Penalties and rewards for over- and underages of catch allocations

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Many fisheries are managed using a total allowable catch (TAC) that is subsequently sub-allocated to different fisheries sectors. These allocations are then monitored separately to ensure the adherence of each fishery to its particular allocation quota and to the overall TAC. In some management arenas, there are systems of "payback" where over- and underages are punished or rewarded using particular decision rules. Differences between fishing gear, the sizes and ages of fish being targeted by those gears, and the spatio-temporal distribution of the fishers using those gears can lead to different precision, accuracy, and cost of monitoring the allocation, affecting the probability that an overall management objective is reached. Weaknesses in monitoring may be exploited by user groups in their competition for larger catches and, subsequently, bigger allocations, so differential monitoring precision and accuracy can lead to both short- and long-term reallocations, i.e. a new set of winners and losers. Simulations in a management strategy evaluation framework were used to demonstrate the implications of alternative decision rules regarding payback on conservation and sustainability objectives and rebuilding time frames. The efficacy of the rules under alternative monitoring systems was also examined. Decision rules allowing payback prolong rebuilding (compared with perfect implementation or more precautionary TACs), especially if monitoring is biased (catches misreported) or imprecise. When precision of reported catches was increased and/or bias decreased, better yields and stock abundance resulted. When overages were penalized and underages not rewarded, recovery was achieved earlier. Conversely, policies in which transgressions were ignored and underages rewarded did not perform well. Underreporting by one nation may result in stocks that are well below the stock size conservation standards, yet produce substantial gains in yield for that nation, unless other nations retaliate by underreporting.

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Introduction

A common method of limiting the overall fishing mortality on a stock of fish is by specifying a total allowable catch (TAC), which is equal to the sum of sub-allocations to different gears, areas, periods, or political entities. The amount of the TAC typically depends on the condition of the stock. If the stock is at or above the level that produces maximum surplus (SS_{MSY}), then a TAC is set to maintain the stock above SS_{MSY} or to maintain yield until such time as the stock is reduced to SS_{MSY}. However, if the stock is depleted sufficiently below SS_{MSY}, then the TAC is usually set to allow the stock to rebuild, and in some management arenas, a period for rebuilding is specified. In both of these situations, exceeding the TAC ("overage") can be expected to produce negative results. In the first case, exceeding the TAC will cause the stock to decline to a less productive level, leading to an overfished status and lower yields to the fishery. For a rebuilding stock, exceeding the TAC will extend the amount of time required to rebuild, maintain the stock at a less productive level, and delay the long-term realization of larger sustainable yields.

In addition to determining the appropriate level of TAC, decisions need to be made regarding the sub-allocations to each nation engaged in the fishery. In principle, these decisions should be linked. Legault (1998) pointed out that the calculation of a TAC is based on an assumed allocation (selectivity), and when subsequent allocations deviate from what was assumed in deriving the TAC, the original management target is not obtained. Similarly, for rebuilding stocks, shifts in fishery strategies after a TAC has been implemented may delay or inhibit the achievement of the recovery target and lead managers to consider mid-course corrections (Rosenberg and Brault, 1993; Powers, 1996).

The International Commission for the Conservation of Atlantic Tunas (ICCAT) has typically dealt with the sub-allocation of quotas by negotiating country-specific proportional allocations that sum to the TAC. Note that in some instances, the sum of the country-specific allocations is the *de facto* TAC, rather than the TAC being specified initially. Although such a system, if perfectly implemented, would result in the target TAC, the question remains as to what to do when the allocations are not perfectly implemented. ICCAT has approached this by allowing a system of over- and underages which may be utilized (or paid back) later in time:

> "For any species under quota/catch limit management, underages/overages from one year may be added to/must be subtracted from the quota/catch limit of the management period immediately after or one year after that year, unless any recommendation on a stock specifically deals with overages/underages, in which case that recommendation will take precedence" (ICCAT, 2001a).

The decision rule chosen to determine the rate and timing of utilization of over- and underages has ramifications on how likely it is that the target management objective will be reached and, indeed, whether the target will be reached at all. In the above recommendation, the decision rule is simple: payback of overages and utilization of underages are allocated one-for-one within two years of the act. For other stocks of fish, the decision rule has been modified in various ways by (i) adjusting the rate of subsequent utilization of underages (e.g. only 50% of underages may be transferred to subsequent years), (ii) designating the specific year(s) in which the adjustment may be made, (iii) short-term transfer of underages to other nations' allocations, and (iv) limiting the range of years that the rule is to apply (ICCAT, 2001a).

The success of these decision rules will depend largely on the ability and commitment to monitor the sub-allocations precisely and accurately. Although the examples given above relate to country-specific allocations, the same conceptual problems arise when monitoring catches emanating from different gears or different constituency groups within a nation or region. An example of the latter would be a commercial fishery vs. a recreational fishery in which systems to monitor within-year commercial quotas may be relatively efficient, but in-season recreational monitoring is difficult and expensive (Powers and Restrepo, 1993). Additionally, the concept of penalties on overages arises with establishment of precautionary annual catch limits required by recent modifications to fisheries legislation in the USA (Rosenberg *et al.*, 2007). Therefore, the problem is ubiquitous, and any number of fishery sector categorizations might be analysed (nation vs. nation, recreational vs. commercial, and purse-seine vs. trawl). However, here we use the short-hand term, nations or countries, to denote any such categorization.

We explored the consequences of alternative decision rules regarding over- and underages through simple management strategy evaluations (MSEs). An MSE is an iterative simulation algorithm where stock dynamics with fishing are simulated, an assessment model is applied, and management action is determined (typically a TAC or fishing mortality rate is specified). The sequence of events just described is then repeated by implementing the management action (with or without implementation error and/or changes in the fishery), projecting the stock forward to the next assessment step, then performing another assessment and recommending another management action. By incorporating various sources of uncertainty and implementation error in the simulation phase, the effectiveness of different management actions can be evaluated with respect to robustness and probability of achieving the desired target (Punt and Butterworth, 1995; Cooke, 1999; Polacheck *et al.*, 1999). Evaluation of management strategies was the focus of a recent ICES symposium (Rice and Connolly, 2007) at which a panoply of science, management, and policy issues were addressed. Of particular interest in the context of our study is the recognition of the linkage between management strategies and the incentives that they create among users (Delaney *et al.*, 2007; del Valle and Astorkiza, 2007; Schwach *et al.*, 2007).

Here, we consider two separate objectives via simple MSEs. In the first, we evaluate several decision rules related to payback policies against a conservation standard, i.e. given the abilities of the nations to monitor catch, how likely it would be that the decision rule would result in a realized catch that, on average, was equal to the TAC, and how likely it would be that the spawning stock would be maintained at SS_{MSY}. We do not attempt to determine the most appropriate management strategy or management objectives, and rather examine the effects of alternative over-/underage policies relative to each other for a given management objective.

In a second MSE, we evaluated selected strategies of the nations as they interacted with each other within the constraints of the decision rule (i.e. how closely they choose to monitor their catch). These analyses were conducted in a game-theoretic framework (Gintis, 2000), where the best strategy for a nation was determined by the maximum "payoff"—in this case, in terms of yield or spawning-stock size. Results from these MSEs are intended to provide guidance for defining rules regarding over- and underages and for determining the conditions for which those rules are appropriate.

Model

An age-structured model served as the operating model for simulating the stock dynamics (Appendix Table A1). In both our MSEs, we assumed that there are two nations ($i = 1, 2$) which share a fishery resource. Each nation has a base allocation $A_i(t)$ for year t, which is a proportion $p_i(t)$ of the TAC:

$$\begin{aligned} \text{TAC}(t) &= A_1(t) + A_2(t) \\ p_i(t) &\equiv \frac{A_i(t)}{[A_1(t) + A_2(t)]}. \end{aligned} \tag{1}$$

The TAC is specified by the management body to maintain the resource at (or recover it to) a maximally sustainable level (SS_{MSY}).

