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Determining policy-efficient management strategies in fisheries using data envelopment analysis (DEA)

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ABSTRACT

In this paper, the authors analyze a wide range of recreational management strategies for their impacts on red snapper yield, economic surplus and the fish stock. Simulating a wide range of policies, the authors find Data Envelopment Analysis (DEA) inspired policy efficiency frontiers that lead to finding those management strategies that offer the greatest level of economic surplus for any biological target, looking at both the east and west Gulf of Mexico fisheries. Red snapper has been declared overfished since 1988 and the 2005 SEDAR 7 stock assessment declared red snapper were overfished and undergoing overfishing. In November 2009, the update of the assessment declared that overfishing was no longer occurring but that the red snapper stocks needed to be rebuilt. In this analysis, it was found that red snapper are neither overfished or undergoing overfishing. The main difference between the present model and the SEDAR 7 model is that the latest model uses a higher mortality rate for juveniles and a density dependent model. The authors also suggest that the east and west should be managed as separate units.

1. Introduction

The Red Snapper (RS) (*Lutjanus campechanus*) stock in the Gulf of Mexico has been assessed as overfished and undergoing overfishing.[1] In an effort to rebuild the RS fishery, the Gulf of Mexico Fishery Management Council (GMFMC) and the National Marine Fisheries Service (NMFS) have enacted a complex suite of regulations on the commercial and recreational fisheries.[2] The objective of this paper is to evaluate the relative efficiency of a variety of management strategies for the Gulf's red snapper recreational fishery. This analysis will improve upon existing bioeconomic analyses of the proposed RS rebuilding plan through 2032 [1–4] in two important ways: (1) the authors include in the bioeconomic model all types of fishermen targeting RS, including the for-hire recreational sector [7] and; (2) they explore the impact of RS policies on All Reef Fish (ARF) fisheries, including red snapper.[3]

Their most generalizable contribution is in the approach they use to consider the outputs of their bioeconomic model in which they consider the tradeoffs that must be made between the multiple goals that might be pursued by fisheries managers. Biologists are generally concerned with setting regulations so that a fish stock will not be overfished and, if it is overfished, setting regulations on fishing effort (inputs) or outputs (landings) to rebuild the stock. Economists are typically concerned with combining inputs in such a way that will harvest fish in the most economically efficient way to maximize the Present Value (PV) of economic surplus. The authors will use Data Envelopment Analysis (DEA) to estimate a frontier of policy-efficient strategies that considers these two "outputs" of a policy: fish stock and economic surplus. Using simulation analysis, they will examine strategies that are a combination of TAC, bag limits, size limits and opening date in the Gulf of Mexico RS recreational fishery.

There have been many publications measuring technical efficiency in fisheries using stochastic production frontiers or

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[1] A study in 1988 determined the red snapper was overfished [5]. In 1990, Amendment 1 for the Reef Fish FMP reduced the size limit for commercial and recreational fishermen, and set a bag limit for recreational fishermen and a total allowable catch for commercial fishermen [6]. In an update of the December 2, 2009 Amendment, a panel of scientist in New Orleans recommended increasing the catch of red snapper. "Roy Crabtree, the regional administrator for the National Marine Fisheries Service, said the assessment showed that overfishing has ended, but not that 'red snapper has been rebuilt or recovered'" http://www.chron.com/disp/story.mpl/metropolitan/6754722.html. This result was due to using a higher natural mortality rate for juvenile red snapper.

[2] The policies include a prohibition on the use of long lines within the 50-fathom depth, a maximum Total Allowable Catch (TAC) split between the commercial and recreational fishermen, closures when the TAC is reached, size limits for both commercial and recreational fishermen, bag limits for recreational fishermen, trip limits for commercial fishermen, Individual Fishing Quota (IFQ, which replaced the closure and trip limits regulations for the commercial fishermen) and the mandatory use of Bycatch Reduction Devices (BRDs) by shrimp vessels (which catch juvenile RS).

[3] Agar and Sutton [18] looked at multispecies fisheries using a stylized bioeconomic model and determined that gear modification as well as the biological and economics characteristics were important rebuilding strategies.

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DEA [8–16]. These generally use panel data collected from commercial harvesters to examine the fishers' technical efficiency of production. If analysis over time is desired, an index of stock to take account of the change in the stock is needed. If the analysis focuses on a multi-species fishery, then a composite fish stock index for changes in the abundance of each species is created [17].

This analysis uses frontier analysis in a new and different way, focusing not at the level of individual fishers, but on the efficiency of strategies across the entire fishery. The authors use the General Bioeconomic Fishery Simulation Model (GBFSM) to predict economic surplus and actual stocks of fish, negating the need to develop a composite fish stock index. Efficiency frontier analysis is then used to find those strategies that are most successful in achieving the biological and economic policy objectives.

This paper is organized as follows. In the next Section the authors spell out the complexities in identifying optimal policies in multi-species fisheries in which policies have spill over effects on other fisheries. They then present in some detail in the General Bioeconomic Fishery Simulation Model (GBFSM) which will be used to evaluate different policies and then discuss how this simulation model will be used to find the frontier of policy efficient policy options. The remainder of the paper is then focused on using the GBFSM and the policy frontier to evaluate policy options for the management of the Gulf of Mexico's red snapper fishery.

2. Theory

According to the Magnuson–Stevens Fishery Conservation and Management Act of the United States, fisheries are to be managed to maintain Optimum Yield (OY) while minimizing bycatch to the extent practicable [19]. The OY is typically equated with Maximum Sustainable Yield (MSY) of the fishery subject to relevant economic, social and ecological factors which may reduce MSY [19]. Hence, in this paper, it is assumed that the stock associated with OY cannot be lower than the MSY stock (precautionary approach), but could be greater. Powers [20] has pointed out that the ''MSY cannot be calculated until management has defined 'extent practicable'.'' While Powers' research note specifically addresses discards of juvenile RS by shrimp trawl vessels, the discard problem is actually more complicated. When managers introduce Total Allowable Catch (TAC), bag limits, size limits and/or seasonal closures, the discards of the adult RS by recreational and commercial fishermen will change. Fig. 1 depicts the equilibrium stock index (ratio of the fished stock, S, to virgin stock ratio, S_0) and the equilibrium yield curve. The stock ratio that leads to the MSY of this species is called SS_{MSY}. In this figure, the authors show that hypothetically a change in policy that affects the level of juvenile bycatch allowed and the regulations that govern harvesting of adult red snapper can shift the yield curve up or down and the peak of the curve to the right or left changing the MSY.

The standard economic framework focuses on the Maximum Economic Yield (MEY) where the economic yield from the fishery is maximized. Economic yield (or surplus) is equal to net revenue from the commercial fishery plus the net benefits of the recreational fishery. The stock that corresponds with the MEY is typically greater than that associated with MSY [21,22]. On the other hand, if the managers are seeking to maximize the ''present value'' of economic yield, the resulting final equilibrium stock will be less than that associated with MEY since there is an incentive to extract higher levels in the near term with the knowledge that this will result in lower returns later [21]. Hence, the equilibrium stock associated with the maximization of the PV of economic yield, PV-MEY, will typically be lower than that associated with

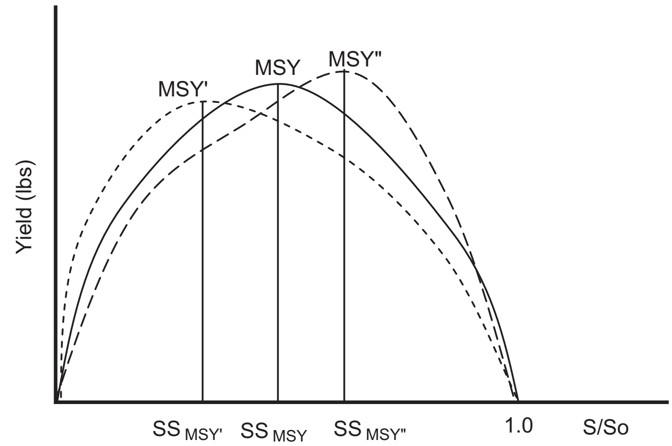

Fig. 1. Population yield curve function of bycatch and range of management allowed.

