area closure, an area of the ocean is closed to fishing with particular fishing gears during certain time periods. Time-area closures are commonly used to manage spatially and temporally acute bycatch problems (Goodyear 1999). For example, the National Marine Fisheries Service (NMFS) in the USA uses time-area closures to manage bycatch of nontarget species and excessive catches of under-sized fish by Atlantic longlining vessels (NMFS 2006).

Despite their widespread use, few studies consider the economics of time-area closures while also accounting for the population dynamics of affected species. In contrast, many studies have examined the economic impacts (e.g. Holland and Brazee 1996; Sanchirico and Wilen 2001; Smith and Wilen 2003; Smith et al. 2010) and efficiency (e.g. Brown and Roughgarden 1997; Sanchirico et al. 2006; Costello and Polasky 2008; Neubert and Herrera 2008) of permanent, marine protected areas, often focusing on the impacts of marine reserves on a single, target species and a single fishery. Time-area closures impact catches of target species, non-target species that can be sold, and non-target species that do not have commercial value for fishermen. For commercially valuable catches, time-area closures provide a means for fishery managers to influence catch rates of different species by non-selective gears. Time-area closures can also be used to achieve a partial allocation of catches across space and potentially across fleets or sections of a fleet when managing highly migratory species, such as tunas. Studies of time-area closures focused on reducing non-saleable bycatch typically assume that implementing time-area closures will incur economic costs (e.g. Grantham et al. 2008). However, the policy case for implementing time-area closures will be stronger if they increase the profitability of fisheries. The use of time-area closures to steer fishing effort provides an obvious means by which time-area closures could offer economic benefits. Time-area closures have the potential to increase overall profits from fisheries if they help managers to allocate catches of commercially valuable species to gears, locations and times when prices for fish are higher, costs of fishing are lower and the ecological impacts of fishing on stocks are less severe (see Electronic Supplementary Material (ESM): Optimal Allocation for an analytical illustration of this point).

We examine a case study concerning whether a time-area closure provides an economically efficient management strategy for reducing incidental catches of Atlantic bluefin tuna (*Thunnus thynnus*, Scombridae) by pelagic longline fishermen in the Gulf of Mexico. These fishermen are principally targeting a second species, yellowfin tuna (*Thunnus Albacares*). In a related paper (Armsworth et al. (2010) henceforth ABER10), we use static optimization to examine the long-run economic efficiency of time-area closures for managing this Gulf bycatch problem. In that paper, we calculate management strategies that would produce the annual maximum economic yield (MEY) summed across fisheries in equilibrium. We show that whether time-area closures would increase MEY depends on what is assumed about strategies for rebuilding the heavily depleted bluefin population. If a time-area closure were imposed in isolation and recent effort levels elsewhere were maintained, the bluefin population could not rebuild and implementing a time-area would decrease MEY. However, a time-area closure would increase MEY if the bluefin population were allowed to rebuild.

Given the dependence of the Gulf management recommendation on what is assumed about rebuilding and that rebuilding the slow-growing bluefin population will take decades, it is important to examine how sensitive these long-run predictions are to what is assumed about how society trades off net revenues earned today relative to those earned sometime in the future. Typically, this is captured in bioeconomic models through the use of a discount rate; the higher the discount rate, the more future benefits and costs are discounted relative to those accruing today (Clark 1990; Armsworth and Roughgarden 2001; Goulder and Stavins 2002). In addition, it is important to understand what management actions are needed over the short-term to move towards long-term management objectives. Specifically, in those circumstances where a implementing a time-area closure in the Gulf of Mexico is predicted to be economically optimal, it is important to understand when the closure should first be implemented as part of a comprehensive plan to rebuild the bluefin population.

Our models focus on time-area closures, but draw on broader bioeconomic theories concerning the optimal management of multispecies fisheries and the optimal allocation of quotas among competing fishery interests (Bishop and Samples 1980; Murawski and Finn 1986; Clark 1990; Cook and McCaw 1996; Mesterton-Gibbons 1996; Armsworth and Roughgarden 2001; Matsuda and Abrams 2006). The most similar models to those that we present are designed to identify profit maximizing management strategies from other tuna fisheries (Bertignac et al. 2001; Pintassilgo and Costa Duarte 2002; Bjorndal and Brasao 2006), although none of these focuses specifically on the use of time-area closures. These deterministic simulation models use dynamic optimization to identify profit maximizing management strategies. Typically the management objectives of bodies governing fisheries will not be simply to maximize overall profits (Dichmont et al. 2010), something we return to in the "Discussion". However, determining the maximum profit that can be provided by fish stocks enables fishery managers to compute the cost to the public if alternative policies are chosen, perhaps ones designed to meet particular ecological objectives or to protect jobs in particular fishing communities.

Case study

We focus on the management of US fisheries exploiting Atlantic bluefin tuna (henceforth bluefin). Bluefin tuna command high prices and are prized catches in many fisheries (Carroll et al. 2001; Martinez-Garmendia and Anderson 2005). As a consequence, the management of Atlantic bluefin tuna is contentious (Safina 1998; Sissenwine et al. 1998; Fromentin and Powers 2005; Porch 2005; Safina and Klinger 2008). International tuna management in the Atlantic is the responsibility of the International Commission for the Conservation of Atlantic Tunas (ICCAT); NMFS implements ICCAT recommendations within US waters and for US flagged vessels.

Electronic tagging has revealed information about the behavior of Atlantic bluefin tuna on their foraging and spawning grounds (Block et al. 2001, 2005; Teo et al. 2007a, b; Walli et al. 2009). The western fishery is a mixed stock assemblage with fish from the Gulf of Mexico and the Mediterranean Sea mixing on the foraging grounds. Tagging has shown that some adult Atlantic bluefin tuna leave their foraging grounds in the NorthWest Atlantic and enter the Gulf of Mexico in the late Winter and Spring to spawn (Block et al. 2001, 2005). Bluefin prefer deeper slope waters in the northern Gulf for spawning (Teo et al. 2007a, b). ICCAT closed the Gulf of Mexico to directed fishing for bluefin in 1982 to protect the spawning stock. However, bluefin are now caught as bycatch in the Gulf by pelagic longline fishermen targeting Atlantic yellowfin tuna (henceforth yellowfin). Bluefin catches on longlines in the Gulf of Mexico averaged 100.4 mt between 2004 and 2008 (NMFS 2009). Longline fishermen are permitted to retain some incidentally caught bluefin for sale. Yellowfin are distributed more widely in the Gulf of Mexico and are caught there all year round (Power and May 1991; Teo and Block 2010). Bluefin caught on Gulf longlines fetch lower prices per kilogram than those caught on their NorthWest Atlantic foraging ground; yellowfin catches fetch lower prices still (ESM: Model Parameters). There have been calls for NMFS to prohibit the use of longline gear in an area encompassing the bluefin spawning grounds when peak numbers of bluefin are present in the Gulf (NMFS 2006; USDC DC 2008).

The spawning stock biomass of Western Atlantic bluefin tuna is estimated to have declined by 82% since 1970 (ICCAT 2009a). The population is overfished and overfishing continues (Sissenwine et al. 1998; NMFS 2006). In the 1970s, catches averaged 5,000 mt, with much of this being taken by a Japanese longline fishery in the Gulf of Mexico. Bluefin catches averaged around 2,500 mt for 25 years following the closure of the Gulf to directed fishing, with the USA catching around 55–60% of this total (ICCAT 2009a). In the past 5 years, US bluefin fisheries have collapsed; in 2006–2008, they caught less than 25% of their allocated quota and in 2009, the US fisheries caught less than 40% of their allocated quota. The US Atlantic yellowfin catch accounts for only 4–6% of the total Atlantic yellowfin catch (ICCAT 2009b), with a quarter to a third of this being taken by longliners in the Gulf of Mexico.