To fulfil stewardship obligations to the management body, each nation must implement programmes to monitor and report the catches of their fishery. Their investment in this obligation is reflected in a capacity to implement the programme with specified precision and accuracy. We define $D_{ij}(t)$ as the decision at time t by nation i regarding the precision of implementation ($j = 1$), and the bias in implementation ($j = 2$). Although bias has a statistical connotation implying weaknesses in monitoring, it can equally include cases of unreported catch. In the ICCAT context, under- or unreported catches are a problem and are referred to as IUU catches (illegal, unregulated, and unreported). In domestic US fisheries, under- or unreported catches occur through unmonitored discards or misreported catches. Therefore, our use of the term "bias" refers specifically to mis- or underreporting. A given nation makes joint decisions for both precision and bias; thus, $\{D_{i1}(t), D_{i2}(t)\}$ is a nation's decision set. Precision is expressed as the coefficient of variation (CV) of the catch (standard deviation/estimate $\times$ 100); bias is expressed as the percentage by which the catch is chronically underestimated or underreported.

A nation's allocation might be exceeded in a given year. In other years, the allocation might not be reached. Over- or underages are "paid back" in subsequent years using payback scheme r, resulting in an adjusted allocation for each nation $H_{ir}(t)$. The realized yield obtained by a nation was modelled as

$$Y_i(t) = H_{ir}(t)(1 + D_{i2}(t)) \exp[\lambda(t)]. \quad (2)$$

The variable $\lambda(t)$ is a random deviate distributed normally with mean zero and standard deviation $D_{i1}(t)$. Thus, $\exp(\lambda(t))$ is lognormally distributed. Lognormal deviation was used to depict proportional precision in monitoring. Bias or misreporting is the proportion by which landings exceed the allocation and is depicted by the parameter $D_{i2}(t)$.

The observed yield $\hat{Y}_{ij}(t)$ was the catch resulting from the unbiased (reported) portion of the monitoring, i.e.

$$\hat{Y}_i(t) = H_{ir}(t) \exp[\lambda(t)]. \quad (3)$$

Overages $[O_i(t)]$ and underages $[U_i(t)]$ were computed from the observed yield as follows:

if $\hat{Y}_i(t) > H_{ir}(t)$, then $O_i(t) = \hat{Y}_i(t) - H_{ir}(t)$ and $U_i(t) = 0$;

if $\hat{Y}_i(t) < H_{ir}(t)$, then $O_i(t) = 0$ and $U_i(t) = \hat{Y}_i(t) - H_{ir}(t)$.

Thus, the adjusted allocation was

$$H_{ir}(t) = A_i(t) + d_r(t)[U_i(t-n)] - z_r(t)[O_i(t-n)], \quad (4)$$

where $d_r(t)$ $[0 \leq d_r(t) \leq 1]$ and $z_r(t)$ $[z_r(t) = 0$ or $z_r(t) \geq 1]$ are the functions that discount underages (d) and penalize overages (z). The lag between the time at which an over-/underage is detected and the time in which adjustment to the allocation can be made is n. Several simple linear payback rules were evaluated here, where the functions were constant over time: $d_r(t) = d_r$ and $z_r(t) = z_r$. The term "payback policy" refers to the particular choice of z and d.

Implementation decisions were based on the results of a stock assessment, which assumed that the population resource dynamics were governed by

$$\frac{dB(t)}{dt} = f[B(t), \varepsilon(t)] - F_{TAC}(t)B(t). \quad (5)$$

In Equation (5), $B(t)$ is the biomass of the fish stock at time t, $\varepsilon(t)$ is process error, $f[B(t), \varepsilon(t)]$ is the fish stock's production function, and $F_{TAC}(t)$ is the rate of fishing mortality reflecting management objectives. Maximum sustainable yield (MSY) was the objective used here $[TAC(t) = F_{TAC}(t)B(t) = F_{MSY}(t)B(t)]$. The cases examined here were patterned after a stock with low productivity similar to bluefin tuna [*Thunnus thynnus*; for which recruitment variability $\varepsilon(t)$ is lognormal with a CV of 30%]. The specific functional form of Equation (5) is an age-based model with Beverton–Holt recruitment. Parameters used to define Equation (5) are given in Appendix Table A1; the initial spawning stock with no fishing is $SS_{No\ fishing} = 2619$, $MSY = 51.68$, and $SS_{MSY} = 928$ (units are arbitrary).

These simulations assume that the assessment estimates current biomass, fishing mortality, and TAC without error. Clearly, this assumption is unrealistic. However, we adopt this simplifying approach to emphasize the dynamics of payback policies. As these policies have not been studied extensively, our goal is to isolate first-order effects of paybacks under simplified conditions. Moreover, details of how assessment uncertainty is modelled (e.g. bias, correlation, variance) could overshadow the payback analyses. Although these details will affect the success or failure of payback policies, the simulations using simplified assumptions provide guidance on the likely impacts of assessment imperfection.

Additional structural assumptions were needed to define the simulated population dynamics and the dynamics of the payback rule. First, it was assumed that there was a two-year lag ($n = 2$) between the occurrence of an over-/underage and the payback that addresses it. For example, if the over- or underage occurred in year t, it was detected in year $t+1$, and the remedial action was implemented in year $t+2$. This mimics the implementation process required for many management bodies in which lags in management actions are common (Powers, 2004).

It was also assumed that over- and underages were computed relative to the errors in precision and not to the errors in bias. A nation may know that bias exists and its general magnitude, but choose to ignore or downplay it when implementing monitoring. However, it was assumed in the simulations that the stock assessment process adjusted the catches for the bias, so the determination of management targets (TACs) was assumed to be unbiased. This is not an uncommon occurrence, because scientists can use alternative data sources such as trade statistics to adjust catch estimates (SCRS, 2007). It is acknowledged that these adjustments are not official and that the adjustments sometimes cannot be assigned reliably to an offending nation. Therefore, the adjustments are not definitive bases for scientists to evaluate compliance; rather, they are used in the assessment in an attempt to scale the stock magnitude and the resulting TAC properly.

The final structural assumption is the frequency with which the assessment-strategy evaluation takes place. In the simulations, we specified that assessments were conducted every three years, at which time a new TAC was specified. This is consistent with recent recommendations for assessment frequency for a variety of stocks and management arenas (SCRS, 2007).

All simulations began from an unexploited population, which was then overfished for ten years ($F = 3\,F_{MSY}$), depleting the resource to ~32% of the level at MSY. Next, the stock assessment, the payback policy, and monitoring implementation decisions were initiated, and the overall management policy was set to $F = F_{MSY}$. Therefore, the initial year of accounting for a chosen payback strategy was year 12 (ten years of overfishing followed by two years of an assessment interval). Initial deterministic simulations with no fishing indicated that the stock could recover to MSY conditions in ~14 years. However, under a policy of F_{MSY} (one in which the fishing mortality rate is set at F_{MSY}), the recovery is much more protracted. Therefore, the emphasis of this analysis and the simulations was on the dynamics during the recovery period. We emphasize that the goal of this analysis is to examine the effects of payback policies on stock status and other objectives, and not on whether F_{MSY} is the most appropriate F-policy.