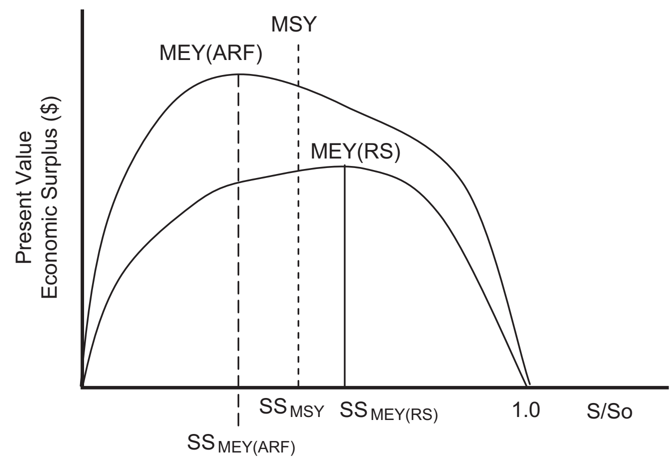

Fig. 2. Population, and economic yield for red snapper and economic yield for all reef fish.

the static sustainable MEY. It is possible for the stock associated with PV-MEY to be greater or less than MSY.

The relationships considered so far become much more complicated when we move from single-species framework to a multiple species. Characterizing the efficiency of a fishery like RS is complicated by the fact that strategies for RS affect all reef fisheries in the Gulf. For example, in recent years, recreational fishermen have had their RS season narrowed down to just a few months. When the recreational RS fishery is closed the recreational fishermen (including for-hire and private boats) turn their attention to other fish. Therefore, when evaluating the efficiency of a strategy, the authors must consider not just RS economic surplus, but that of ARF including RS. The relationship between stock and economic value is illustrated in Fig. 2. In this case, the MEY(RS), which focuses only on a single species, is to the right of MSY, but when ARF is taken into account, MEY(ARF) is to the left of MSY. Since MEY(ARF) leads to a stock below MSY, in this case the optimal policy for RS would be to target MSY. However, if MEY(ARF) was to the right of MSY, then the strategy that will produce MEY(ARF) should be adopted. In other words, because of interactions among the fisheries, it is possible that a strategy that looks quite efficient from the perspective of a single species, can be quite inefficient when all species are taken into account.

While Figs. 1 and 2 are more or less standard, it is rarely appreciated that these curves are actually frontiers rather than functions. For example, in Fig. 2, if the RS stock is at SS_{MEY} and if the policy is such that there is an excessively high level of discard mortality, then the frontier will not be reached. The point on the yield curve is achieved when discard mortality is minimized. Similarly, the economic yield curve is reached only if, for a particular level of total mortality, net benefits to the fishermen are maximized. If costs are too high or revenues are too low, then the frontier will not be achieved. Inefficiencies can arise because of inefficient practices or technology and this is widely appreciated in the fisheries economics literature on efficiency. But inefficiencies can also arise because of poorly designed policies. For example, well-intentioned policies that result in excessive discards, or derby fishing that cause commercial prices to collapse, will result in revenue or benefits well short of the frontier. The present analysis focuses on this second type of efficiency. By looking at the biological and economic impacts of a wide range of strategies, the authors are able to characterize how close each strategy is to the policy efficiency frontier.

3. Methods

3.1. General Bioeconomic Fishery Simulation Model (GBFSM)

The GBFSM is a multiple species, multiple length-based model using cohort analysis and instantaneous mortality. The model predicts landings of each species by the major vessel types that harvest these species as directed catch and as bycatch (discards). A description of the model and its parameterization for the shrimp and reef-fish fisheries of the Gulf of Mexico can be found in Griffin [2]. For the current analysis, modifications were made to GBFSM to allow fishing effort to be re-directed to other fisheries, thereby allowing a given vessel class to continue to fish for other fish. For example, when the TAC is filled, recreational vessels can no longer land RS but they can redirect their fishing effort toward other species, such as vermilion snapper or other reef fish.

The dimensions of GBFSM used in this analysis are a follows:

1) four species of fish (shrimp, RS, vermilion snapper and other reef fish);
2) two regions fished (east and west of the Mississippi River);
3) two depths fished (inshore and offshore);
4) eight vessel types (shrimp vessels <60 ft, shrimp vessels ≥ 60 ft, commercial handline with 2000 pound RS endorsement (HL2000), commercial HandLine (HL), commercial LongLine (LL), recreational for-hire Head Boat (HB) and Charter Boat (CB) and Private Recreational Boat (PB).

In this analysis, for all species, the authors treat the fish east and west of the Mississippi River as separate stocks.[4] The model is calibrated using a variety of data sources. The commercial effort (trips) and landings data are from logbook data for the period of 1993–2005. The recreational data are from MRFSS, head boat and Texas Parks and Wildlife Department for 1993–2002. Commercial cost data for reef fish vessels were provided by NMFS Miami Lab. The shrimp landings data (1965–2006) comes from the NMFS at Galveston. The authors used an approach [23] to expand shrimp effort (days fished) to all shrimp landings files.[5]

The period from 1985 to 2002 is defined as an ''historical'' era, and the authors use the generated data for this period to calibrate GBFSM. The maximum age of RS was set at 35 years; therefore the authors also adopt a ''prehistoric'' period (1935–1984) to get the old fish in the model. The data base is sufficient to generate a quasi-prehistoric data set for the 1935–1984 period, and is used as a ''burn-in'' to scale the model results, which is a procedure similar to that adopted by SEDAR 9 [24]. This prehistoric period allows the authors to ''get the appropriate number of old fish in the model at the appropriate length and weight.''[6] The model uses the von Bertalanffy [25] growth equation where length is a function of actual age on months. After calibrating the prehistoric period (1935–1984), they calibrate the model to predict the historic period (1985–2002), which facilitates realistic policy analysis beyond 2002. They used this same method for vermilion snapper and other reef fish.[7] The authors then run the model from 1993 to 2005 to calibrate the cost and revenue data. Their policy analysis begins in 2006. They use the actual yearly policies for 2006, 2007 and 2008. Differences in strategies proposed will be for the period 2009 through 2032. Prices and unit cost are in 2005 dollars.

The interaction between PV of Consumer Surplus (CS) for RS anglers, vermilion anglers and other reef fish anglers is determined by the recreational demand equation at the end of each simulation time step (month). The recreational demand equation is described in detail in Chapter 3 of Griffin et al. [29]. The coefficients used in the simulation are taken from Model 4 in Table 3.3, with all variables evaluated at their means with two exceptions. Costs per trip are held constant at the average levels by vessel class. Secondly, recreation demand varied during each simulation in response to variation in the Catch Per Unit of Effort (CPUE) by month and vessel class.

In this simulation model, the authors did not determine the directed effort by recreational vessels and species before calibrating the model. Instead, the simulation model first predicts total effort by all recreational vessels, then effort is allocated by vessel and species based on CPUE as follows:

$$DE_{svm} = RE \cdot CPUE_{svm} \bigg/ \left(\sum_{v} \sum_{s} CPUE_{svm} \right)$$

where DE_{svm} is the directed recreational effort to species s by vessel v in month m, RE is the total recreational effort and $CPUE_{svm}$ is the catch per unit effort by vessels, species and month. If the RS fishery is open, then the total recreational effort must be allocated across RS, vermilion snapper and other reef fish. This will cause a positive value for PV of CS for RS and will reduce the PV of CS for vermilion snapper and other reef fish. If the RS fishery is closed, directed effort will only be between vermilion snapper and other reef fish, but all three recreational vessels types will continue to catch RS as bycatch at a reduced catchability coefficient and the RS will be discarded.

3.2. Data Envelopment Analysis (DEA)

Using this model, the authors are able to estimate the policy efficiency of any strategy that might be imposed on the recreational RS fishery. This is accomplished by simulating the economic and biological consequences of 5632 different strategies.