In 2006, NMFS published a review indicating that a time-area closure of the Gulf of Mexico longline fishery was not justified (NMFS 2006). NMFS partly based its evaluation on the likely economic impacts of a closure. NMFS analyses made a number of simplifying assumptions. For example, the NMFS study took no account of the population dynamics of the species involved or of the cost of fishing. NMFS also assumed bluefin catches in fisheries outside the Gulf would not increase to offset the reduction of catches in the Gulf longline fishery resulting from a time-area closure. US law precludes NMFS from setting lower overall bluefin catch quotas than those recommended by ICCAT; instead NMFS's role is one of allocating quotas among competing fisheries interests, making some quota reallocation a likely accompaniment to any time-area closure. In ABER10, we examined how an evaluation of the economic impacts of a time-area closure would be affected by including these factors but focused only on long-run equilibrial outcomes. We also ignored discounting. Here, we examine whether the inclusion of discounting can change model predictions and we determine the short-term management actions needed to move towards long-run management goals.

Methods

We outline the model structure here and summarize parameter values in the ESM: Model Parameters.

Additional details are given in ABER10 and the Supporting Information for that paper, including the results of extensive sensitivity testing.

Our model accounts for the population dynamics of both bluefin and yellowfin. The interannual population dynamics for each species is given by an age-structured, discrete time population model with Beverton-Holt stock-recruitment dynamics in which the oldest individuals are aggregated in a plus class. For example, the dynamics for bluefin are given by

$$B^1_{t+1} = \frac{\alpha_b \,\mathrm{SSB}^b_t}{\beta_b + \mathrm{SSB}^b_t}\,, \qquad B^{i+1}_{t+1} = s^i_t B^i_t \quad \text{for} \quad i \in \{2, ..., 9\}$$
$$B^{10+}_{t+1} = s^9_t B^9_t + s^{10+}_t B^{10+}_t\,, \tag{1}$$

where the plus class for bluefin contains individuals aged 10 years and older; α_b and β_b are bluefin stock-recruitment parameters; B^i_t is the abundance of bluefin aged i at the start of year t; SSB^b_t is the spawning stock biomass of bluefin and s^i_t the survival rate of bluefin in that year. The initial abundance of each species in each age class is taken from recent stock assessments based on the estimated abundance in 2003 hindcast from catches of fish that have subsequently grown to enter the fishery.

We use a behavioral submodel to track bluefin survivorship within a year based on the exposure of individuals to fishing by different fleets (Fig. 1). The submodel accounts for variation in when individuals enter and exit the Gulf of Mexico and are exposed to Gulf longlining based on data from satellite and archival tagging studies (Block et al. 2001, 2005, Teo et al. 2007a, b). We assume bluefin mature at age 8 years; we test the sensitivity of the models to a later bluefin maturation age in ABER10. We assume each year a sexually mature resident Western Atlantic bluefin tuna enters the Gulf once to spawn. We assume that the date an individual first enters the Gulf (τ_1) is a random variable from a distribution having the probability density function

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

where τ_0 and τ_T specify the first and last entry dates in the cohort (Fig. 1). We assume this probability is independent of the entry decisions of others and is independent across years. We assume individuals remain in the Gulf for a fixed period Δ. We use $\tau \in [0, 1)$ to measure time within a year. The probability an individual is in the Gulf at time τ is given by

$$p(\tau) = \mathrm{Prob}[\tau_1 < \tau \leq \tau_1 + \Delta] \tag{3}$$

(Fig. 1). We assume that an individual's spawning effort is distributed uniformly during its time in the Gulf with intensity $1/\Delta$,

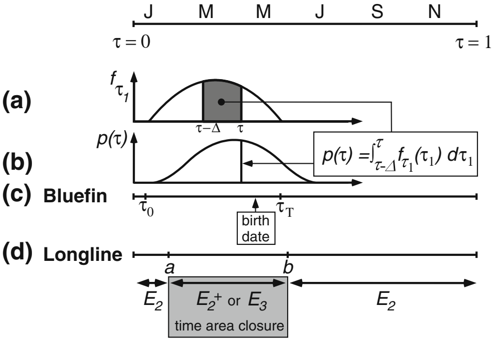


Fig. 1 Timing of events in the Gulf of Mexico. Timelines illustrating model assumptions about how Atlantic bluefin tuna spawning behavior in the Gulf of Mexico interacts with the time-area management decision for the Gulf longline fishery. **a** Probability density function describing the probability that an individual mature bluefin will enter the Gulf on a given date. **b** Resulting probability that a mature bluefin is found in the Gulf on a given date under the assumption that individuals only enter the Gulf once per year and have a fixed residency after entering. **c** Parameters τ_0 and τ_T govern the first and last dates on which bluefin enter the Gulf. All individuals within the cohort are assigned the same birth date for the purposes of calculating individual biomass at age later in life. **d** The Gulf of Mexico longline fishery operates year round at effort level E_2. The optimization allows for the possibility that effort levels can be reduced in time interval $[a, b]$ in an area surrounding the bluefin spawning ground (to level E_3), but that effort may be displaced outside this area (giving a higher effort level, indicated by E_2^+)

$$\mathrm{SSB}^b_t = \sum_{i=8}^{10+} \int_0^1 \frac{1}{\Delta} p(\tau) w_{bi}(\tau) B^i_t(\tau) \mathrm{d}\tau\,. \tag{4}$$

The optimization maximizes profits through the choice of effort levels in two fisheries, one representing the Gulf longlining fleet. The other fishery is included to capture possible benefits for other US fisheries of the Gulf management decision and any resulting bluefin quota reallocation. We use a parameterization for historically the largest of the commercial bluefin fisheries, the commercial handgear fishery off New England. We use subscript 1 to indicate variables and parameters associated with this fishery, e.g., effort in the handgear fishery in year t is denoted $E_1(t)$. The New England handgear fishery opens on June 1st, and we assume that bluefin that were aged 6.6 years on January 1st enter the handgear fishery in mid-July (then aged 7.2 years). We treat bluefin and yellowfin mortality due to fishing by other fleets as exogenous to the optimization. In ABER10, we show that model results regarding the use of a time-area closure are not sensitive to making the management of additional fleets endogenous to the optimization.

To allow the possibility of time-area management, we allow the Gulf fishing year to be differentiated in space and time (Fig. 1). We break the annual fishing calendar in the Gulf longline fishery into three time periods $[0, a)$, $[a, b)$ and $[b, 1)$ defined by parameters $a, b \in (0, 1)$. The basic effort level in the Gulf longline fishery is denoted E_2. During time period $[a, b)$, we allow a reduced effort level $E_3 \leq E_2$ to be applied in some fraction A of the Gulf fishing grounds that contains the bluefin spawning area. By reducing effort around the bluefin spawning grounds, $A(E_2 - E_3)$ units of surplus effort are created. We assume that a proportion D of this surplus effort can be reallocated to other longline fishing areas (having combined area $1 - A$). Therefore, the intensity of longline fishing away from bluefin spawning during period $[a, b)$ is given by $E_2 + DA(E_2 - E_3)/(1 - A)$ when expressed in trips per unit area per unit time. We present results for the full range of possibilities ranging from only small areas needing to be set aside to encompass the bluefin spawning grounds ($A = 1/3$) to fishing effort across the entire Gulf fishery having to be reduced to protect spawning bluefin ($A = 1$) and ranging from no effort displacement ($D = 0$) to full and free effort displacement ($D = 1$). We discuss the implications of our assumptions about effort displacement and alternative formulations in the "Discussion".