To estimate F_{MSY} in an assessment, the proportional allocation of catches between nations must be known. The initial allocation in our MSEs gave 30% to Nation 1 and 70% to Nation 2 ($p_1 = 0.3$; $p_2 = 0.7$), although we note that Nation 1 targets small fish relative to the targeting of large fish by Nation 2 (Appendix Table A1). For most cases explored, the proportional allocation ($p_1 = 0.3$; $p_2 = 0.7$) was maintained throughout a simulation. However, additional simulations were included in which the resource was reallocated (new p_i values were computed and F_{MSY} recomputed for each assessment period) based on the reported catches by nation $[\hat{Y}_i(t)]$ averaged over the previous assessment period. In these instances, the allocation was allowed to evolve with the degree of deviation in realized catch resulting from payback policies. In the "reallocation" simulations, the fishery was simulated under constant allocation until year 30, at which time the reallocation strategy was initiated. Initial simulations in which reallocation started at year 12 showed that management was unstable and that national proportions quickly evolved to allocations in which one nation took all the catch. Therefore, a start-up period was used and reallocation started in year 30.

A nation's objectives might include annual realized yield Y_i, the annual variability in yield, the observed or reported yield $(\hat{Y}_i)$, adjusted allocations, annual effort or employment, spawning stock expressed relative to the spawning stock at MSY (SS/SS_{MSY}), and cost, to name a few. Cost, effort, reported yield, and annual variability objectives were examined in initial simulations. The results using these objectives were strongly correlated with the results using realized yield or spawning-stock objectives. Therefore, we focused on results when national objectives were to maximize yield or spawning stock.

Only one national objective was analysed at a time, not interactions between objectives within a nation. Accounting periods (the years over which payoffs were computed) were designed to reflect the emphasis on the recovery period of the stocks. Therefore, payoffs for national objectives of realized yield were averaged for years 12–55 of the recovery, whereas SS/SS_{MSY} was computed for year 55, the year when median recovery occurred ($SS/SS_{MSY} = 1$), when there was perfect implementation $[D_{ij}(t) = 0$ for all i, j, t; $z = d = 0]$. Discounting of these objectives was not considered in these simulations, i.e. catches late in the accounting period were given equal weight to earlier ones. The yield statistic examined was the realized catch Y_i, rather than the reported catch. It was assumed that national objectives would be to maximize realized catch whether or not it was known and/or reported.

National strategies

Nations make tactical decisions in implementing their allocations. Tactics include (either singly or in combination): (i) selecting the level of their investment in monitoring (i.e. the resulting precision of their catch estimates), (ii) implementing a within-season closure mechanism to ensure that overages are small or non-existent, (iii) leaving portions of their total catch unmonitored (and unreported) because the investment of monitoring their entire fishery is too onerous, (iv) spreading the risk of over-/underages across several years such that, on average, they meet their allocation, (v) defining the year from which adjustments are made advantageously such that their future allocations (and catches) are improved, and (vi) using their monitoring as a mechanism to improve their position relative to their future allocation. Underages may be viewed by other nations as an indicator that the underage nation does not have the capacity to meet its allocation; therefore, underages are viewed as opportunities to negotiate reallocations. In this context, an overage sometimes is perceived as a better outcome than an underage.

All the above strategies have been observed in various management arenas. Despite the complexity of motivations, we have attempted here to capture the essence of those actions by singling out a set of national strategies for evaluation. These strategies define actions to be taken by one nation, but do not in any way constrain the strategy chosen by another nation. The strategies were:

(i) A nation chooses its decision set $[D_{i,1}(t), D_{i,2}(t)]$ and does not alter it during the simulation; this is referred to as a "constant" strategy for specified levels of precision and bias; the notation used for this strategy in the tables is Const(x%, y%), which indicates a constant strategy in which the precision CV is x%, and the bias or misreporting is y%.

(ii) A nation makes an initial decision $[D_{i,1}(t), D_{i,2}(t)]$ which is maintained over time until its adjusted allocation decreases two years in a row: $[H_{ir}(t-1) < H_{ir}(t-2) < H_{ir}(t-3)]$. At that time, the nation chooses the decision with the next highest cost. If the adjusted allocation increases two years in a row $[H_{ir}(t-1) > H_{ir}(t-2) > H_{ir}(t-3)]$, monitoring is relaxed and the decision on the next lowest cost is taken. Otherwise, the current decision set is maintained. This is referred to as an "adaptive" strategy.

(iii) If Nation 2 has an overage in the previous year $[O_i(t-1) > 0]$, then Nation 1 chooses the same decision set in year t that Nation 2 used in year $(t-1)$. This is referred to as a "tit-for-tat" strategy.

For adaptive or tit-for-tat strategies, the frequency with which a nation examines its investment decision $D_{ij}(t)$ was specified to be two years. In reality, these decisions would probably be made at longer intervals, but by specifying two years, we attempted to force a tighter coupling between a nation's decisions and the management consequences.

Simulations

Two separate objectives were examined using MSEs: (i) how payback rules perform in terms of recovery of the stock, and (ii) how national monitoring impacts the effectiveness of the payback rules.

MSE-1, the influence of payback rules on recovery

The effect of a given payback policy on the probability of recovery (spawning stock maintained at or above SS_{MSY}) and the likelihood that realized catch was equal to the TAC were investigated through Monte Carlo simulation. In this set of simulations, both nations employed a constant strategy for precision and bias (underreporting). Four payback policies were compared, including no payback ($z = 0$; $d = 0$), full payback ($z = 1$; $d = 1$), and two intermediate payback cases ($z = 1$; $d = 0$) and ($z = 0$; $d = 1$). Each payback policy was simulated 250 times over a 100-year time horizon. Each outcome was compared with perfect implementation of the management policy $[D_{ij}(t) = 0$, for all i, j, $t]$ with no payback ($z = d = 0$). These case studies are defined in Table 1.

MSE-2, the influence of payback rules on national strategies and national yields

The second stage of the analysis examined national monitoring strategies (the precision and bias in the reporting of catches), through simulated games based on 100-year trajectories of the fishery. In particular, the effects of the payback policy on the strategies that nations might choose were evaluated. In these simulations, one stochastic realization was generated for each combination of strategies tested. However, all comparisons used

Table 1. Definition of case studies examined through Monte Carlo simulations (MSE-1, the influence of payback rules on recovery; see text).

Case	CV (%)	Bias (%)	Payback policy		
			z	d	Description
A	0	0	0	0	No payback
B	20	0	0	0	No payback
C	20	0	0	1	No payback overages; one-for-one for underages
D	20	0	1	0	No payback underages; one-for-one for overages
E	20	0	1	1	One-for-one payback for over- and underages
F	20	20	1	0	No payback underages; one-for-one for overages
G	20	20	0	1	No payback overages; one-for-one for underages
H	20	20	1	1	One-for-one payback for over- and underages

Note that in these simulations, both nations implemented monitoring and reporting with the same CV and bias within a case.

the same sequence of random numbers for recruitment deviation and imprecision in monitoring, so the "state of nature" was the same always. Therefore, relative differences in outcomes reflected differences in strategies and not background random variability. This was tested by conducting a Monte Carlo simulation of a 4×4 game randomly iterated 100 times. Although the payoffs varied between iterations, the solution to the games (the chosen national strategy) did not. The solution to the game was the same for all 100 iterations, so in subsequent tests, emphasis was placed on the results of single realizations.

Nine 4×4 games were evaluated using 16 simulations to create a grid of outcomes or payoffs resulting from national strategies of monitoring precision and bias (underreporting) for a given payback policy. These nine games were: two constant-strategy games with alternative levels of precision and no bias (bias = 0% and CV = 5%, 10%, 20%, or 50%), one constant-strategy game with alternative levels of underreporting (bias) with perfect precision (CV = 0% and bias = 10%, 20%, 50%, or 100%), two constant-strategy games with alternative levels of underreporting (bias) with imperfect precision (CV = 20% and bias = 10%, 20%, 50%, or 100%), two mixed-strategy games in which nations chose between constant, adaptive, and tit-for-tat strategies, and two constant-strategy games where proportional allocations between nations were not fixed at $p_1 = 0.3$ and $p_2 = 0.7$, but were reallocated at each assessment.