[4] Studies have shown strong demarcation between the populations of red snapper living east and west of the Mississippi river [26]. Two stocks were used in SEDAR 7 [6] which were supported by two assessment workshop papers: SEDAR7-AW-6 [27] and SEDAR7-AW-34 [28].

[5] Days fished for 2006 could not be expanded to all trips due to the very poor quality of the sampling data.

[6] GBFSM is a cohort model instead of an age structured model [33]. The authors prefer the cohort model because actual sample data are collected in the length of fish instead of the age of fish. Therefore, they calibrate the model to the length of the fish and not the age of the fish. However, the model keeps track of the age of the fish, and can report results by both length and age. In addition, they use actual age instead of year-class age, which is adopted in SEDAR assessments.

[7] Details of the shrimp, red snapper, vermilion snapper and other reef fish will be provided in an online appendix or by request.

Using the outcomes from these policies they can then calculate the efficiency of each strategy.

The authors start by looking at the actual 2009 policy, which defines the base strategy for our analysis. This strategy consists of the following policies:

(1) There is a Gulf wide TAC of 5.0 million lbs (mp) of which the commercial fishermen get 51% and the recreational fishermen get 49%;
(2) The commercial fishermen have a minimum size limit of 13 in and the recreational fishermen of 16 in;
(3) The recreational fishermen have a bag limit of 2 fish; and
(4) The recreational fishermen open season is from June 1 to September 30. However, the commercial fishermen do not have a closed season since they went to an Individual Fishermen's Quota (IFQ) in 2007.

Each of the alternative strategies involves a variation on these four policy choices. Only a change in the TAC directly affects commercially landed RS. However, changing the recreational bag limit, minimum size limit or their opening date will affect the commercial fishermen through a stock effect. The "base" strategy used is obtained by holding constant the 2009 strategy through 2032. The base model is used as a reference point from which all alternative strategies are evaluated. That is, for each alternative strategy, the authors measure the change in stock and economic yield relative to the base strategy.

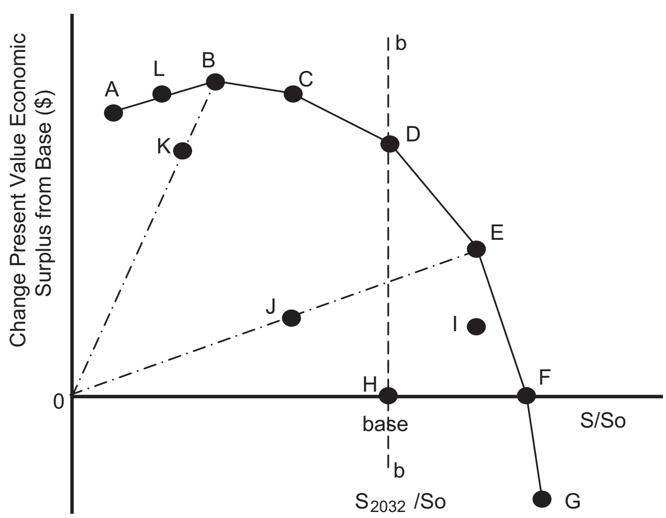

Fig. 3. Production Possibility efficiency frontier for strategies where the output is change in surplus (ΔS) and ratio of current stock of fish to the virgin stock of fish.(S/S_0).

Fig. 3 is a hypothetical representation of the DEA analysis used to determine which strategies are efficient. The vertical axis measures the cumulative discounted consumer and producer surplus (ΔS) for the time period 2009–2032 expressed as the difference from the base-case scenario. The horizontal axis is the ratio of the 2032 stock to the estimated virgin stock (S/S_0). Point H indicates the base simulation referring to the current strategy and it is the reference point for the change in stock ($\Delta S=0$). The first stage in the DEA analysis is to determine which strategies are on the policy efficiency frontier. In Fig. 3, these would be points A, B, C, D, E, F, G and L. These are efficient because there are no strategies that can lead to an increase in surplus without reducing the 2032 stock. The efficiency of any MS would be the distance from the origin to the point divided by the distance for the origin to the policy efficiency frontier; e.g., the efficiency of point J would be 0J/0E. In the authors example, the base strategy (point H) is inefficient since it lies inside the policy efficiency frontier so that $0H/0F<1$. Any point northeast of point H would be superior to the base strategy generating more surplus *and* higher stocks. Points F and E would be considered superior to the base and efficient since they lie on the efficiency frontier and have efficiency value of 1.0. Point I would be superior to the base strategy but is inefficient since it lies inside the efficiency frontier and would have an efficiency value less than 1.0. Points northwest of the base strategy, (J and K) would be superior to the base strategy with respect to the ΔS but inferior with respect to S_{2032}/S_0. They would also be inefficient since they lie inside the policy efficiency frontier.

4. Results

4.1. Base case

Fig. 4 shows the simulated conditions of the RS stock in the east and west for the time period 1965–2032 where 2009–2032 is projected under the base strategy. The S/S_0 ratio is estimated to have hit a low of 0.49 in the east in 1984 and a low of 0.36 in the west in 2004. These ratios differ significantly from those reported in the SEDAR 7 [7] assessment, which suggests that they are at a low of

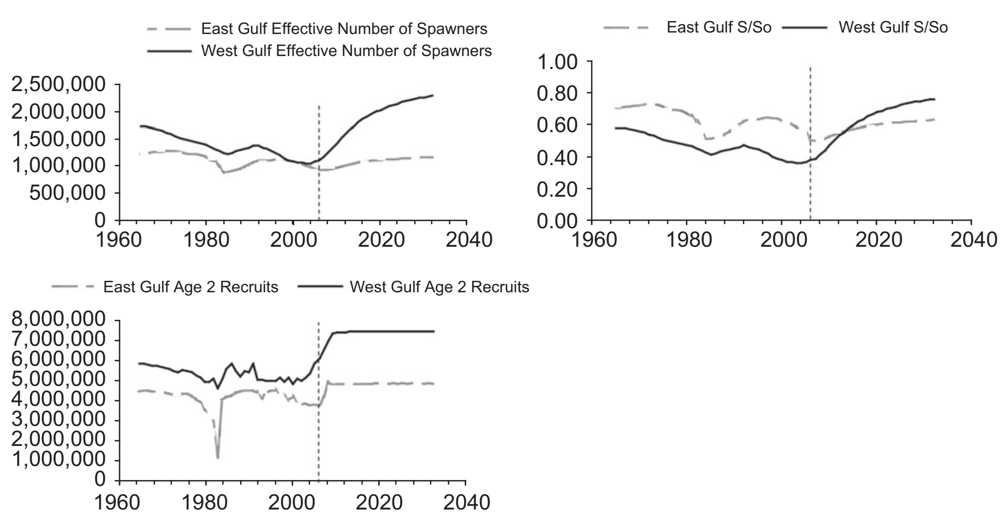

Fig. 4. Base strategy for the effective number of spawners, the ratio of current stock to virgin stock (S/S_0) and number of age 2 fish recruited into the red snapper fisher in the east and west Gulf of Mexico.

Table 1
Comparison of cumulative present value of surplus ($mil) base recreational RS strategy by region, vessel class and fisheries for 2009–2032.