Pulling these assumptions together, and assuming catch rates are proportional to fishing intensity, the intra-annual population dynamics for bluefin are given by

$$\frac{\mathrm{d}B_t^i}{\mathrm{d}\tau} = \begin{cases} -Z_b^i B_t^i(\tau) \quad \text{for} \quad i = [1-5]\,, \\ -(Z_b^i + q_{b1}^i E_1 \chi_{[u_{b1}^i, 1]}(\tau)) B_t^i(\tau) \quad \text{for} \quad i = [6, 7]\,, \\ -(Z_b^i + (1-p) q_{b1}^i E_1 \chi_{[u_{b1}^i, 1]}(\tau) \\ \quad + p q_{b2}^i \hat{E}_2(\tau)) B_t^i(\tau) \\ \text{for} \quad i = [8 - 10_+]\,, \end{cases} \tag{5}$$

where $s_t^i = B_t^i(1)/B_t^i(0)$. Here, Z_b^i is the exogenous mortality of bluefin aged i comprising both natural mortality and fishing mortality imposed by other fleets; q_{b1}^i and q_{b2}^i are the catchability coefficients for bluefin in the commercial handgear fishery and on Gulf longlines respectively; $\chi(\tau)$ is a characteristic step function acting to switch on fishery mortality based on the date within a season u_{b1}^i when each cohort recruits to the handgear fishery either because the season opens or because individuals reach the lower size threshold for the gear; and $\hat{E}_2(\tau) = E_2 \chi_{[0,a)}(\tau) + E_3 \chi_{[a,b)}(\tau) + E_2 \chi_{[b,1)}(\tau)$ uses characteristic functions to describe the time varying longline fishing intensity in the Gulf experienced by adult bluefin. The Gulf residency probability $p(\tau)$ determines when adult bluefin are exposed to Gulf longlining versus fishing on the North-West Atlantic feeding ground.

For yellowfin, we extend these notations in the obvious fashion. For example for the special case where $A = 1$, intraseasonal dynamics are given by

$$\frac{\mathrm{d}Y_t^i}{\mathrm{d}\tau} = \begin{cases} -Z_y^i Y_t^i(\tau) \quad \text{for} \quad i = 0\,, \\ -(Z_y^i + q_y^i \hat{E}_2(\tau) \chi_{[u_{y2}^i, 1]}(\tau)) Y_t^i(\tau) \quad \text{for} \quad i = [1 - 5_+]\,. \end{cases}, \tag{6}$$

where Y_t^i is the abundance of yellowfin aged i. The dynamics for the more general case ($A < 1$) are similar but must account for spatially differentiated fishing mortality. We also assume that yellowfin spawning occurs in August each year (Lang et al. 1994).

To set the Gulf management decision in the wider context of bluefin management, we compare two alternative policy scenarios. In one termed the *status quo* scenario, we examine the implications of the Gulf management decision if taken unilaterally by NMFS. Specifically, we optimize across effort levels in the handgear fishery and Gulf longline fishery, but we assume fishing mortality rates from other fisheries external to the optimization (including Canadian and Japanese fisheries) continue at their historical levels. The *rebuilding* scenario examines the alternative policy extreme in which the Gulf manage decision is taken as part of a wider program of rebuilding measures. This time, we switch off exogenous sources of fisheries mortality, in effect bringing all fisheries mortality under the control of the regulator and the optimization. This is sometimes referred to as a sole owner assumption in fisheries bioeconomics (Clark 1990). In our case study, this assumption allows a regulator to realize increased long-run profits by implementing more conservative management actions that rebuild the bluefin population. Revenue increases that are possible in the rebuilding scenario are partly due to rebuilding of the bluefin stock and partly due to the commercial handgear fishery taking over the catch allocation of fisheries now left out of the model. To control for this latter effect and to enable comparisons between the status quo and rebuilding scenarios, we provide a rescaling based on the recent catch allocation to the commercial handgear fishery when required.

We examine profit maximization as a management objective. Fishery profits are determined by the dockside value of landings of bluefin and yellowfin assuming constant prices within each fishery minus the cost of fishing effort including labor costs. This gives annual net revenue functions R_1 for the commercial handgear and R_2 for the longline fishery

$$\begin{aligned}
R_1(t) &= \sum_{i=6}^{7} \int_{u^i_{b1}}^{1} p_{b1} q^i_{b1} E_1(t) w_{bi}(\tau) B^i_t(\tau) e^{-\rho\tau}\, \mathrm{d}\tau \\
&\quad + \sum_{i=8}^{10+} \int_{u^i_{b1}}^{1} p_{b1}(1-p(\tau)) q^i_{b1} E_1(t) w_{bi}(\tau) B^i_t(\tau) e^{-\rho\tau}\, \mathrm{d}\tau \\
&\quad - \int_{u_{b8}}^{1} c_1 E_1(t) e^{-\rho\tau}\, \mathrm{d}\tau \\
R_2(t) &= \gamma \left(\sum_{i=8}^{10+} \int_{0}^{1} p_{b2} p(\tau) q^i_{b2} \hat{E}_2(\tau) w_{bi}(\tau) B^i_t(\tau) e^{-\rho\tau}\, \mathrm{d}\tau \right. \\
&\quad + \sum_{i=1}^{5+} \int_{u^i_{y2}}^{5+} p_{y2} q^i_{y2} \hat{E}_2(\tau) w_{yi}(\tau) Y^i_t(\tau) e^{-\rho\tau}\, \mathrm{d}\tau \\
&\quad \left. - \int_{0}^{1} c_2 \hat{E}_2(\tau) e^{-\rho\tau}\, \mathrm{d}\tau \right) \qquad (7)
\end{aligned}$$

where (p_{b1}, p_{b2}, p_{y2}) are the prices of bluefin in the handgear fishery, bluefin in the longline fishery and yellowfin in the longline fishery respectively; (c_1, c_2) are the per trip costs of fishing in each fishery; parameter γ accounts for the fact that labor costs in the longline fishery are handled through a share-based system (Larkin et al. 2000); and other notations are extended in the obvious fashion. The functions w_{bi} and w_{yi} describe biomass growth of individuals with age (ESM: Model Parameters); we attribute all bluefin the same spawning date for growth purposes to simplify dynamics (Fig. 1). We have given these equations for the special case where $A = 1$. Similar expressions apply when $A < 1$, but additional terms are needed to deal with the separation of yellowfin catches inside and outside the Gulf of Mexico time-area management zone, A. The annual revenue terms account for discounting within the year (the $e^{-\rho\tau}$ terms) with ρ being the continuous time discount rate. We sum the annual discounted profits from the fisheries overall to arrive at a measure of the combined net present value of the fisheries,

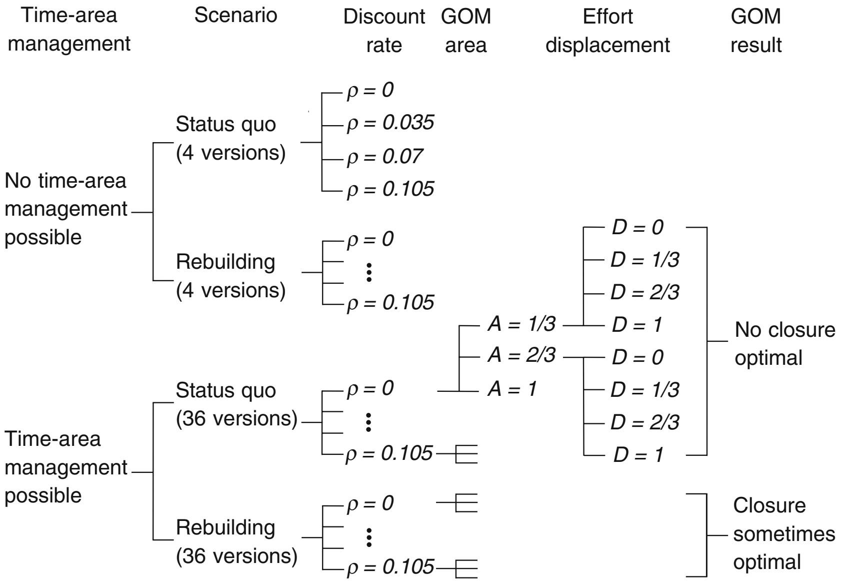
$$V = \sum_{t=0}^{T} (R_1(t) + R_2(t)) e^{-\rho t}. \qquad (8)$$

and it is this quantity that we seek to optimize. We show results for a range of discount rates, including the case of no discounting $\rho = 0$ for completeness. When $\rho = 0$, V does not converge to a finite limit as T increases and is simply the total revenue accumulated by time T. The state variable dynamics (Eq. 1) still converge to equilibrium when $\rho = 0$.