Nash equilibria were computed iteratively from the 4×4 payoff matrices (Gintis, 2000; Lindroos and Kaitala, 2000). The Nash solution is the payoff where a unilateral change in strategy by one of the nations can produce no better payoff for itself. For example, in a 4×4 game in which each nation's objective is to maximize yield, if Nation 1 can improve its yield by changing strategy regardless of what Nation 2 does, then it will do so. However, Nation 2 will then decide whether it can improve its own outcome given the change in strategy by Nation 1. When both nations can no longer increase their yield, the game has achieved Nash equilibrium. Not every game has a stable equilibrium, however. Nash equilibria are similar to evolutionarily stable strategies (Maynard Smith, 1982), in the sense that the game has reached an "uninvadable" equilibrium point where no player can improve its position.

Results

MSE-1, the influence of payback rules on recovery

Recovery of the stock biomass differed between the simulations (case studies) outlined in Table 1 (Figures 1–3). In all simulations, recovery of the simulated stock was protracted, requiring some 50 years or more to achieve the target biomass and MSY. When monitoring was unbiased (no underreporting), the one-for-one payback policy ($z = 1$; $d = 1$; Case E) performed comparably with perfect implementation in terms of stock recovery. The excess overage induced by a CV of 20% was compensated for by payback of the underages. When overages were penalized and underages not rewarded ($z = 1$; $d = 0$), recovery was achieved earlier (Case D). Conversely, a policy in which transgressions were ignored and underages rewarded ($z = 0$; $d = 1$) did not perform well (Case C).

Case B (no bias and no payback, with CV = 20%) performed almost as well as perfect implementation (Case A) and a one-to-one payback (Case E) in these simulations. This is because one-to-one policies and simulations with low CVs are nearly symmetrical in their effects. Random overages and one-to-one policy corrections, on average, are close to the perfect implementation model. However, if the correction effects are asymmetrical, the mean effects would be more different. Additionally, if variation in implementation was larger (CV larger) or the assessment unbiased but imprecise, then the probability distributions would be wider and the effects of asymmetry in the payback policy would be more pronounced.

When an underreporting (bias) rate of 20% was included in addition to a CV of 20%, the stringent payback policy ($z = 1$; $d = 0$) performed better than the one-for-one policy ($z = 1$; $d = 1$). However, neither performed comparably with perfect implementation (Figure 3).

MSE-2, the influence of payback rules on national strategies and national yields

The nine 4×4 game outcomes (compared with perfect implementation) are summarized in Tables 2–5, and the complete payoff and game solutions for one example (Case 4) are given in Appendix Table A2.

One-for-one payback policies performed well in terms of yield maximization and recovery to SS_{MSY} when there was variation in monitoring precision but no underreporting (Tables 2–5; Case 1). Although Nash equilibrium strategies occurred when there was less precision in monitoring, the marginal benefits were small, and the incentives thus created were insignificant. With a more stringent payback policy in which overages were penalized and no credit was given for underages (Case 2), the Nash strategy resulted in a slightly lower yield history with resultant benefits for recovery.

When underreporting was an option for a national strategy, incentives were created for yield-maximizing nations to underreport (Cases 4–5 in Tables 2–5). Indeed, the best strategy in these simulations was to underreport to the greatest extent possible. The effect of this was mitigated somewhat by more stringent payback policies (Case 5). However, a national strategy where underreporting was instituted (or tolerated) remained the best solution to the game. When yield maximizing was the objective, if one nation underreported, it was in the best interest of the

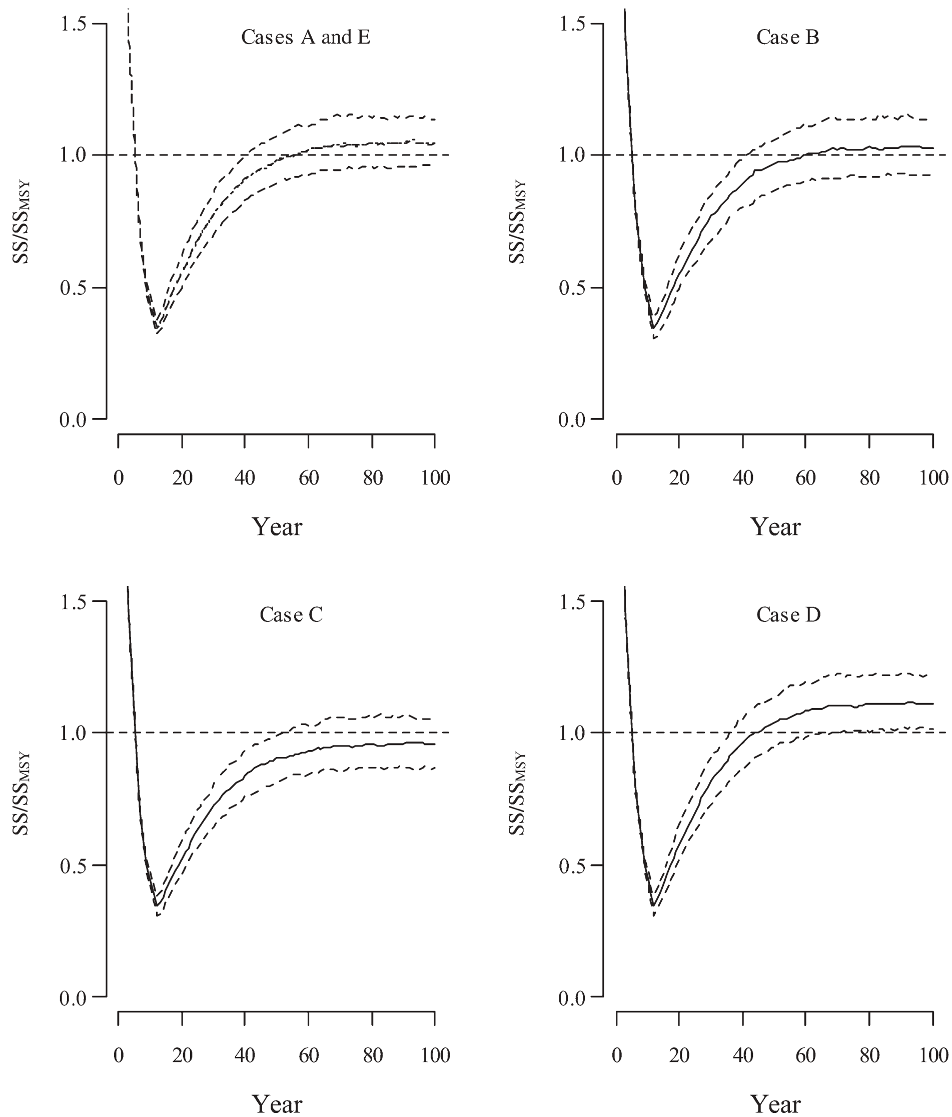

Figure 1. Trajectories of spawning-stock biomass relative to that at MSY (median trajectories with 80% probability intervals): Case A (perfect implementation, $z = d = 0$; CV = 0%, bias = 0%) and Case E (one-for-one with imperfect implementation, $z = d = 0$; CV = 20%, bias = 0%) have overlapping median trajectories, but the results of A are slightly more optimistic than E. Case B: no payback ($z = 0$; $d = 0$; CV = 20%, bias = 0%); Case C: no overage penalty and credit for underages ($z = 0$; $d = 1$; CV = 20%, bias = 0%); Case D: overage penalty and credit for underages ($z = 1$; $d = 0$; CV = 20%, bias = 0%).

other nation also to underreport. Therefore, recovery and potential yield suffered in the process.