Fishery component	Region East	West	Gulf
Commercial fisheries			
Shrimp commercial Producer Surplus (PS)	246.6	1403.3	1649.9
Red snapper commercial Producer Surplus (PS)	10.2	29.6	39.8
Vermilion snapper commercial Producer Surplus (PS)	18.2	27.2	45.4
Other reef fish commercial Producer Surplus (PS)	148.8	29.7	178.5
Red snapper Commercial producer Surplus (CS)	3.5	9.2	12.7
For-hire sector			
Red snapper for-hire Producer Surplus (PS)	128.2	33.3	161.5
Vermilion snapper for-hire Producer Surplus (PS)	75.4	12.8	88.2
Other reef fish for-hire Producer Surplus (PS)	426.1	176.8	602.9
Recreational consumer surplus			
Red snapper angler Consumer Surplus (CS)	1450.3	144.4	1594.8
Vermilion snapper angler Consumer Surplus (CS)	268.0	37.5	305.6
Other reef fish angler Consumer Surplus (CS)	6209.9	912.1	7122.0
Subtotals			
All red snapper fisheries	1592.2	216.5	1808.8
Non-red snapper reef fish	7146.4	1196.1	8342.6
All commercial fisheries	427.3	1499.0	1926.3
All recreational fisheries (including for-hire sector)	8557.9	1316.9	9875.0
Total CPV	8985.2	2815.9	11801.3

0.05 in the east and 0.02 in the west. As explained in the Appendix, this large discrepancy is due to the fact that the GBFSM uses a density dependent model whereas SEDAR 7 does not and, because GBFSM has a natural mortality for age 0 and age 1, RS is higher than that used in the SEDAR 7 assessment. In the base simulation, age 2 recruits in the east hit a maximum of approximately 4.8 m fish by 2008 and remained fairly constant through 2032. In the west, age 2 recruits hit a maximum of approximately 7.4 m fish by 2010 and remained fairly constant through 2032. It should be noted, however, that in the early 1980s in the east, the age 2 recruits took a sharp decrease in 1983 to almost 1 m age 2 recruits due to a spike in recreational fishing trips. In 1984 a 12 in minimum size was implemented and the model indicates that this was successful in bringing the age 2 recruits back up to historical levels.

The PV of producer PS and CS under the base strategy is given in Table 1. The authors do not include CS for shrimp sector since there are no current estimates of price flexibilities for shrimp and, in any case, demand for Gulf shrimp is certainly highly elastic since the supply from the Gulf is quite small relative to imports which have been the primary determinant of domestic shrimp prices in recent years [30]. CS measures for vermilion snapper and other reef fish are not included because of lack of data. The simulation period is from 2006 to 2032. Since for all simulations (below) the same strategies are imposed during the historical period from 2006 to 2008, Table 1 presents Cumulative Present Value (CPV) for the base case by fisheries for the period from 2009 to 2032. Throughout this analysis, all CPVs are calculated using a 7% discount rate and expressed in 2005 dollars.

A few important points are apparent in Table 1. Together, the CPV for all fisheries is substantial, slightly more than $11.8 billion. It has been estimated that the most valuable fishery is the other reef fish recreational fishery, followed by the commercial shrimp fishery. The value of the recreational for-hire sector is about half that of the shrimp sector. Together, the CPV(CS) for other reef fish anglers and vermilion snapper anglers is almost five times greater than the surplus to RS anglers. The PS that accrues to the for-hire vessels is dominated by the other reef fish, but is almost an order of magnitude smaller than the aggregate recreational CS.

As seen in Table 1, commercial fisheries dominate in the west, while recreational fisheries dominate in the east. This pattern began to appear around 1977 and increased gradually through 1996 as the commercial RS fishery shifted to the west. Then, the recreational fishery shifted east because of the seasonal closure, which began in 1997, directly affecting the part-year residents and spring break vacationers that predominated the west. In recent years, the commercial RS fishery has begun to shift back to the east, although approximately 80% still remains in the west.

4.2. Efficiency frontier

Using the base case as a reference point, the authors turned to a much broader set of strategies to identify the strategies that are on the policy efficiency frontier. The analysis focused on the following range of policy variables for RS recreational fishery:

TAC: from 5 to 36 m pounds in one m pound increments with 51% allocated to the commercial sector and 49% to recreational sector ($n=32$) (base=5.0).
Minimum size limit: from 13 to 16 in in one inch increments ($n=4$) (base=16).
Bag limit: from 1 to 4 fish ($n=4$) (base=2).
Opening of the recreational fishing season: from January 1 to June 1 in half month increments ($n=11$). The GBFSM will close the RS recreational fishery when its share of the TAC is filled (base=June 1).

This led to $5632=32\times4\times4\times11$ strategies, each of which was simulated for the 2009–2032 period.

4.3. Total yield and surplus frontier

Fig. 5 presents the results of the authors' simulation analysis and the resulting policy efficient frontier. In this and all remaining analyses, the entire Gulf is managed with a single set of policies, though the consequences of the management for the east and west are presented separately. Fig. 5 shows the results for the 5632 simulations for the east and west. The vertical axis measures the RS yield in mp in the year 2032, the last simulated year, and the horizontal axis represents the ratio S/S_0. The frontier of policy

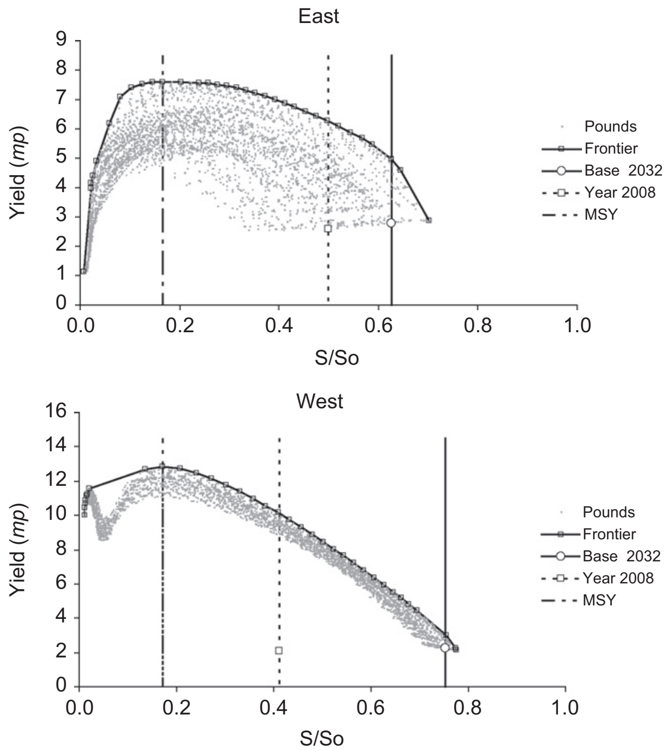

Fig. 5. Sustainable yield curve produced by DEA for red snapper fisheries in the Gulf of Mexico.

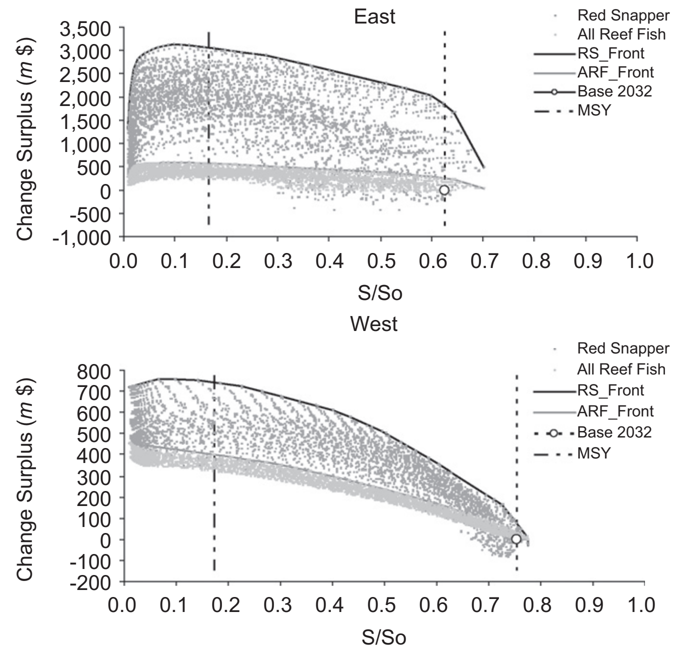

Fig. 6. Comparison of the change in the Present Value Total Surplus for All Reef Fish (ARF) and the Total Surplus for just Red Snapper (RS) fishery when the Gulf is managed as a single unit.

efficient strategies is the upper envelope of the array of outcomes. The interesting thing to note is the spread of the individual strategies in the east is much wider than in the west. In the east, many strategies are far from the frontier, while in the west all of the strategies are grouped relatively close to the frontier. Thus, it is particularly important for policy makers to pay close attention to impacts in the east since they could end up with outcomes where both the stock and the harvests could be greater.