We use constrained optimization routines in Matlab to identify time-varying management strategies that maximize the net present value of the fisheries (Eq. 8). We only allow new effort levels to be set once every 8 years, i.e., once per bluefin generation, to account for policy inertia. In the "Discussion", we review the appropriateness of restricting the control set in this way, the sensitivity of model predictions to so doing and alternative formulations that we could have adopted. Once the new long-term outcome is reached, we assume an equilibrial effort level in each fishery is applied from that time forward. Specifically, we simultaneously optimize across $E_i(t)$ for fisheries $i = 1 - 3$ and time periods $t = 1 - 8, 9 - 16, 17 - 24, 25 - 32$ years and from year 33 onwards, truncating the population dynamics after 100 years. By assuming the final management decision applies sustainably from year 33 forward, we preclude the optimal solution from cashing in the stock by harvesting to open access levels at the end of the time horizon of interest. Repeating the optimizations but pushing out this terminal time past 100 years did not change the results. We assumed that a significant expansion of the Gulf longline fishery is unlikely and therefore applied a constraint that $E_2 \leq 1,500$ trips per year; in ABER10, we show that the outcome of the evaluation of the effectiveness of a time-area closure is not sensitive to changing this maximum effort level. Despite the use of characteristic step functions to differentiate the fishing year, the objective function in Eq. 8 is smooth in all control variables.

To simplify the analyses, we used fixed windows of time for differentiating the Gulf fishing year. In the status quo scenario, we varied these dates over a fixed grid and optimized across time varying effort levels to see whether a differentiated fishing year offered an improvement over one that was not broken up in this way. However, as described below, no differentiation of the Gulf fishing year was optimal in the status quo scenario. For the rebuilding scenario, differentiating the fishing year to allow time-area management sometimes allowed an increase in the net present value of the fisheries. In this case, we still treated (a, b) as fixed across years but used optimal timings for differentiating the fishing year that were obtained from the static optimizations without discounting in ABER10 (ESM: Table S6). These optimal timings vary across the

Fig. 2 Model contrasts. Scenario and parameter combinations contrasted in this paper. We review model results for 80 parameter combinations that span questions regarding the policy scenario examined and the interaction of the discount rate ρ with area and displacement parameters (A and D) that together determine the cost of a time-area closure in forgone fishing opportunities for Gulf longliners



different parameter combinations that we consider and typically cover the time when peak numbers of bluefin are in the Gulf but not the tail-ends of the spawning season, as illustrated in Fig. 1.

Figure 2 summarizes the sets of models and sources of parameter variation that we emphasize in this paper. Specifically, we focus on the implications for the Gulf management decision of the assumed policy scenario (status quo versus rebuilding), and the interaction of the choice of discount rate (ρ) with the fraction of the longline fishing grounds that would need to be closed to protect spawning bluefin (A) and how freely effort can be displaced outside this area (D), two parameters that govern how costly a time-area closure would be in terms of foregone fishing opportunities for longliners. In addition, we benchmark the results when time-area management is possible against those obtained when assuming the Gulf fishing year cannot be differentiated in this way.

Results

Long-run outcome

We first concentrate on the long-run outcome implemented in the fifth generation and applied from that time forward. When the discount rate is zero, these long-run dynamics are analogous to the equilibrial results presented in ABER10. With a zero discount rate, the long-run profit maximizing management strategy never involves a time-area closure in the status quo scenario where mortality from other fleets external to the optimization is assumed to continue at historical rates. However, a time-area closure is always part of the long-run profit maximizing solution in the rebuilding scenario when there is no discounting, irrespective of the area of the Gulf that must be closed to encompass the bluefin spawning ground (parameter A) or how easily longlining effort is displaced from this area (parameter D) as illustrated in Fig. 3 (cells highlighted with a solid border). While the optimization allows for intermediate effort levels to be employed around bluefin spawning ($0 \leq E_3 \leq E_2$), the long run profit maximizing management strategy always involves a full closure ($E_3 = 0$) in the rebuilding scenario with $\rho = 0$.

When we include positive discount rates, the long-run recommendation in the Gulf in the status quo scenario remains unchanged; time-area management in the Gulf never forms part of the profit maximizing management strategy and imposing a time-area closure to protect spawning bluefin would incur an overall economic cost, the size of which depends on the duration and size of the closure. The economic benefits available to directed bluefin fisheries from reallocating catches if implementing a closure in the Gulf are insufficient to offset the costs of foregone Gulf fishing opportunities. With the profit maximizing solution in the status quo scenario, Gulf longliners continue to catch substantial bluefin bycatches and a small and marginally profitable handgear fishery operates (Table 1).

The long-run outcome for the rebuilding scenario with positive discount rates is parameter dependent (cells highlighted with dashed border in Fig. 3). If the discount rate is small and costs in foregone fishing opportunities for Gulf of Mexico longliners, as specified

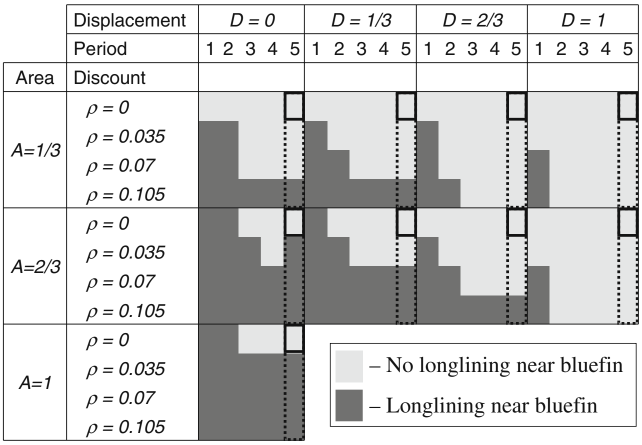


Fig. 3 Gulf of Mexico management recommendation around bluefin spawning time in the rebuilding scenario. No time-area closure is optimal in the *dark cells* in the grid. The area surrounding the bluefin spawning grounds should be closed during the peak bluefin spawning season in the *light cells*. The grid shows this outcome across five time periods (Periods 1 to 5 correspond to years 1–8, 9–16, 17–24, 25–32, and 33–100) with the long-run recommendation that applies from year 33 onwards highlighted with *solid and dashed lines*. The outcome is shown for four discount rates ($\rho = [0, 0.035, 0.07, 0.105]$) and parameter scenarios ranging from a small fraction ($A = 1/3$) of the longline fishing grounds having to be close to encompass the bluefin spawning grounds with effort freely displaced outside this area ($D = 1$) to the entire Gulf fishery having to be closed to protect spawning bluefin ($A = 1$). No time-area closure is optimal in the status quo scenario

by the area (A) and displacement (D) parameters, are small (top right in Fig. 3), then a time-area closure forms part of the long-run optimal management strategy. However, if the discount rate and costs incurred in forgone fishing opportunities are larger then a closure may no longer form part of the long-run profit maximizing management strategy (bottom left in Fig. 3). For a time-area closure to maximize profits, the bluefin stock must be large enough that the increased value to directed bluefin fisheries of preventing bycatches on Gulf longlines outweighs the costs to the longline fishery. The optimal long-run stock size of bluefin gets smaller as the discount rate increases (Table 1). If the optimal stock size becomes small enough then the balance of benefits and costs regarding a closure tips, because of the diminished benefits to the directed bluefin fisheries. Thus, no closure is optimal over the long term for large discount rates and sufficiently costly closures (large A, small D). The long run outcome in the rebuilding scenario involves much larger directed bluefin fisheries than in the status quo scenario (weighted values in parentheses in Tables 1 and 2) and larger bluefin catches in Gulf as well in those cases where no time-area closure is optimal (e.g., Table 1, Rebuilding scenario with $\rho = 0.105$).