When implementation precision is perfect (Case 3 in Tables 2–5), there is effectively no payback policy, because payback is measured relative to the reported yield, and in this case, reported yield is exact. However, there can still be bias in this instance, creating incentives for misreporting.

Adaptive and tit-for-tat strategies did not perform appreciably better than constant strategies for either yield-maximizing or recovery objectives regardless of payback policy tested (Cases 6–7).

Finally, when reallocation was adjusted based on reported catches by nation over the previous assessment period, strong incentives were created to underreport (Cases 8–9), especially for the nation receiving the smaller allocation (Nation 1 in this case). A more stringent payback policy actually increases the incentive to underreport in this instance.

Discussion

MSE is an important aspect of the fisheries assessment and management process (Rice and Connolly, 2007). Heretofore, most of the emphasis has been placed on determining robust management through these analyses. However, more interest is now being expressed in the incentives created by alternative management tactics, and the impact that the incentives have on management success (Delaney *et al.*, 2007; del Valle and Astorkiza, 2007; Schwach *et al.*, 2007).

Payback policies are mechanisms that allow flexibility in dealing with over- and underages from allocated TACs in a fishery. As such, they are most effective when monitoring errors are random rather than biased. For example, a one-for-one payback policy ($z = d = 1$) works well in mimicking perfect implementation when random errors are symmetrical. That is,

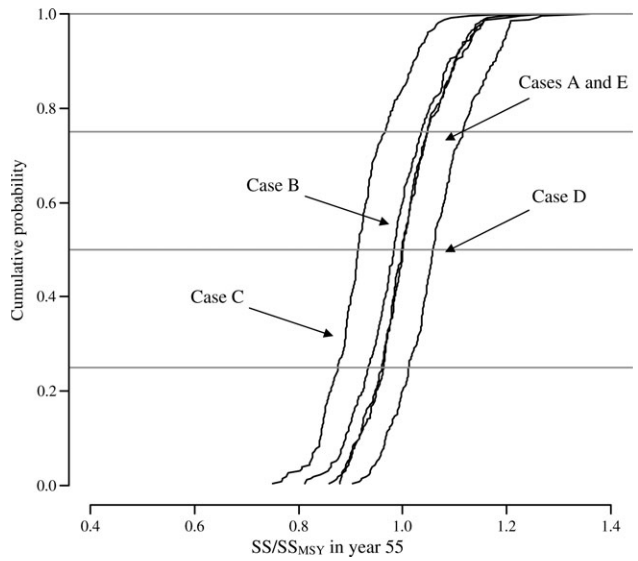

Figure 2. Cumulative probability distribution of relative spawning stock in year 55, the year of median recovery with perfect implementation (Case A). Cases B–D have a 20% CV and no bias. Note, A and E are almost indistinguishable, and the cases are defined in Table 1.

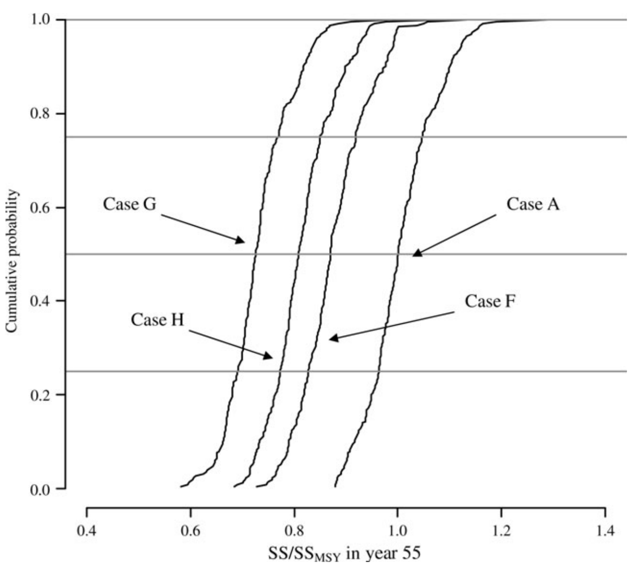

Figure 3. Cumulative probability distribution of relative spawning stock in year 55, the year of median recovery with perfect implementation (Case A). Except Case A, these cases include 20% bias in addition to a 20% CV. The cases are defined in Table 1.

if the magnitude of over- and underages is equally likely, then the one-for-one policy adjusts for those random errors. Even in the simulations where precision was lognormal (asymmetrical), the one-for-one policy performed well. The magnitude of the payback (for example, $z = d = 1$ vs. $z = 1.5$, $d = 0.5$) determines how much the range of over-/underages is narrowed. We have presented results for simulations that bracketed the range from no paybacks to one-for-one paybacks. Although we explored many alternatives for z and d, the results were predictable in a qualitative sense. For example, rewarding underages ($d = 1$) while ignoring overages ($z = 0$) results in slower rebuilding than $z = d = 1$.

Alternative payback policies in which over- or underages are disproportionately rewarded or penalized are effectively adjusting monitoring precision distributions such that they are asymmetrically truncated. This, in turn, results in long-term adjustment to the management policy. Therefore, in these simulation results, asymmetrical paybacks amount to adjustments that divert management away from an F_{MSY} objective.

When underreporting is not an issue, payback policies may create incentives for individual nations to implement imprecise monitoring schemes. However, those incentives are not strong.

Underreporting of catches attributable to biased monitoring schemes or intentional collusion induces a number of problems that are not well addressed by a payback policy. As paybacks are designed to adjust for errors in random monitoring, the policy is an indirect and imperfect mechanism to deal with underreporting. For example, when there is no imprecision in monitoring, the particular payback policy does not matter, because catches are reported exactly at the allocation (Case 3 in Tables 2–5) regardless of the degree of bias or underreporting. Although payback policies can mitigate the effects of underreporting to some extent, they operate through the precision of the reported catch. If catches are precise, paybacks will not be effective regardless of the magnitude of underreporting. For example, an especially recalcitrant country might report its catches exactly at its allocation (precise reporting), yet it may grossly underreport. As there are no over- or underages, the payback policy is irrelevant.

An additional consequence of underreporting by one nation is the creation of incentives for all yield-maximizing nations to underreport. In this regard, our simulation results are consistent with Hannesson (2007). In a game where nations decide strategically to implement or tolerate underreporting, the optimal solution is for both nations to underreport. This result is mitigated somewhat if the yield objective is longer term. For example, yield payoffs were computed as the average yield over the recovery period (years 12–55, in this case). If, for example, the yield payoff for Nation 2 was the long-term average for years 55–100, the game solution shifts towards lower levels of underreporting by Nation 2. National objectives for maximizing a long-term sustainable yield are not the same as maximizing yield during recovery. Hence, long-term sustainability objectives lessen incentives for underreporting. Although a fishery may be sustainable with a large magnitude of underreporting, yield and recovery objectives are compromised in the process. The choice of payback policies does not address the problem directly. As Hannesson (2007) noted, underreporting by one nation may result in stocks that are well below SS$_{MSY}$ and substantial gains for the nation that underreports, unless the other nation retaliates by also underreporting.