Fig. 6 presents the outcome of the 5632 strategies in economic and biological terms. The vertical axis is the difference between each strategy's Cumulative Present Value (CPV) of surplus and the CPV achieved in the base strategy (ΔCPV). As in Fig. 5, the horizontal axis is the S/S_0 in year 2032. The white dot on the vertical dashed line indicates the base strategy, where $\Delta CPV_{2032}=0$. The authors present both the ΔCPV(RS) and the ΔCPV(ARF), which are the lighter colored symbols.

There are several things that can be gleaned from this figure. First, if only the ΔCPV(RS) is considered then, in the east, the ΔCPV(RS) can be as much as \$3115.4 m more or \$450.9 m less than the base strategy. However, when taking into account the effect on the ΔCPV(ARF), the range of outcomes is much tighter; the ΔCPV(ARF) can be increased by no more than \$585.4 m and can fall by no more than \$62.6 m. The same is true in the west (Fig. 6). This narrowing occurs because any gains from changing RS recreational strategy are largely offset by changes in the surplus in all other reef fisheries. For example, a strategy that leads to improvements in the RS fishery may push effort onto other species, so that the net effect is much smaller than when only RS is taken into account. Hence, when the authors report efficiency measures below, they will be careful to specify whether they are referring to the surplus for RS or ARF.

A second feature of the results in Fig. 6 is that the proportion of the strategies that are ''sustainable'' differs across regions. Of the 5632 strategies considered, almost half of these (2671) lead to a stock in 2032 to the left of MSY in the east, while only around a quarter (1577) lead to a stock to the left of MSY in the west. This result is due to the fact that most of the recreational fishing is in the east, while the greatest stock of RS is in the west. As a result, in terms of controlling the stock, more concern must be given to the effect on the stock in the east than in the west.

Third, we also see in Fig. 6 that the base strategy has a higher stock ratio in the west ($S_{2032}/S_0=0.76$) than in the east ($S_{2032}/S_0=0.63$). This suggests that the base strategy has a much more conservative outcome in rebuilding the RS stock in the west than in the east. We also see that the base strategy is much further from the policy efficiency frontier in the east (0.892 for RS and 0.892 for ARF) than in the west (0.979 for RS and 0.979 for ARF).

Finally, in Fig. 6, any data point to the northeast of the white dot is superior to the base strategy. Since there are more recreational fishermen in the east, there are more opportunities to increase surplus in that region. If the authors pick a point as near as possible to the intersection for the vertical dashed line and the RS efficiency frontier, then they have a strategy that will maintain the same level of RS stock as the base strategy in 2032 which will increase the yield (Fig. 5) and increase the ΔCPV(RS) (Fig. 6) for the west and significantly for the east.

The clearest implication of Fig. 6 is that the impacts in the east and west are different. Although the Gulf is managed as a single unit, the fact that the RS stocks are largely separate (as is assumed in GBFSM) means that the impacts of a single policy will affect the two regions differently—a strategy that looks efficient in the west, may be quite inefficient in the east.

In Fig. 7, the authors present only the policy efficient frontiers, showing both the yield frontiers from Fig. 5 and the economic frontiers from Fig. 6. Symbols on the frontiers indicate the base strategy and the policy efficient strategies that yield MSY and MEY. Since all MEY points lie to the left of MSY, the OY strategy would be to target MSY. The base strategy is far more conservative than the MSY strategies. This is an important policy implication since it indicates that instead of the RS stocks being overfished, as stated in the SEDAR 7 RS stock assessment, they actually are underfished

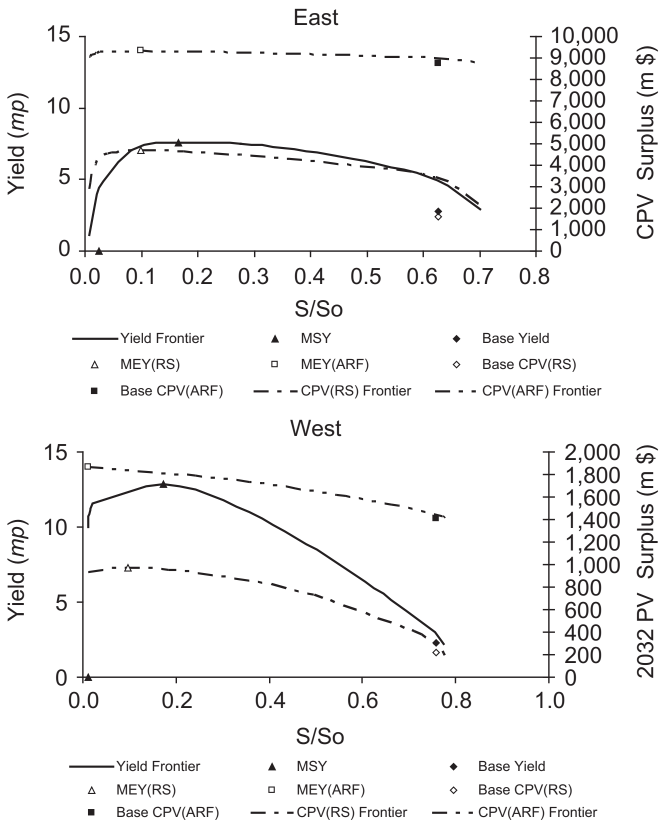

Fig. 7. DEA calculations for yield and Cumulative Present Value (CPV) for years 2009–2032 in the east and west Gulf.

Table 2
Base and MSY recreational RS strategies in the east and west Gulf for 2009–2032.

	Base	MSY(east)	MSY(west)
Gulf-wide recreational RS strategies			
TAC (mp)	5	30	32
Bag (no.)	2	1	1
Min size (in)	16	13	13
Open date	1-June	16-January	16-January
Red snapper S/So			
East	0.63	0.16	0.13
West	0.76	0.24	0.17
Efficiency w.r.t. change in surplus			
East (RS)	0.89	0.91	0.89
West (RS)	0.98	0.78	0.76
East (ARF)	0.89	0.95	0.94
West (ARF)	0.98	1.00	1.00
Red snapper landings (mp)			
East commercial	0.70	3.23	3.44
West commercial	1.85	11.91	12.35
East recreational	2.09	4.36	4.10
West recreational	0.42	0.57	0.51
Gulf commercial	2.55	15.14	15.79
Gulf recreational	2.51	4.93	4.61
Gulf total	5.06	20.07	20.40
Change in surplus from base (m $)			
East (RS)	0.00	2759	2755
West (RS)	0.00	524	545
East (ARF)	0.00	537	544
West (ARF)	0.00	375	398
Gulf (RS)	0.00	3283	3300
Gulf (ARF)	0.00	912	942

under current policies. The result is not that surprising when one considers that SEDAR 7 did not allow for density dependence, which Gazey et al. [31] have demonstrated exists.[8] From the perspective of just the RS surplus, not only is the base strategy suboptimal in the east and west, it is also quite inefficient in the east. When the authors look at the base CPV(ARF), however, they find that it is very near its frontier, implying that with respect to ARF the base strategy is rather efficient.

Table 2 shows the set of policies associated with the base, MSY(east) and MSY(west) identified in Fig. 7. The MSY(east) and the MSY(west) are much more aggressive than for base strategy. While the base strategy opens the RS recreational fishery on June 1, the two optimal policies open January 16. Both the east and west have a 1-fish bag limit compared to the base 2-fish bag limit and they both have a size limit of 13 in versus the base which is 16 in. The most striking feature of the results in Table 2 is a Gulf-wide TAC of 30 mp for MSY(east) and 32 mp for MSY(west). This is perhaps surprising since there has never been that much RS actually landed in the Gulf. The maximum landing in the Gulf was about 14 mp in both 1964 and 1965. The reason for this result is that we hold constant a commercial share of the TAC at 51%, the highest level of commercial landings in any of the MSY strategies presented in Table 2 is about 15–16 mp. However, our model finds that recreational landings are significantly less than their 49% share of these large TACs (less than 5.0 mp). Hence, although, the Gulf-wide TAC is 30–32 mp, the total yield for the Gulf is a little above 20 mp. The result of sub-TAC harvests by the recreational fisherman follows from the estimated demand functions in which recreation demand is found to be relatively inelastic to an increase in the allowable catch; even if the recreational TAC is increased substantially, actual harvests may not increase that much. Moreover, as the stock declines, the catch per day will fall, leading to a reduction in recreational effort directed at RS. Hence, except for the base strategy, the MSY TACs do not impose binding constraints on the recreational fishery.