The expectation from single species harvesting theory would be that the long-run spawning stock biomass of bluefin corresponding to the profit maximizing strategy would decrease as the discount rate increases (Clark 1990). This expectation is realized in the rebuilding scenario where increasing discount rates lead to reductions in the optimal size of the bluefin population over the long-run (Table 1, Fig. 4), although substantial rebuilding of the bluefin population from present-day levels is recommended even for large discount rates. In contrast, the effect of the discount rate on optimal bluefin population sizes in the status quo scenario is very limited (Table 1, Fig. 4). Increasing

Table 1 Long-term annual catch in each fishery, the long-term stock size in each species, and net present value of each fishery resulting from the profit maximizing management strategy when $(A, D) = (2/3, 2/3)$ for status quo and rebuilding scenarios with a range of discount rates, $\rho = [0, 0.035, 0.07, 0.105]$

	Harvest(T) mt (DW)				SSB(T) Th mt (RW)		Net present value $ M				
	Handgear		Bf LL	Yf LL	Bf	Yf	Handgear		LL	Total	
Status quo											
$\rho = 0$	74.5		72.7	1,550	14.9	145	4.5		218	223	
$\rho = 0.035$	79.2		72.4	1,550	14.9	145	0.5		61.5	62.0	
$\rho = 0.07$	85.6		72.1	1,550	14.8	145	0.1		32.3	32.4	
$\rho = 0.105$	92.1		71.7	1,550	14.7	145	0.0		21.9	21.9	
Rebuilding											
$\rho = 0$	4,020	(945)	2.8	1,400	38.2	146	3,660	(862)	152	3,810	(1,014)
$\rho = 0.035$	4,110	(966)	2.5	1,400	34.5	146	690	(162)	49.1	739	(212)
$\rho = 0.07$	4,150	(978)	2.2	1,400	30.8	146	229	(53.9)	32.0	261	(85.9)
$\rho = 0.105$	4,020	(945)	134	1,550	27.5	145	102	(24.0)	24.7	127	(48.7)

Values in parentheses have been rescaled by the past catch share of bluefin by the commercial handgear fishery ("Methods") to facilitate comparisons between the two scenarios. When $\rho = 0$, the NPV is just the summed net revenue accumulated over the 100-year time horizon

Table 2 Profit maximizing effort levels in the commercial handgear fishery (E_1), baseline effort level in the Gulf longline fishery (E_2) and effort levels in the Gulf longline fishery in an area encompassing the bluefin spawning grounds during peak spawning time (E_3) for five time periods with the final effort levels applying over the long-term (periods 1–5 corresponding to years 1–8, 9–16, 17–24, 25–32, 33–100)

	E_1 Th trips year^{-1}					E_2 Th trips year^{-1}					E_3 Th trips year^{-1}				
Period	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Status quo															
$\rho = 0$	0	0	0	0	3.9	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
$\rho = 0.035$	0	0	0	0	4.2	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
$\rho = 0.07$	0	0	0	0	4.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
$\rho = 0.105$	0	0	0	0	4.9	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Rebuilding															
$\rho = 0$	0	5.3 (1.2)	65.3 (15.4)	59.9 (14.1)	83.3 (19.6)	1.5	1.5	1.5	1.5	1.5	0	0	0	0	0
$\rho = 0.035$	0	37.5 (8.8)	85.1 (20.0)	87.3 (20.6)	93.8 (22.1)	1.5	1.5	1.5	1.5	1.5	1.5	0	0	0	0
$\rho = 0.07$	0	61.9 (14.6)	100 (23.6)	103 (24.4)	106 (24.9)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	0	0	0
$\rho = 0.105$	0	83.4 (19.6)	111 (26.1)	112 (26.4)	114 (26.8)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5

Effort levels shown for a range of discount rates, $\rho = [0, 0.035, 0.07, 0.105]$, for the status quo and rebuilding scenarios for the case where area and displacement parameters are $(A, D) = (2/3, 2/3)$. Effort levels in parentheses have been rescaled by the past catch share of bluefin by the commercial handgear fishery ("Methods") to facilitate comparisons between the two scenarios

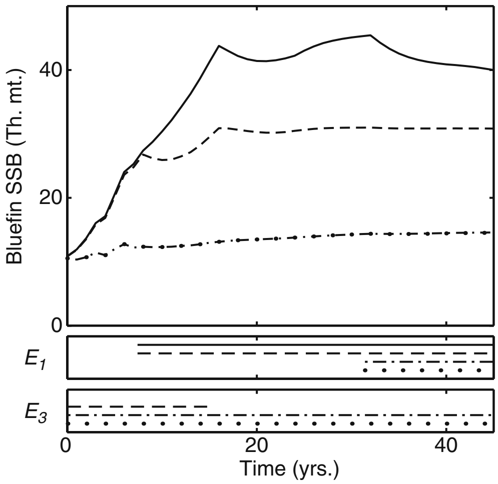


Fig. 4 Projected spawning stock biomass (SSB RW) of bluefin under optimal management. *Upper panel*: projected SSB for bluefin corresponding to optimal management from dynamic optimization when $(A, D) = (2/3, 2/3)$ for rebuilding scenario (*solid and dashed*). Same for status quo scenario (*dot-dash and dots*, which are very similar). For *solid and dot-dash*, the discount rate $\rho = 0$. For *dashed and dots*, $\rho = 0.07$. *Second panel* shows when handgear fishery should operate—a *line* indicates that the fishery is operating at that time in the optimal strategy. The fishery should be closed initially to allow some rebuilding in all cases. It should be reopened sooner for the rebuilding scenario (*solid and dashed*) than the status quo scenario (*dot-dash and dots*). The *bottom panel* shows when a time-area closure is optimal. The Gulf should be closed around bluefin spawning time ($(a, b) = (0.05, 0.47)$) each year when $\rho = 0$ in the rebuilding scenario (absence of *solid line* means no fishing optimal). When $\rho = 0.07$, a time-area closure should only come into effect once the bluefin population has rebuilt sufficiently (*dashed*). In the status quo scenario, a time-area closure is never optimal (*dot-dash and dots*)

the discount rate from 0 to 0.105 leads to the long-term spawning stock biomass decreasing by 28% in the rebuilding scenario but only by 1.3% in the status quo scenario. The lack of impact of the discount rate on the optimal bluefin population size in the status quo scenario arises because of the high level of mortality on bluefin already imposed by fisheries exogenous to the optimization. Currently, these exogenous mortality rates are so high that the difference between the bluefin biomass supporting MEY (equivalent to a discount rate of zero) and that corresponding to open access conditions (equivalent to an infinite discount rate) is relatively small (ABER10), meaning there is little scope for major changes in the optimal bluefin biomass to result from an increase in the discount rate.

Approach path

Optimal short-term management actions can differ from those recommended over the long-run in dynamic harvesting models. We observe a temporal shift in the management recommendation for the Gulf for many parameter combinations in the rebuilding scenario (Fig. 3). Specifically, even if a time-area closure forms part of long-run management strategy, often one should only be implemented once sufficient rebuilding of the bluefin population has taken place and longlining around the bluefin spawning grounds should be allowed to continue until this time (Figs. 3 and 4). In contrast, the Gulf management recommendation for the status quo scenario (never implement a closure) is consistent through time, as it is for parameter combinations in the rebuilding scenario that either strongly favor (top right in Fig. 3) or disfavor (bottom left in Fig. 3) a closure (implement a closure right away and never implement a closure, respectively).

In both the status quo and rebuilding scenarios, the management recommendation for the directed bluefin fisheries (here represented by the New England commercial handgear fishery) is the same: a short-term moratorium of directed bluefin fisheries should be implemented to allow rebuilding (Table 2, Fig. 4). In the status quo scenario, the current bluefin stock is predicted to be depleted to the point that a moratorium in directed bluefin fisheries would be profit improving for the USA, even if one were imposed unilaterally. The results for the rebuilding scenario suggest that a shorter moratorium would be needed and would be much more effective at increasing profitability of directed bluefin fisheries if other nations and fisheries (e.g., Canadian and Japanese fisheries catching bluefin tuna from the Western Atlantic spawning stock) would also commit to more conservative management to allow rebuilding. After this short-term closure, fishing effort gradually expands in directed bluefin fisheries in the optimal strategy (Table 2).