Underreporting may be viewed as a mechanism to subvert the proportional allocations (the p_i values in the simulations), especially for the nation receiving the smaller allocation. When allocations are renegotiated periodically (TACs reallocated in the simulations), further incentives are created for the smaller fishing nation to underreport. In some simulations, reallocation coupled with underreporting shifted the allocation from a 30/70 split to 48/52. Additionally, more stringent paybacks favour further underreporting, rather than less, when TACs are reallocated. Therefore, underreporting opportunities can allow users

Table 2. Summary of results (MSE-2, the influence of payback rules on national strategies and national yields; see text) when both nations maximize yield.

Case	Strategy alternatives	Payback	Reallocate?	Nation 1		Nation 2	
				Yield	Solution strategy	Yield	Solution strategy
0	CV = 0; bias = 0	n/a	No	12.20	–	27.84	–
1	Bias = 0; % precision ∈ [5, 10, 20, 50]	$z = d = 1$	No	12.22	Const(50%, 0%)	27.98	Const(50%, 0%)
2	Bias = 0; % precision ∈ [5, 10, 20, 50]	$z = 1, d = 0$	No	12.15	Const(5%, 0%)	27.63	Const(5%, 0%)
3	CV = 0; % bias ∈ [10, 20, 50, 100]	n/a	No	11.93	Const(0%, 100%)	25.18	Const(0%/100%)
4	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = d = 1$	No	11.93	Const(20%, 100%)	25.23	Const(20%, 100%)
5	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = 1, d = 0$	No	12.23	Const(20%, 100%)	26.12	Const(20%, 100%)
6	Mixed	$z = d = 1$	No	12.22	Const(20%, 50%)	26.54	Const(20%, 50%)
7	Mixed	$z = 1, d = 0$	No	**	No solution	**	No solution
8	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = d = 1$	Yes	12.28	Const(20%, 100%)	21.55	Const(20%, 100%)
9	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = 1, d = 0$	Yes	13.27	Const(20%, 100%)	24.37	Const(20%, 100%)

n/a (not applicable) is for cases where the reported catch was exactly equal to the TAC, so there were no overages. The notation used for a constant strategy in this and Tables 3–5 is Const(*x*%, *y*%), where the precision CV is *x*%, and the bias or misreporting is *y*%. The symbol ** denotes where no Nash solution existed. The mixed strategy alternatives refer to a game between Const(10%, 10%), Const(20%, 50%), adaptive, and tit-for-tat. The first row of the table (and the same row in Tables 3–5) is the result for perfect implementation (CV = 0; bias = 0) with no payback ($z = d = 0$) for comparing game results.

Table 3. Summary of results (MSE-2, the influence of payback rules on national strategies and national yields; see text) when Nation 1 maximizes yield and Nation 2 maximizes SS/SS_{MSY}.

Case	Strategy alternatives	Payback	Reallocate?	Nation 1		Nation 2	
				Yield	Solution strategy	SS/SS_{MSY}	Solution strategy
0	CV = 0; bias = 0	n/a	No	12.20	–	0.94	–
1	Bias = 0; % precision ∈ [5, 10, 20, 50]	$z = d = 1$	No	12.22	Const(50%, 0%)	0.96	Const(50%, 0%)
2	Bias = 0; % precision ∈ [5, 10, 20, 50]	$z = 1, d = 0$	No	12.61	Const(5%, 0%)	1.04	Const(50%, 0%)
3	CV = 0; % bias ∈ [10, 20, 50, 100]	n/a	No	17.03	Const(0%, 100%)	0.55	Const(0%, 10%)
4	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = d = 1$	No	17.05	Const(20%, 100%)	0.57	Const(20%, 10%)
5	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = 1, d = 0$	No	17.02	Const(20%, 100%)	0.64	Const(20%, 10%)
6	Mixed	$z = d = 1$	No	14.29	Adaptive	0.71	Const(10%, 10%)
7	Mixed	$z = 1, d = 0$	No	14.06	Adaptive	0.76	Const(10%, 10%)
8	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = d = 1$	Yes	16.63	Const(20%, 100%)	0.55	Const(20%, 10%)
9	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = 1, d = 0$	Yes	17.44	Const(20%, 100%)	0.63	Const(20%, 10%)

n/a (not applicable) is for cases where reported catch was exactly equal to the TAC, so there were no overages. The mixed strategy alternatives refer to a game between Const(10%, 10%), Const(20%, 50%), adaptive, and tit-for-tat strategies.

Table 4. Summary of results (MSE-2, the influence of payback rules on national strategies and national yields; see text) when Nation 1 maximizes SS/SS_{MSY} and Nation 2 maximizes yield.

Case	Strategy alternatives	Payback	Reallocate?	Nation 1		Nation 2	
				SS/SS_{MSY}	Solution strategy	Yield	Solution strategy
0	CV = 0; bias = 0	n/a	No	0.94	–	12.20	–
1	Bias = 0; % precision ∈ [5, 10, 20, 50]	$z = d = 1$	No	0.96	Const(50%, 0%)	27.98	Const(50%, 0%)
2	Bias = 0; % precision ∈ [5, 10, 20, 50]	$z = 1, d = 0$	No	1.03	Const(50%, 0%)	28.48	Const(5%, 0%)
3	CV = 0; % bias ∈ [10, 20, 50, 100]	n/a	No	0.49	Const(0%, 10%)	34.93	Const(0%, 100%)
4	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = d = 1$	No	0.5	Const(20%, 10%)	35.05	Const(20%, 100%)
5	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = 1, d = 0$	No	0.58	Const(20%, 10%)	35.27	Const(20%, 100%)
6	Mixed	$z = d = 1$	No	0.67	Const(10%, 10%)	30.73	Const(20%, 50%)
7	Mixed	$z = 1, d = 0$	No	0.73	Const(10%, 10%)	30.40	Adaptive
8	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = d = 1$	Yes	0.52	Const(20%, 10%)	31.43	Const(20%, 100%)
9	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = 1, d = 0$	Yes	0.6	Const(20%, 10%)	33.84	Const(20%, 100%)

n/a (not applicable) is for cases where reported catch was exactly equal to the TAC, so there were no overages. The mixed strategy alternatives refer to a game between Const(10%, 10%), Const(20%, 50%), adaptive, and tit-for-tat strategies.

Table 5. Summary of results (MSE-2, the influence of payback rules on national strategies and national yields; see text) when both nations maximize SS/SS_{MSY}.

Case	Strategy alternatives	Payback	Reallocate?	Nation 1		Nation 2	
				SS/SS_{MSY}	Solution strategy	SS/SS_{MSY}	Solution strategy
0	CV = 0; bias = 0	$z = d = 0$	No	0.94	–	0.94	–
1	Bias = 0; % precision ∈ [5, 10, 20, 50]	$z = d = 1$	No	0.96	Const(50%, 0%)	0.96	Const(50%, 0%)
2	Bias = 0; % precision ∈ [5, 10, 20, 50]	$z = 1, d = 0$	No	1.11	Const(50%, 0%)	1.11	Const(50%, 0%)
3	CV = 0; % bias ∈ [10, 20, 50, 100]	n/a	No	0.85	Const(0%, 10%)	0.85	Const(0%, 10%)
4	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = d = 1$	No	0.86	Const(20%, 10%)	0.86	Const(20%, 10%)
5	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = 1, d = 0$	No	0.93	Const(20%, 10%)	0.93	Const(20%, 10%)
6	Mixed	$z = d = 1$	No	0.85	Const(10%, 10%)	0.85	Const(10%, 10%)
7	Mixed	$z = 1, d = 0$	No	0.89	Const(10%, 10%)	0.89	Const(10%, 10%)
8	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = d = 1$	Yes	0.85	Const(20%, 10%)	0.85	Const(20%, 10%)
9	CV = 20%; % bias ∈ [10, 20, 50, 100]	$z = 1, d = 0$	Yes	0.93	Const(20%, 10%)	0.93	Const(20%, 10%)

n/a (not applicable) is for cases where reported catch was exactly equal to the TAC, so there were no overages. The mixed strategy alternatives refer to a game between Const(10%, 10%), Const(20%, 50%), adaptive, and tit-for-tat.

to manipulate the management system and subterfuge policy objectives.