Since historical landings have never been greater than 14.0 mp and the authors are suggesting that MSY is about 20 mp, it is fair to ask if their model predictions are realistic. The authors believe they are for two reasons. First, in 1964 and 1965 there were no regulations for the red snapper fishery so commercial and recreational fishermen could land as many red snapper as they wanted and any size they wanted. It was not until 1984 that the first regulation was implemented which was a 12 in minimum size limit and according to Fig. 4 this stopped the sharp decline in age-2 recruits in the east. Hence, the policy environment has improved so that high levels of catch can probably be sustained. Second, according to the isopleths of MSY of the SEDAR 7 stock assessment, these Gulf-wide landings are within a realistic range.

In Table 2, we find evidence for the problem created by having a single Gulf-wide strategy. Although there is only 2 mp difference in the TACs for east and west (Table 2), choosing a strategy that will yield MSY(west) will result in a stock in the east that is left of MSY(east) which would not be acceptable to fishery managers. On the other hand, choosing a strategy that will produce MSY(east) will result in a stock in the west that is to the right of MSY(west) which would be acceptable to fishery managers.

In Table 2, the authors also present the ΔCPV from the base strategy. Both the east and west MSY strategies increase the surplus relative to the base strategy by approximately the same amount. The increase in the ΔCPV(RS) in the east is approximately five time greater than the ΔCPV(RS) in the west. This is because the east has 80% of the recreational trips and the west has 80% of the commercial

[8] As discussed below, in response to Gazey et al. [30], policies have recently changed. However, it can be seen that even the revised policies are both suboptimal and inefficient.

trips. However, when taking ARF into account, the gain is ΔCPV is much less then when only considering RS. This is because as the RS TAC increases, both the commercial and recreational fishermen will spend more of their time directing effort at RS and less time directing effort at vermilion snapper and other reef fish. Hence, while the PS and CS increase for RS, it declines for vermilion snapper and other reef fish (Table 3) and that will have a benefit to all other reef fish stocks. Therefore, when considering strategies for RS the impact on all other reef fish must be considered.

As noted above, the base strategy is not only suboptimal in the east and west, it is also quite inefficient in the east. Other strategies exist that could achieve greater economic outcomes while maintaining the same level of stock as the base strategy in 2032. Focusing on one region at a time, in Table 4 the authors show strategies that are at least 95% efficient with respect to the ΔCPV(RS) and ΔCPV(ARF), and ensure that the 2032 stock level is maintained at or above the base stock ratio, i.e. where $S_i/S_0 \geq S_{2032}/S_0$ by region. The strategies that maximize regional surplus subject to the constraint that the final stock ratio is at least equal to base S_{2032}/S_0 ratio are similar for the east and west. The east TAC is two mp greater the west, the size limit is 1 in less than the east and the opening date is only a half month later in the west, but both begin in January. Both the recreational and commercial fishermen harvest their share of the TAC. The ΔCPV(RS) for the east best strategy (1783.1 m $) is twice that of the best strategy for the west (891.8 m $) which is due to there being more recreational fishermen in the east then in the west and the recreational fishermen can harvest an additional 1.0 mp of RS. Finally, choosing the best strategy for the east would leave west RS stock with a ratio just shy of the base strategy (0.73 versus 0.76). Choosing the best strategy for the west would rebuild the RS stock in the east to a slightly greater level than the base level (0.64 versus 0.63).

Finally, at the bottom of Table 4 is a summary of the outcome of the newly adopted strategy for 2010. The GMFMC met in February 2010 to consider increasing the TAC for RS since SEDAR determined that the stock was not undergoing overfishing based on the higher juvenile natural mortality rate proposed by Gazey et al. [31]. The Council set the TAC for 2010 at 6.91 mp. The authors include this strategy in Table 4, rounding the TAC to 7 mp. The efficiency rates and stock levels are below the base and the best east and west strategies. The predicted ΔCPV(RS) will be $791.5 m but the gain for ΔCPV(ARF) will only be $153.8 m. This is below the best strategy for the east and west except for the ΔCPV(ARF) of the west best strategy. The main difference between the February 2010 strategy and the best east and

Table 3
Change in surplus from base to MSY by region and species for years 2009–2032.

Fishery component	MSY(east)			MSY(west)		
	East	West	Gulf	East	West	Gulf
Commercial fisheries						
Red snapper commercial Producer Surplus (PS)	78.8	296.3	375.2	82.9	316.4	399.2
Vermilion snapper commercial Producer Surplus (PS)	0.0	0.0	0.0	0.0	0.0	0.0
Other reef fish commercial Producer Surplus (PS)	0.0	0.0	0.0	0.0	0.0	0.0
Red snapper Commercial Producer Surplus (CS)	12.3	47.3	59.7	13.0	50.5	63.5
For-hire sector						
Red snapper for-hire Producer Surplus (PS)	113.2	12.3	125.5	114.7	11.8	126.5
Vermilion snapper for-hire Producer Surplus (PS)	−10.5	−2.3	−12.8	−10.7	−2.2	−13.0
Other reef fish for-hire Producer Surplus (PS)	−197.3	−22.1	−219.3	−198.7	−21.2	−219.9
Recreational consumer surplus						
Red snapper angler Consumer Surplus (CS)	2554.6	168.3	2,722.8	2,544.3	166.3	2,710.6
Vermilion snapper angler Consumer Surplus (CS)	−69.0	−16.5	−85.5	−68.8	−16.4	−85.2
Other reef fish angler Consumer Surplus (CS)	−1944.9	−108.8	−2,053.7	−1,932.5	−107.2	−2,039.6

Table 4
Summary of base and 2010 strategies, and strategies on or near the policy efficiency frontier where $S_i/S_0 \geq S_{2032}/S_0$ by region

	S/S_0		Recreational RS strategies				Change total surplus east and west (m $)		Efficiency rate		Red snapper landings east and west (m lbs)		
	East	West	TAC (mp)	Bag limit (no.)	Min size limit (in)	Open date	Red snapper	All reef fish	Red snapper	All reef fish	Com.	Rec.	Total
Base management strategy													
East	0.626		5	2	16	1-June	0.0	0.0	0.89	0.89	0.7	2.1	2.8
West		0.757					0.0	0.0	0.98	0.98	1.8	0.4	2.3
Gulf							0.0	0.0			2.6	2.5	5.1
East best strategy where $S_i/S_0 >= S_{base}/S_0$													
East	0.644		8	1	16	1-January	1662.7	220.6	1.00	1.00	1.2	3.4	4.6
West		0.731					120.4	52.5	0.99	0.99	2.9	0.5	3.4
Gulf							1783.1	273.0			4.1	3.9	8.0
West best strategy where $S_i/S_0 >= S_{base}/S_0$													
East	0.637		6	1	15	16-January	826.9	93.1	0.93	0.93	0.8	2.6	3.4
West		0.752					43.2	27.5	0.98	0.99	2.2	0.4	2.6
Gulf							870.0	120.6			3.1	2.9	6.0
Gulf of Mexico Fishery Management Council management strategy, February 2010													
East	0.566		7	2	16	1-June	718.9	125.6	0.83	0.85	1.0	2.9	3.9
West		0.723					72.6	28.2	0.96	0.96	2.6	0.5	3.2
Gulf							791.5	153.8			3.6	3.5	7.0

west strategies is the bag limit reduced to 1-fish and the opening date of the recreational RS fishery in January rather then June.