The models can be used to estimate the economic benefits of rebuilding irrespective of the particular management actions taken in the Gulf. To do this, we compare the combined net present value of the fisheries in the status quo and rebuilding scenario when no time-area management is permitted and $E_2 = E_3$, applying the weighting factor described in the "Methods" needed to allow such a comparison. Rebuilding increases the net present value of the fisheries by a factor of 2.2 to 5.0 depending on the discount rate. In ABER10, we estimated that rebuilding would increase annual profits by a factor of 5.6. Including discounting and shifting the emphasis from long-run annual profits to net present value, which integrates revenues across the entire time course of rebuilding, reduces the overall estimate of the economic value of rebuilding. However, rebuilding the bluefin population still clearly would offer very substantial economic gains. In contrast to the overall value of rebuilding, the increase in net present value of the fisheries offered by implementing a time-area closure over that offered by the optimal strategy when no time-area management is possible is small when compared with the overall value of the rebuilt fisheries themselves (0–1.9%).

If implementing a closure, foregone costs in Gulf longline catches are experienced right away. Benefits from enhanced profits from directed bluefin fisheries accrue later, once sufficient rebuilding has taken place. Increasing the discount rate has the effect of weighting short-term costs more strongly relative to long-term gains. As such, the relative contribution made by the Gulf longline fishery to the overall net present value of the fisheries increases as the discount rate increases (Fig. 5).

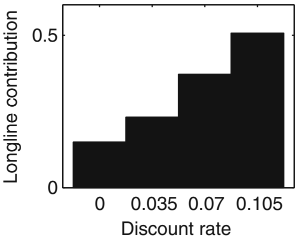


Fig. 5 Proportion of the net present value of the fisheries that derives from the Gulf of Mexico longline fishery. Proportion of the combined net present value of the longline and the commercial handgear fisheries in the rebuilding scenario contributed by the longline fishery for different discount rates ($\rho = [0, 0.035, 0.07, 0.105]$). The contribution to overall net present value from the handgear fishery is weighted by the past catch share of this fishery ("Methods"). Results shown for the case where area and displacement parameters $(A, D) = (2/3, 2/3)$

Discussion

Time-area closures can offer net economic benefits when they provide a means to allocate catches to fisheries that exploit stocks more profitably (ESM: Optimal Allocation). The case study concerns the management of incidental catches of spawning Atlantic bluefin tuna by longline fishermen targeting a second species, yellowfin tuna, in the Gulf of Mexico. The case study reveals conditions under which a time-area closure in the Gulf would increase the combined net present value of the fisheries involved. In our particular example, implementing a time-area closure would increase the value of the fisheries only under some conditions and the available profit improvement is small relative to the overall value of the fisheries involved.

The model predictions about the economic optimality of a time-area closure depend on the parameters and scenarios considered (Fig. 2). The bluefin population is currently heavily depleted and if the Gulf decision is taken in isolation while fishing elsewhere continues at historical intensities, then implementing a time-area closure would incur net economic costs. This prediction is in agreement with the overall recommendation by NMFS regarding a time-area closure in this region (NMFS 2006). On the other hand, if there were a broader commitment to rebuild the bluefin population through reduced quotas in the North Atlantic, then a time-area closure in the Gulf of Mexico would increase overall profits across fisheries exploiting bluefin tuna further, provided the impacts on the Gulf fishery and the discount rates employed to devalue future benefits and costs were not too large. We first reported a contingent outcome for the Gulf management question in ABER10 based on long-run, equilibrial results that ignored discounting. Here, we have extended those analyses to consider the implications of discounting and to evaluate the management outcome over the full time path taken to arrive at any equilibrial outcomes, which is important given the current, depleted state of the bluefin population. The conditions on parameters and assumptions for which a time-area closure would improve profits are more stringent when the management objective is to maximize the combined net present value of the fisheries than they are when the goal is to achieve equilibrial MEY. When aiming for equilibrial MEY, a time-area closure is predicted always to be optimal in the rebuilding case (solid cells in Fig. 3; ABER10). However, a time-area closure only sometimes forms part of the optimal management plan in the rebuilding scenario when the management objective is to maximize net present value of the fisheries (Fig. 3). Moreover, in this situation, even if a time-area closure would increase long-run profits, one may only be implemented once sufficient rebuilding has already taken place (Fig. 3). Finally, the relative economic benefit provided by the optimal management strategy that allows for a time-area closure over the optimal strategy that does not, which was already small when aiming for equilibrial MEY, is reduced further when aiming to maximize the net present value of the fisheries, because the costs of a closure are front-loaded relative to the benefits that accrue as rebuilding proceeds.

The intuition behind the contingent outcome that we find (a time-area closure would be costly in the status quo scenario but could increase the combined net present value of the fisheries in the rebuilding scenario) is rooted in a comparison of the relative profitability of the different fisheries involved and in the nature of incidental catches, which are neither valueless bycatch nor as valuable as catches in the directed fisheries. While bluefin are heavily depleted, directed bluefin fisheries remain relatively unprofitable. In the status quo scenario, it is more economical to allow Gulf longliners to continue to catch bluefin. Although bluefin caught in the Gulf fetch lower prices, the cost of fishing for them is effectively zero, because it exploits joint production savings available through the non-selective nature of the longlining gear (see ESM: Incidental Catches for an analytical illustration of this point). However, were bluefin allowed to rebuild, directed bluefin fisheries would become much more valuable. In this instance, the net value of an individual fish to the directed bluefin fisheries becomes greater than it is to a Gulf longliner, even when accounting for the cost savings made possible by nonselective gear (ESM: Incidental Catches).

The relative profitability of the longline fishery and directed bluefin fisheries changes along the rebuilding path. As the bluefin population increases, the directed bluefin fisheries become relatively more profitable. This leads to the prediction that even in cases where a time-area closure forms part of the long-run profit-maximizing solution one might only be implemented once sufficient rebuilding has already taken place (Fig. 3). This economic prediction contrasts with suggestions to implement a time-area closure in order to allow rebuilding to proceed (USDC DC 2008). Indeed, running the models for the status quo scenario while setting all bluefin mortality in the Gulf longline fishery and New England commercial handgear fishery to zero makes clear that the key to rebuilding the bluefin population will be reducing overall fishing mortality rates in the North Atlantic (imposed exogenously in the status quo scenario) rather than specific management recommendations implemented in either of these fisheries in isolation. This result is similar to recent findings of Taylor et al. (unpublished data) that consider different mixing scenarios between the western Atlantic and eastern Atlantic bluefin populations.

The model allows an estimation of the economic value of rebuilding irrespective of the particular management actions taken in the Gulf. When moving attention from equilibrial annual revenues (ABER10) to the net present value of the fisheries, the economic value of rebuilding diminishes, but still remains considerable; a commitment to rebuilding would increase the value of the fisheries by a factor of 2.2 to 5.0, depending on how future benefits and costs are weighted relative to those experienced today. Smaller discount rates lead to larger estimates of how much more valuable the fisheries would be with a commitment to rebuilding.