Simple adaptive (where monitoring precision and bias are relaxed when yield improves and are tightened when yield declines) or tit-for-tat (where a nation selects the monitoring strategy employed by the other nation in the previous period) strategies were inconsistent in their performance relative to constant strategies. The original motivation for the tit-for-tat and adaptive strategies was to mimic results from repeated prisoners' dilemma games, in which tit-for-tat strategies performed well (Axelrod and Hamilton, 1981). The basis of these repeated strategies is that players cooperate unless provoked, players retaliate if provoked, and players are quick to forgive. The outcomes are closely linked to the players' actions. However, the simulation study used here had considerable lags and uncertainties between actions and outcomes. Therefore, the strategies did not perform well. Gintis (2000) noted the effect of discount rates on tit-for-tat strategies, suggesting conditions in which those strategies might be improved. Clearly, more research on applications to fisheries management policies is needed.

There are a number of reasons why payback flexibility might be needed to address imprecision in implementing TACs. Developing countries (with developing fisheries) may have an allocation, but they do not have the capacity to catch that allocation immediately. Therefore, they may wish to distribute that allocation over time as the fishery develops. Alternatively, a common strategy has been to develop chartering arrangements with vessels from other countries with stipulations that (i) catches are counted against the developing country's allocation and historical record of catches, (ii) landings are to be made in the developing country's ports, and (iii) some portion of the crew is required to be populated by the developing country's nationals.

Allocations to some countries are based on a fishery that targets species other than the one being allocated. Therefore, the allocation is for bycatch in the other fishery, and the quantity of the bycatch from year to year is less predictable. Additionally, the country can make the decision that shutting the directed fishery within season to meet the bycatch allocation is too costly in terms of the foregone directed harvest. Therefore, the country would prefer to distribute the bycatch over a number of years, such that the average is close to the original allocation.

Another practical reason for allowing payback flexibility is that monitoring some types of fishery is more difficult and expensive, especially within season. Therefore, annual adjustments after the fact may be useful (i.e. the use of over- and underages).

For the purposes of the simulations, it was assumed that the stock assessment procedures adjusted perfectly for any biases in reporting. However, assessment adjustments clearly are not perfect and may themselves be biased. This source of error was not addressed here, and would likely further dilute the effectiveness of paybacks. This again argues for precautionary controls (Rosenberg *et al.*, 2007).

The simulations tested here do not include assessment uncertainty, i.e. assessment results have no variance or bias. We suspect that if assessments are unbiased but with a monitoring CV >0, the effect on payback policies will be similar to those with a higher level of imprecision. However, if the assessment is biased or serially correlated, or if lags are protracted, interaction with payback policies is expected to be more complex. Clearly, these situations could create additional incentives for misreporting. Moreover, discounted yields would put more emphasis on obtaining catches earlier within a management accounting period. This too could accentuate incentives for manipulation.

The original allocation (p_1 vs. p_2 in these simulations) is an important parameter in assessing and determining the TAC. The history behind the original allocation criteria is an important issue to many countries. This in turn affects how underreporting is perceived by that nation, particularly for overfished stocks. Allocations are often based on historical participation. If historical participants contributed to overfishing, new participants inherently view an historical allocation as unfair and feel that any gains while the stock is recovering should accrue to them disproportionately. These views are coupled with traditional conflicts (developing vs. developed countries, high seas vs. coastal states) to encourage direct or indirect reallocation and incentives for underreporting. However, the simulated solutions to these games clearly show that conservation sustainability objectives are compromised. Allocation criteria in some management arenas have been expanded to include such issues as coastal states rights, stewardship responsibilities, and the needs of developing states (ICCAT, 2001b). However, it is unclear how effective these have been.

Payback policies may be an effective tool to adjust for imprecise monitoring of TACs, but biased monitoring or underreporting substantially reduces the effectiveness of those policies. If biased underreporting is a problem, more direct measures, such as a precautionary fishing mortality rate policy, in which the fishing mortality rate and TAC are reduced, are likely to be more effective. However, lower TACs punish reporting nations, whereas underreporting nations are affected less. Management policies in which the cost of mis- and underreporting are increased appear to have the most potential for improving the situation. These may be manifest by loss of fishing access rights, trade measures, and loss of access to markets.

These analyses used a relatively low productivity stock as an example. A more highly productive stock would be expected to behave somewhat differently in terms of payback policies. TAC management may not be the most appropriate strategy for highly productive stocks, which tend to show great interannual variability. However, if TAC management were to be used, care would have to be taken to select reporting and implementation lags appropriately so that the payback system was not unstable (e.g. if paybacks of overages reduced an allocation to zero). We suspect that for payback policies to be effective for highly productive stocks, the adjustments (z and d values) would have to be small and incremental, and management lags would have to be small. Alternatively, a system of input (effort) controls might be used with its own payback regime. However, that alternative has not been examined here.

Finally, although our simulations focused on the competition among nations to achieve higher catches and allocations, there can be similar dynamics between sectors of domestic fisheries. In those situations, investment in "strategies" reflects funding for such things as surveys to monitor recreational catch, observer programmes to estimate underreporting and discards, and port agents and other canvassing programmes to monitor commercial landings. Lack of commitment to fund these tasks can lead to manipulation of the management process in which allocations are subverted.

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References

Axelrod, R., and Hamilton, W. D. 1981. The evolution of cooperation. Science, 211: 1390–1396.

Cooke, J. G. 1999. Improvement of fishery-management advice through simulation testing of harvest algorithms. ICES Journal of Marine Science, 56: 797–810.

Delaney, A. E., McLay, H. A., and van Densen, W. L. T. 2007. Influences of discourse on decision-making in EU fisheries management: the case of North Sea cod (*Gadus morhua*). ICES Journal of Marine Science, 64: 804–810.

del Valle, I., and Astorkiza, K. 2007. Institutional designs to face the dark side of total allowable catches. ICES Journal of Marine Science, 64: 851–857.

Gintis, H. 2000. Game Theory Evolving. Princeton University Press, Princeton, NJ. 528 pp.

Hannesson, R. 2007. Cheating about the cod. Marine Policy, 31: 698–705.

ICCAT. 2001a. Recommendation by ICCAT regarding compliance with management measures which define quotas and/or catch limits. ICCAT Report for the biennial period, 2000–1, Part I, Vol. 1, Annex 7: 148–150.

ICCAT. 2001b. ICCAT criteria for the allocation of fishing possibilities. ICCAT Report for the biennial period, 2000–1, Part II, Vol. 1, Annex 8: 211–212.

Legault, C. M. 1998. Linking total catch quotas and allocation schemes. North American Journal of Fisheries Management, 18: 454–457.

Lindroos, M., and Kaitala, V. 2000. Nash equilibria in a coalition game of the Norwegian spring-spawning herring fishery. Marine Resource Economics, 15: 321–339.

Maynard Smith, J. 1982. Evolution and the Theory of Games. Cambridge University Press, Cambridge. 226 pp.

Polacheck, T., Klaer, N. L., Millar, C., and Preece, A. L. 1999. An initial evaluation of management strategies for the southern bluefin tuna fishery. ICES Journal of Marine Science, 56: 811–826.

Powers, J. E. 1996. Benchmark requirements for recovering fish stocks. North American Journal of Fisheries Management, 16: 495–504.