In summary, the authors looked at a single Gulf-wide strategies that will yield MSY(east) and MSY(west) and strategies that will yield a higher ΔCPV(RS) and ΔCPV(ARF), and ensure that the 2032 stock level is maintained at or above the base stock ratio. Referring back to Fig. 6, they saw numerous strategies between the base strategy and MSY(east) and MSY(west) that were near the policy efficient frontier. They then turned their attention to managing the regions, east and west, as separate management units that are at least 95% efficient.

4.4. Single management units for east and west that are 95% efficient

In this section, the authors narrowed their focus to look at a set of strategies that (1) have efficiency ratings of at least 95% for both RS and ARF, (2) result in positive ΔCPV for RS and ARF and (3) result in 2032 stocks that are equal to or to the right of MSY. First they examined strategies that met these criteria for one region at a time, then they examined the smaller set of strategies that satisfy these criteria for both the east and west.

Best Strategies for the East: Fig. 8 shows the percent frequencies of each of the four recreational regulations considered that are 95% efficient. Out of the 5632 simulations, only 191 management strategies (3.4%) meet the three criteria set out above for the east. It can be seen that the TACs range from 6 to 22 mp. At one extreme, the 6 mp TAC is the most conservative TAC for the east and is to the right of the base strategy ($S_i/S_0 \geq S_{2032}/S_0$). As the TAC increases, the terminal stock moves toward the OY (the efficiency frontier at MSY). The number of TACs that are at least 95% drops sharply after 16 mp. The bag limit is the most constraining factor for the east. Only a bag limit of 1- or 2-fish are in the 95% efficient strategies but only the 2-fish bag limit is associated with OY. All four size limits

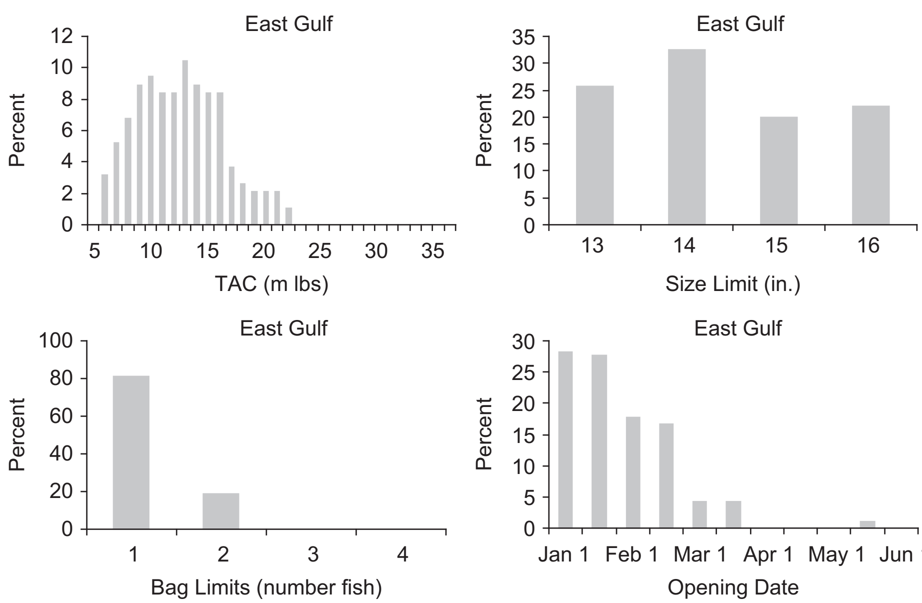

Fig. 8. Frequency of recreational regulations in the East Gulf for strategies (MS) that are at least 95% efficient for Red Snapper (RS) and All Reef Fish (ARF) Total = 191.

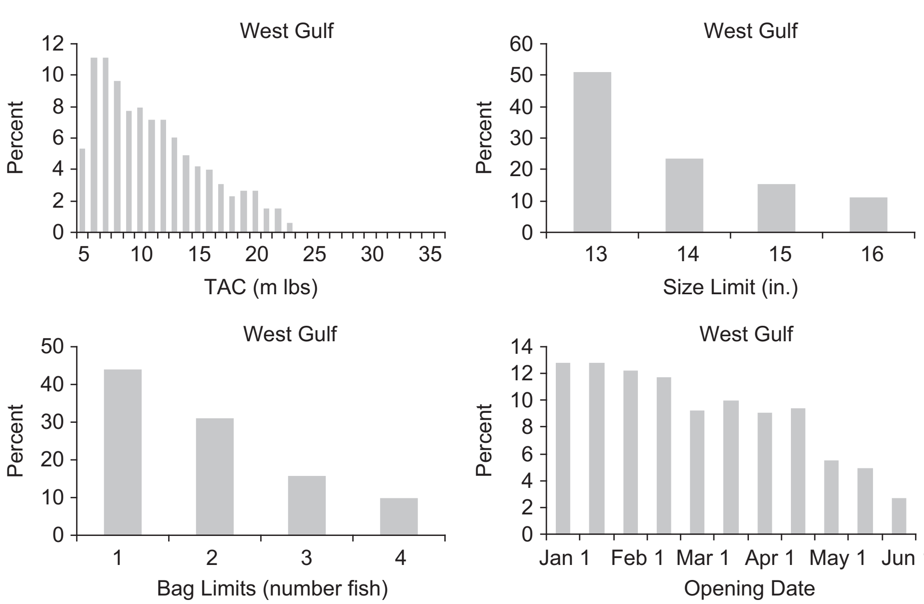

Fig. 9. Frequency of recreational regulations in the West Gulf for Strategies (MS) that are at least 95% Efficient for Red Snapper (RS) and All Reef Fish (ARF) Total = 522.

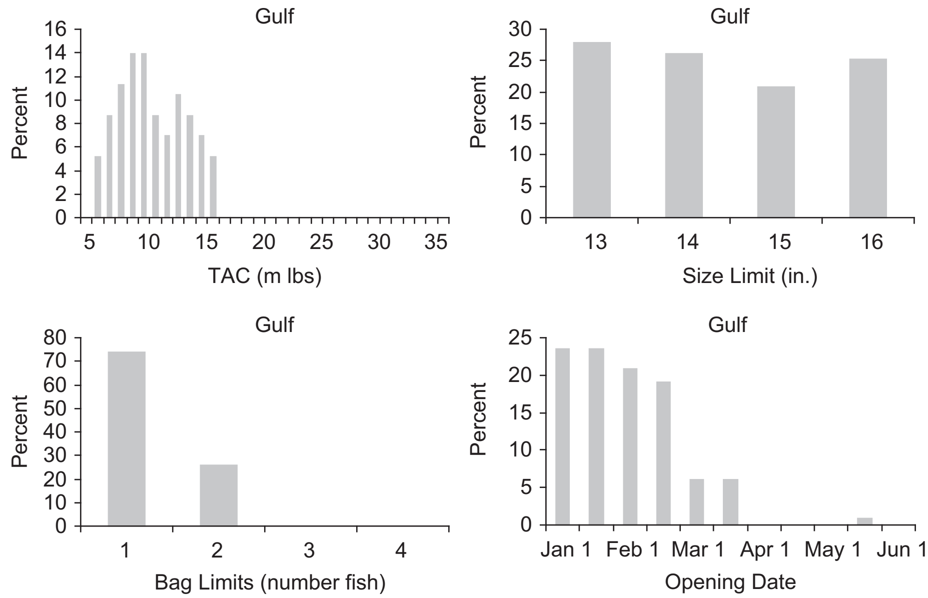

Fig. 10. Frequency of recreational regulations in the Gulf for strategies that are at least 95% efficient in both the East and West Gulf for Red Snapper (RS) and All Reef Fish (ARF) Total=115.

are included in the 95% efficient strategies. However, only the 13 and 14 in are associated with OY. The opening of the season should be no later than March 15. With respect to the west, 115 of these strategies are at least 95% efficient; however, the west will be underfished by a substantial amount.