The dynamic optimization predicts the short-term management measures in the North Atlantic that would maximize the combined net present value of the fisheries. One prediction that warrants further exploration is that a moratorium for targeted bluefin fisheries in the North Atlantic (represented in the models by the commercial handgear fishery) would increase the net present value of the fisheries for both the status quo and rebuilding scenarios. Bioeconomic models commonly predict that aggressive short-term management actions that move towards desired long-run outcomes more quickly would maximize the net present value of fisheries (Clark 1990). Had we assumed the price of bluefin was endogenously determined in the models, the management prediction may have been less severe (e.g., a large quota reduction rather than a full moratorium), but, nonetheless, aggressively conservative short-term management would still likely have maximized profits, particularly given the relatively small global market share of bluefin tuna accounted for by the fisheries in question. While a moratorium is predicted to maximize the combined net present value of the fisheries in the status quo scenario, the economic contribution that a moratorium offers is limited, because the potential value of the depleted handgear fishery remains relatively small without a broader commitment to rebuild the bluefin population by reducing catches elsewhere. The potential economic contribution of implementing aggressive, short-term rebuilding measures in directed bluefin fisheries would be much larger, and the period for which catches and effort levels would need to be suppressed much shorter, if more conservative rebuilding measures were implemented across the board by all fisheries targeting western Atlantic bluefin tuna.

We have emphasized the role of discounting and dynamics and their interaction with key factors influencing the benefits and costs of a closure. More extensive sensitivity testing of the model predictions to parameter variation and particular scenarios of interest to bluefin management are presented in ABER10. During the bluefin spawning season, the spatial distribution of catch-per-unit-effort of bluefin and yellowfin in the Gulf of Mexico is such that yellowfin catches could be, at least partially, maintained while avoiding or minimizing bluefin bycatch (Teo and Block 2010). We examined how recommendations regarding the economic impact of a time-area closure were influenced by different assumptions about the degree to which yellowfin catches could be maintained while protecting spawning bluefin by varying the size of the time-area management unit and displacement of fishing effort from this area. We tested a range of parameters spanning small closures ($A = 1/3$) with free and costless displacement ($D = 1$) to a complete closure of the Gulf longline fishery ($A = 1$). The overall recommendation in the status quo case that a time-area closure would be economically costly is unaffected by these parameters, although they do influence just how costly implementing a closure would be. For the rebuilding case, Fig. 3 demonstrates how assumptions about the size of the time-area management unit and ease of effort displacement interact with the choice of discount rate to determine the recommendation about a time-area closure. In ABER10, we test the sensitivity of model predictions to different assumptions regarding additional costs (e.g., for fuel) incurred when fishing effort is displaced. The results of these sensitivity tests are bounded by the spectrum of possibilities examined here. More spatially resolved predictions about effort displacement could in principle be given by a behavioral economic model of fishing location choices of individual vessels, as has been used to study longlining in the Pacific fleet (Curtis and Hicks 2000) as well as other types of fishery (Hiddink et al. 2006). The outcomes one would expect from embedding such a submodel within the population dynamic models that we present will be bounded by the range of scenarios that we already consider. Species other than bluefin tuna, including white marlin, blue marlin and leatherback turtles, are caught as bycatch when fishing for yellowfin tuna with longline gear (NMFS 2006). Importantly, analyses of different scenarios for the spatial redistribution of displaced effort following any closure designed to reduce bycatch rates of bluefin tuna in the Gulf predict that bycatch rates for other non-target species could be increased (NMFS 2006; Powers and Abeare 2009). This prediction highlights the importance of additional trade-offs when examining what is a multi-faceted policy decision.

In the optimizations, we allowed effort levels in the fisheries to be set once per bluefin generation (every 8 years) rather than every year during rebuilding and we required that a steady state effort level be applied after four generations. In an earlier version of the model, we allowed effort levels to be set every year. The optimal solution for this prototype model was characterized by chattering control or pulse fishing in which effort levels jumped between high and low levels in alternating years (see also Clark 1990; Bjorndal and Brasao 2006). Our assumption of sluggishness in the policy variables precludes this possibility, which we do not feel offers an achievable policy recommendation for these fisheries. The TAC for bluefin tuna set by ICCAT has been characterized by long periods of stasis in the quota (e.g., 1983–1993, 1997–2002, 2003–2006), despite large variations in spawning stock biomass (including a halving of the stock size in the 1980s). Core predictions of our analyses are not sensitive to varying the frequency with which the control variables can be changed from 4–12 years, nor to changing the time after which steady state controls are assumed to apply provided this occurs after at least three bluefin generations in the rebuilding case. An alternative approach would have been to model sluggishness in the policy explicitly. The only formulation of which we are aware to do this is that of Ludwig (1980) who applied variable costs to changes to policies through time. Ludwig's formulation predicts smooth transitions between policies rather than the periods of stasis interspersed with discrete step changes that have characterized Atlantic bluefin tuna management. Thus, a model formulation that accounted for both fixed and variable costs involved in renegotiating multilateral policy agreements might be more appropriate. To parameterize such a model, one would obviously require estimates of the transaction costs of these negotiations.

Our model focuses on the overall net present value of implementing a time-area closure as realized by its impacts on Atlantic bluefin tuna and yellowfin tuna. Of course, this is only one measure against which a policy would be evaluated. The impacts on other species and on different fishing communities would also be considered (NMFS 2006). For example, when a time-area closure is optimal in the rebuilding case, the net present value of the Gulf longline fishery in isolation is smaller with a closure than it would have been in the absence of a closure, while the net present value of the New England handgear fishery is increased, which emphasizes the importance of distributional concerns. However, the distribution of the cost burden through time during rebuilding reveals a more complicated picture. For many parameter combinations, a time-area closure would only be implemented after sufficient rebuilding had already taken place, where this rebuilding was achieved by imposing strict catch limitations on fisheries in the North Atlantic. Therefore, the short-term cost of implementing the optimal management strategy would fall on fisheries elsewhere, and Gulf fishing communities would, if anything, benefit initially from the optimal management plan. Later on, the distribution of benefits and costs reverses with Gulf fishing communities losing revenue with fishing communities elsewhere gaining as a result.

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References

Armsworth PR, Roughgarden JE (2001) An invitation to ecological economics. Trends Ecol Evol 16:229–234

Armsworth PR, Block BA, Eagle J, Roughgarden JE (ABER10) (2010) The economic efficiency of a time-area closure to protect spawning bluefin tuna. J Appl Ecol 47:36–46

Bertignac M, Campbell HF, Hampton J, Hand AJ (2001) Maximizing resource rent from the Western and Central Pacific tuna fisheries. Marine Res Econ 15:151–177

Bishop RC, Samples KC (1980) Sport and commercial fishing conflicts—a theoretical analysis. J Environ Econ Manage 7:220–233

Bjorndal T, Brasao A (2006) The East Atlantic bluefin tuna fisheries: stock collapse or recovery? Marine Res Econ 21:191–210

Block BA, Dewar H, Blackwell SB, Williams TD, Prince ED, Farwell CJ, Boustany A, Teo SLH, Seitz A, Walli A, Fudge D (2001) Migratory movements, depth preferences, and thermal biology of Atlantic bluefin tuna. Science 293:1310–1314

Block BA, Teo SLH, Walli A, Boustany A, Stokesbury MJW, Farwell CJ, Weng KC, Dewar H, Williams TD (2005) Electronic tagging and population structure of Atlantic bluefin tuna. Nature 434:1121–1127

Brown GM, Roughgarden J (1997) A metapopulation model with private property and a common pool. Ecol Econ 22:65–71

Carroll MT, Anderson JL, Martinez-Garmendia J (2001) Pricing U.S. North Atlantic bluefin tuna and implications for management. Agribusiness 17:243–254

Clark CW (1990) Mathematical Bioeconomics: the Optimal Management of Renewable Resources, 2nd edn. Wiley, New York

Cook BA, McCaw RL (1996) Sport and commercial fishing allocations for Atlantic salmon fisheries of the Miramichi River. Can J Agric Econ 44:165–171

Costello C, Polasky S (2008) Optimal harvesting of stochastic spatial resources. J Environ Econ Manage 56:1–18

Crowder LB, Osherenko G, Young OR, Airame S, Norse EA, Baron N, Day JC, Douvere F, Ehler CN, Halpern BS, Langdon SJ, McLeod KL, Ogden JC, Peach RE, Rosenberg AA, Wilson JA (2006) Resolving mismatches in U.S. ocean governance. Science 313:617–618