Powers, J. E. 2004. Strategic interaction in United States Fishery Management Councils. Marine Resource Economics, 19: 417–438.

Powers, J. E., and Restrepo, V. R. 1993. Evaluation of stock assessment research for Gulf of Mexico king mackerel: benefits and costs to management. North American Journal of Fisheries Management, 13: 15–26.

Punt, A. E., and Butterworth, D. S. 1995. The effects of future consumption by the Cape fur seal on catches and catch rates of the Cape hakes. 4. Modelling the biological interaction between Cape fur seals *Arctocephalus pusillus pusillus* and Cape hakes *Merluccius capensis* and *M. paradoxus*. South African Journal of Marine Science, 16: 255–285.

Rice, J. C., and Connolly, P. L. 2007. Fisheries management strategies: an introduction by the Conveners. ICES Journal of Marine Science, 64: 577–579.

Rosenberg, A., Agnew, D., Babcock, E., Cooper, A., Mogensen, C., O'Boyle, R., Powers, J., *et al.* 2007. Setting annual catch limits for US fisheries: an expert working group report. MRAG, Americas, and the Lenfest Ocean Program, Washington, DC. 36 pp.

Rosenberg, A. A., and Brault, S. 1993. Choosing a management strategy for stock rebuilding when control is uncertain. *In* Risk Evaluation and Biological Reference Points for Fisheries Management, pp. 243–249. Ed. by S. J. Smith, J. J. Hunt, and D. Rivard. Canadian Special Publication of Fisheries and Aquatic Sciences, 120. 442 pp.

Schwach, V., Bailly, D., Cristensen, A., Delaney, A. E., Degnbol, P., van Densen, W. L. T., Holm, P., *et al.* 2007. Policy and knowledge in fisheries management: a policy brief. ICES Journal of Marine Science, 64: 798–803.

SCRS. 2007. Standing Committee on Research and Statistics Report of the 2006 Atlantic Bluefin Tuna Stock Assessment Session (Rapporteur J. E. Powers). ICCAT Collective Volume of Scientific Papers, 60: 652–880.

Appendix

Table A1. Population productivity models and parameters used in the simulations.

Recruitment	$R = \varepsilon(t)\,\alpha\,(\mathrm{SSB})/(1 + \beta\,\mathrm{SSB}) = N_{1/2}$
	$\beta = [(R_1/\mathrm{SSB}_1) - (R_2/\mathrm{SSB}_2)]/(R_2 - R_1)$
	$\alpha = R_2(1 + \beta\,\mathrm{SSB}_2)/\mathrm{SSB}_2$
	$R_1 = 1;\ \mathrm{SSB}_1 = 2619 = \mathrm{SSB}_{\mathrm{No\ fishing}}$
	$R_2 = 0.7;\ \mathrm{SSB}_2 = 0.2\,\mathrm{SSB}_1$
	$\varepsilon(t) \sim$ lognormal with parameters $\mu = 0$, $\sigma = 0.3$
Length-at-age	$L_{\mathrm{age}} = 10^3\{1 - e^{-0.15[(\mathrm{age})+1]}\}$
Weight-at-age	$W_{\mathrm{age}} = 10^{-6} L_{\mathrm{age}}^3$
Per capita spawning-biomass-at-age	$\mathrm{SSB}_{\mathrm{age}} = W_{\mathrm{age}}\mathrm{Mature}_{\mathrm{age}}$
Number-at-age	$N_{\mathrm{age}+1} = N_{\mathrm{age}}e^{-Z_{\mathrm{age}}}$
	$Z_{\mathrm{age}} = F_{\mathrm{age}} + M_{\mathrm{age}}$
	$F_{\mathrm{age}} = F_{\mathrm{mult}}S_{1,\mathrm{age}}p_1 + F_{\mathrm{mult}}S_{2,\mathrm{age}}p_2$
Yield-at-age	$Y_{\mathrm{age}} = 1/2C_{\mathrm{age}}[W_{\mathrm{age}} + W_{\mathrm{age}+1}]$
	$C_{\mathrm{age}} = F_{\mathrm{age}}N_{\mathrm{age}}\{1 - e^{-Z_{\mathrm{age}}}\}/Z_{\mathrm{age}}$
Yield	$\mathbf{Y} = \Sigma_{\mathrm{age}}[Y_{\mathrm{age}}]$
Spawning biomass	$\mathrm{SSB} = \Sigma_{\mathrm{age}}[\mathrm{SSB}_{\mathrm{age}}N_{\mathrm{age}}]$
Management and allocation	$F_{\mathrm{TAC}} = F_{\mathrm{MSY}};\ SS_{\mathrm{MSY}} = 928;\ \mathrm{MSY} = 51.68$
	$p_1 = 0.3;\ p_2 = 0.7$

A_{age}	Nation 1 selectivity ($S_{1,\mathrm{age}}$)	Nation 2 selectivity ($S_{2,\mathrm{age}}$)	M_{age}	$\mathrm{Mature}_{\mathrm{age}}$
0–1	0.1	0.0	0.3	0.0
1–2	0.4	0.0	0.2	0.0
2–3	1.0	0.2	0.1	0.0
3–4	0.5	0.4	0.1	0.5
4–5	0.3	1.0	0.1	1.0
5–6	0.3	1.0	0.1	1.0
6–7	0.2	1.0	0.1	1.0
7–8	0.2	1.0	0.1	1.0
8–9	0.2	1.0	0.1	1.0
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
50–51	0.2	1.0	0.1	1.0

Table A2. Payoff matrix and game solutions when each nation has a constant monitoring strategy with 20% CV for precision and alternative levels of bias.

			Nation 2 strategy							
			Const (20%, 10%)		Const (20%, 20%)		Const (20%, 50%)		Const (20%, 100%)	
			Nation 1	Nation 2	Nation 1	Nation 2	Nation 1	Nation 2	Nation 1	Nation 2
Nation 1 strategy	**Const (20%, 10%)**	Y	12.53	28.35	12.05	29.62	10.75	32.55	8.88	**35.05**
		SS/SS_{MSY}	**0.86**	**0.86**	0.81	0.81	0.68	0.68	**0.50**	0.50
	Const(20%, 20%)	Y	13.25	27.41	12.74	28.63	11.35	31.43	9.38	33.82
		SS/SS_{MSY}	0.82	0.82	0.77	0.77	0.65	0.65	0.48	0.48
	Const(20%, 50%)	Y	15.04	24.72	14.47	25.81	12.87	28.30	10.60	30.35
		SS/SS_{MSY}	0.72	0.72	0.68	0.68	0.56	0.56	0.41	0.41
	Const(20%, 100%)	Y	**17.05**	20.74	16.38	21.63	14.54	23.66	**11.93**	**25.23**
		SS/SS_{MSY}	0.57	**0.57**	0.53	0.53	0.44	0.44	0.32	0.32

The notation used for a constant strategy is Const(x, y), where the precision CV is x% and the bias or misreporting is y%. The payback policy was $z = d = 1$. Solutions to 4 × 4 games for objectives Y_1 vs. Y_2, Y_1 vs. SS/SS_{MSY}, SS/SS_{MSY} vs. Y_2, and SS/SS_{MSY} vs. SS/SS_{MSY} are given in emboldened numerals. For example, when the objective of Nation 1 is yield maximization and the objective of Nation 2 is SS/SS_{MSY} maximization, the Nash equilibrium solution occurs when Nation 1 chooses a strategy with 100% bias and Nation 2 chooses a strategy with 10% bias. The national payoffs of this game (emboldened) are $Y_1 = 17.05$ and $SS/SS_{\mathrm{MSY}} = 0.57$, respectively.

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