Best Strategies for the West: There are 522 strategies (9.3%) that are consistent with the authors' three criteria when only the impacts in the west are considered. This is more the 2.7 times the number of strategies met these criteria for the east. This is because policy options are more constrained in the east since it has the smaller stock and a greater number of recreational fishermen. In Fig. 9, the TACs range from 5 to 23 mp with the lower TAC being associated with the higher stock size. All four bag limits are included in the set of strategies; 1- and 2-fish bag limits are associated with the higher stock sized and the 3- and 4-fish bag limits are associated with the OY. While all four size limits are included in the 95% efficient strategies, only the 13 in fish is associated with OY. All eleven opening dates are included in the 95% efficient strategies. January and February opening dates are all along the efficiency frontier but these two months have strategies that are more closely related to OY than other opening dates. Opening dates beginning in May take a sharp jump away from OY. While attractive from the perspective of the west, with respect to the east, 407 of these strategies are not efficient at the 95% level and 120 would lead to 2032 stocks that are to the left of the OY.

Best Strategies for the Whole Gulf: Finally, in Fig. 10 they present the 115 strategies (2.0%) that meet their three criteria for both the east and the west. The lesson here is when a single strategy must be employed for the entire Gulf, it tends to look like a policy focused on the east, though even more conservative with regard to the TAC. There is no single policy that can achieve OY in both the east and west. While it is possible to find a single policy for the entire Gulf that achieves OY in the east, under that policy the west will remain underfished.

5. Conclusion

In this paper, the authors analyzed a wide range of Gulf of Mexico recreational RS strategies for their impacts on yield, economic surplus and the fish stock. They used DEA inspired policy efficiency frontier to estimate an efficient sustainable yield frontier, a PV(RS) economic surplus frontier and a PV(ARF) economic surplus frontier for both the east and west Gulf. As exhibited in their analysis of this particular fishery, the policy frontier framework offers a useful way to evaluate a wide range of strategies taking into account the competing goals that policy makers may have.

The RS stock has been declared overfished since 1988 and the 2005 SEDAR 7 stock assessment declared RS were overfished and undergoing overfishing. In November 2009, the update of the assessment declared that overfishing was no longer occurring but that the RS stocks need to be rebuilt and suggested increasing the Gulf-wide TAC to almost 7 mp. In this analysis, they found that RS are neither overfished nor undergoing overfishing. The main difference in their model and SEDAR 7 model is that the authors use a higher mortality rate for juveniles and a density dependent model.

The results suggest that the base strategy in the west is efficient (0.979 for RS and 0.979 for ARF) but less efficient in the east 0.892 for RS and 0.892 for ARF). However, the base strategy in both the east and west results in a much higher stock level than a strategy that would produce MSY. This suggests that the RS are underfished in both the east and west. At a minimum, the present analysis suggests that policy efficiency gains could be achieved if more aggressive policies were introduced that moved the stock if not to OY, at least in the direction of "Pretty Good Yield" [31].

The authors also found that what may be an efficient strategy in the east may not be an efficient strategy in the west Gulf. Choosing a strategy that is best for the east would result in sustainable stocks for both the east and west, but choosing a strategy that is best for the west would definitely produce overfishing in the east. Therefore, a "one size fits all" strategy is not necessarily the correct approach when changing recreational RS strategy for the whole Gulf. To be efficient the east, requires a lower TAC, a lower bag limit and an earlier opening date then the west. The west has a preference for a smaller size limit. The need for a lower TAC in the east is simply because there is a smaller stock in the east and with a single Gulf-wide strategy a lower TAC must be set so that the RS stock in the east will not be overfished east. Having a lower bag limit allows for a longer fishing season which recreational fishermen prefer. Thus, it is suggested that the east and the west for RS management be divided into two separate management zones. It is, however, important to note that if policies in the east and west differ, then fishermen will adapt to this new policy environment in ways that are not entirely predictable based on historical evidence.

Finally, one very interesting conclusion is that the recreational TAC and recreational seasonal closures for RS become a nonbinding constraint and are unnecessary under some strategies. For example, if the Gulf-wide TAC for RS is set at 30 mp and the recreational fishermen are allocated 49% of the TAC or 14.7 mp, the model predicts that even if they fish all year long, the recreational fishermen will only harvest about 5 mp. The authors suggest that not only should the east and west be managed as separate zones, but there needs to be an evaluation for of the percent given to recreational and commercial fishermen in each management zone.

Acknowledgements

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Appendix

Calibration of GBFSM[9] yielded results that differ in a number of ways from the SEDAR 7 assessments. To calibrate four different species (shrimp, red snapper, vermilion snapper and other reef fish) in a single model, we select January 1 as the beginning of a year in GBFSM. Further, the authors simulate all fish at actual age instead of year classes as does SEDAR 7 assessments, which may contribute to some of the differences between their results and those of previous research. They also use a density dependent model whereas the SEDAR 7 assessment did not. Gazey et al. [30] have shown that red snapper are density dependent. More importantly, unlike SEDAR 7, they incorporate the applicable fishing policies in the appropriate years in our calibrating process, to obtain more realistic estimations. That is, for each year they imposed the policies that were in effect for that year.

The authors considered four cases of natural mortalities for juvenile red snapper in their calibration process, as shown in the Table A1. Case 1 is used in SEDAR 7 and yields a Shrimper Fishing Index of 1. Gazey et al. [30] have suggested that M_0 is much higher for red snapper and they estimated a value of $M_0=2.03$ and $M_1=1.25$. Wells et al. [32] estimated that M_0 could range from 2.6 to 11.0 depending on the habitat characteristics[10] and if it is a trawled or non-trawled fishing area. As the natural mortality of red snappers increases for age 0 and age 1 groups, from Cases 1 to 4, the Shrimper's fishing index decreases from 1 to 0.05926. This relationship suggests that the impact of shrimpers on the red snapper fishing industry diminishes while the natural mortality of juvenile red snappers rises. Gazey et al. [31] report in their estimation that age-0 mortality exceeds 2.03 and age-1 mortality exceeds 1.25 at a probability of 95%. Consequently, the authors selected Case 2 for the calibrating the model. At the December 2, 2009 GMFMC meeting 'Roy Crabtree, the regional administrator for the National Marine Fisheries Service, said the assessment showed that overfishing has ended, but not that 'red snapper has been rebuilt or recovered' http://www.chron.com/disp/story.mpl/metropolitan/6754722.html. This result was due to using a higher natural mortality rate for juvenile red snapper.

It should be noted that, although the present analysis uses a bioeconomic model, it does not represent the official biological research finding of the NMFS about the status of the red snapper stock in the Gulf of Mexico (Gulf). Therefore, the authors present their biological findings as suggestive rather than definitive. However, it is strongly recommended that future stock assessments by SEDAR should consider the recent contributions of Gazey et al. [31] and Wells et al. [32].

For vermilion snapper the natural mortality for all ages was $0.25\ \text{yr}^{-1}$ [23,26,32]. It seems only logical that age 1 fish would have a higher natural mortality than age 2+ fish and age 0 would be higher than age 1 fish. Underestimating natural mortality for age 0 and age 1 fish will result in an overestimate of shrimp bycatch relative to the total number of age 0 and age 1 fish recruited into the fishery. Therefore, given no other guidance from the literature, the authors use a natural mortality for age 0 of $1.0\ \text{yr}^{-1}$, age 1 of $0.5\ \text{yr}^{-1}$ and age 2 and above of $0.25\ \text{yr}^{--1}$.

Table A1
Natural mortality by age for red snapper.

Case	Age			Shrimper's fishing index	Remark
	0	1	2+		
1	0.98	0.59	0.1	1.00000	SEDAR 7, 2005
2	2.03	1.25	0.1	0.36074	Gazey, Gallaway and Fournier
3	4.00	1.25	0.1	0.08519	Intermediate case
4	7.665	1.25	0.1	0.05926	Wells, Cowan, Patterson and Walters

[9] For a detailed discussion of the calibration of the GBFSM see Griffin, et al. [28], Appendix A.

[10] Wells et al. [32] state that, "Shell-rubble and reef habitats may be important for red snapper by providing protection from predators; however, the sand and mud habitat appears to be the most important for enhancing production and early life survival of age 0 fish based upon faster daily growth rates and higher production potential."

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