Curtis R, Hicks RL (2000) The cost of sea turtle preservation: the case of Hawaii's pelagic longliners. Amer J Ag Econ 82:1191–1197

Dichmont CM, Pascoe S, Kompas T, Punt AE, Deng R (2010) On implementing maximum economic yield in commercial fisheries. Proc Natl Acad Sci USA 107:16–21

Fernandes L, Day J, Lewis A, Slegers S, Kerrigan B, Breen D, Cameron D, Jago B, Hall J, Lowe D, Innes J, Tanzer J, Chadwick V, Thompson L, Gorman K, Simmons M, Barnett B, Sampson K, De'ath G, Mapstone B, Marsh H, Possingham H, Ball I, Ward T, Dobbs K, Aumend J, Slater D, Stapleton K (2005) Establishing representative no-take areas in the Great Barrier Reef: large-scale implementation of theory on marine protected areas. Conserv Biol 19:1733–1744

Fromentin JM, Powers JE (2005) Atlantic bluefin tuna: population dynamics, ecology, fisheries and management. Fish Fish 6:281–306

Game ET, Grantham HS, Hobday AJ, Pressey RL, Lombard AT, Beckley LE, Gjerde K, Bustamante R, Possingham HP, Richardson AJ (2009) Pelagic protected areas: the missing dimension in ocean conservation. Trends Ecol Evol 24:360–369

Goodyear CP (1999) An analysis of the possible utility of time-area closures to minimize billfish bycatch by US pelagic longlines. Fish Bull US 97:243–255

Goulder LH, Stavins RN (2002) An eye on the future: discounting. Nature 419:673–674

Grantham HS, Petersen SL, Possingham HP (2008) Reducing bycatch in the South African pelagic longline fishery: the utility of different approaches to fisheries closures. Endanger Species Res 5:291–299

Halpern BS, McLeod KL, Rosenberg AA, Crowder LB (2008) Managing for cumulative impacts in ecosystem-based management through ocean zoning. Ocean Coast Manag 51:203–211

Hiddink JG, Hutton T, Jennings S, Kaiser MJ (2006) Predicting the effects of area closures and fishing effort restrictions on the production, biomass, and species richness of benthic invertebrate communities. ICES J Mar Sci 63: 822–830

Hobday AJ, Hartmann K (2006) Near real-time spatial management based on habitat predictions for a longline bycatch species. Fisheries Manag Ecol 13:365–380

Holland DS, Brazee RJ (1996) Marine reserves for fisheries management. Mar Res Econ 11:157–177

International Commission for the Conservation of Atlantic Tunas (ICCAT) (2009a) Report of the 2008 ICCAT bluefin stock assessment session. ICCAT Collective Volume of Scientific Papers 64:1–352

International Commission for the Conservation of Atlantic Tunas (ICCAT) (2009b) Report of the 2008 ICCAT yellowfin and skipjack stock assessments meeting. ICCAT Collective Volume of Scientific Papers 64:669–927

Lang KL, Grimes CB, Shaw RF (1994) Variations in the age and growth of yellowfin tuna larvae, *Thunnus albacares*, collected about the Mississippi River plume. Environ Biol Fisches 39:259–270

Larkin SL, Adams CM, Lee DJ (2000) Reported trip costs, gross revenues, and net returns for U.S. Atlantic pelagic longlining vessels. Mar Fish Rev 62:49–60

Ludwig D (1980) Harvesting strategies for a randomly fluctuating population. J Conseil Int Explor Mer 39:168–174

Martinez-Garmendia J, Anderson JL (2005) Conservation, markets, and fisheries policy: the North Atlantic bluefin tuna and the Japanese sashimi market. Agribusiness 21:17–36

Matsuda H, Abrams PA (2006) Maximal yields from multispecies fisheries systems: rules for systems with multiple trophic levels. Ecol Appl 16:225–237

Mesterton-Gibbons M (1996) A technique for finding optimal two-species harvesting policies. Ecol Model 92:235–244

Murawski SA, Finn JT (1986) Optimal effort allocation among competing mixed-species fisheries, subject to fishing mortality constraints. Can J Fish Aquat Sci 43:90–100

National Marine Fisheries Service (NMFS) (2006) Final consolidated Atlantic highly migratory species fishery management plan. National Oceanic Atmospheric Administration, National Marine Fisheries Service, Office of Sustainable Fisheries, Silver Spring, MD

National Marine Fisheries Service (NMFS) (2009) Annual report of the United States of America to ICCAT. National Oceanic Atmospheric Administration, National Marine Fisheries Service, Office of Sustainable Fisheries, Silver Spring, MD

Neubert MG, Herrera GE (2008) Triple benefits from spatial resource management. Theor Ecol 1:5–12

Palumbi, SR (2004) Marine reserves and ocean neighbourhoods: the spatial scale of marine populations and their management. Annual Review of Environment and Resources 29:31–68

Pintassilgo P, Costa Duarte C (2002) Optimal management of the Northern Atlantic bluefin tuna. Marine Res Econ 17:47–67

Porch CE (2005) The sustainability of western Atlantic bluefin tuna: a warm-blooded fish in a hot-blooded fishery. Bull Mar Sci 76:363–384

Power JH, May LN Jr. (1991) Satellite observed sea-surface temperatures and yellowfin tuna catch and effort in the Gulf of Mexico. Fish Bull US 89:429–439

Powers JE, Abeare SM (2009) Fishing effort redistribution in response to area closures. Fish Res 99:216–225

Safina C (1998) Song for the Blue Ocean: Encounters Along the World's Coasts and Beneath the Seas. Henry Holt, New York

Safina C, Klinger DH (2008) Collapse of bluefin tuna in the Western Atlantic. Conserv Biol 22:243–246

Sanchirico JN, Wilen JE (2001) A bioeconomic model of marine reserve creation. J Environ Econ Manage 42:257–276

Sanchirico JN, Malvadkar U, Hastings A, Wilen JE (2006) When are no-take zones an economically optimal fishery management strategy? Ecol Appl 16:1643–1659

Sissenwine MP, Mace PM, Powers JE, Scott GP (1998) A commentary on Western Atlantic bluefin tuna assessments. Trans Am Fish Soc 127:838–855

Smith MD, Wilen JE (2003) Economic impacts of marine reserves: the importance of spatial behavior. J Environ Econ Manage 46:183–206

Smith MD, Lynham J, Sanchirico JN, Wilson JA (2010) Political economy of marine reserves: understanding the role of opportunity costs. Proc Natl Acad Sci USA. doi:10.1073/pnas.0907365107

Teo SLH, Block BA (2010) Comparative influence of ocean conditions on yellowfin and Atlantic bluefin tuna catch from longlines in the Gulf of Mexico. PLoS ONE 5(5):e10756. doi:10.1371/journal.pone.0010756

Teo SLH, Boustany A, Dewar H, Stokesbury MJW, Weng KC, Beemer S, Seitz AC, Farwell CJ, Prince ED, Block BA (2007a) Annual migrations, diving behavior, and thermal biology of Atlantic bluefin tuna, *Thunnus thynnus*, on their Gulf of Mexico breeding grounds. Mar Biol 151:1–18

Teo SLH, Boustany AM, Block BA (2007b) Oceanographic preferences of Atlantic bluefin tuna, *Thunnus thynnus*, on their Gulf of Mexico breeding grounds. Mar Biol 152:1105–1119

United States District Court for the District of Columbia (USDC DC) (2008) Blue Ocean Institute v. Gutierrez, 585 F. Supp. 2d 36 (DDC 2008)

Walli A, Teo SLH, Boustany A, Farwell CJ, Williams T, Dewar H, Prince E, Block BA (2009) Seasonal movements, aggregations and diving behavior of Atlantic bluefin tuna (*Thunnus thynnus*) revealed with archival tags. PLoS ONE 4(7):e6151. doi:10.1371/journal.pone.0006151