Environmental and Resource Economics (2022) 82:483–506
https://doi.org/10.1007/s10640-022-00687-w

Overcapacity in Gulf of Mexico reef fish IFQ fisheries: 12 years after the adoption of IFQs

Juan Agar[1] · **William C. Horrace**[2] · **Christopher F. Parmeter**[3]

Accepted: 8 April 2022 / Published online: 2 May 2022

Abstract

We study the impacts of individual fishing quota programs on overcapacity and the technical efficiency of the Gulf of Mexico red snapper and grouper-tilefish fisheries. We deploy generalized panel data stochastic frontier methods, which allow us to decompose time invariant heterogeneity into both vessel specific heterogeneity and persistent inefficiency. This type of decomposition has recently seen interest in a variety of applied production settings but marks the first use in fishery studies. Our main findings show that roughly 20% of red snapper fleet size could have harvested the entire red snapper quota and that the time-varying technical efficiency of the red snapper fleet grew by 6% post-IFQ. We also find that 57% of the Gulf reef fish IFQ fishery (red snapper combined with grouper-tilefish), had it operated at full efficiency, could have harvested the quota in the early stages of the IFQ program (2011–2016), and that the time-varying technical efficiency of the fleet rose by 5% post-IFQ. “The views and opinions provided or implied in this manuscript are those of the authors and do not necessarily reflect the positions or policies of NOAA”.

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1 Introduction

The Magnson-Stevens Act (MSA) mandates recurring evaluations of the performance of US catch shares programs. Comprehensive evaluations are required every 5 to 7 years. In January 2007, the Gulf of Mexico (Gulf) Fishery Management Council (Council)

This paper was previously circulated under the title “Fleet Capacity Dynamics in the Gulf of Mexico Red Snapper Fishery: 12 years after the IFQ”.

✉ Christopher F. Parmeter
cparmeter@bus.miami.edu

William C. Horrace
whorrace@syr.edu

1 NOAA, Miami, USA

2 Department of Economics, Syracuse University, Syracuse, USA

3 Department of Economics, University of Miami, Miami, USA

implemented Amendment 26 to the Fishery Management Plan for Reef Fish Resources of the Gulf of Mexico (GOMRF FMP), which established an individual fishing quota (IFQ) program for the commercial red snapper (*Lutjanus campechanus*) fishery. The purpose of the program was to reduce overcapacity and, to the extent possible, lessen the incentive to out-compete other fishermen for a share of the total allowable quota. The initial 5-year review of the IFQ program indicated that the program had been successful mitigating derby fishing conditions but the harvesting potential of the fleet remained significantly above the reproductive potential of the resource. (Solís et al. 2015b) estimated that about 1/5 of the fleet could harvest the entire commercial quota. In 2010, Amendment 29 to GOMRF FMP established the grouper-tilefish IFQ program, which has 13 fish species from the families *Serranidae* and *Malacanthidae*, of which red grouper (*Epinephelus morio*) accounts for more than 50% of the revenues SERO (2019a). The main objectives of this program are to mitigate derby-fishing conditions and reduce overcapacity in these commercial fisheries. The 5-year review of this latter program also showed that it had been successful mitigating derby-fishing conditions, but overcapacity remained high.

This study examines the on-going performance of these programs towards reducing overcapacity and augmenting technical efficiency. To this end, we consider two scenarios. The first scenario considers the red snapper IFQ as a fishery unto itself; whereas the second scenario considers it part of the Gulf reef fish IFQ fishery (red snapper plus grouper-tilefish) because most of the fleet lands both red snapper and grouper-tilefish species. (SERO 2019a) reports that the proportion of grouper-tilefish vessels landing red snapper rose from 78% in 2010 to 91% in 2018.

To contribute to the Council's decision-making, this study takes advantage of novel econometric developments that account for vessel-specific heterogeneity, which helps generate improved technical efficiency (TE) and overcapacity measures. Accounting for vessel specific heterogeneity is important beyond academic interest because TE estimates can vary widely depending on whether transient inefficiency, persistent inefficiency, or both, are modeled explicitly; thus, failing to understand the implications of these sources of inefficiency could result in policies that have unintended consequences (Kumbhakar and Lien 2018).

Our study follows several recent papers focusing on IFQs more generally, both in the Gulf of Mexico (Solís et al. 2014, 2015a, b) and elsewhere.[1] For example (Schnier and Felthoven 2013), using the vessel exit model of Tsionas and Papadogonas (2006) study the impact of IFQs and exit decisions due to the implementation of IFQs in the Bering Sea and Aleutian Island fisheries in Alaska while (Mainardi 2019) (who also develops a selection model to pair with a stochastic frontier framework) studies IFQ impacts in the Falkland/Malvinas Islands (see also Mainardi 2021). Reimer et al. (2017) provide a detailed discussion of the policy implications of studying IFQs in a pre-post setting.

We also connect with the large literature studying TE in fisheries around the globe: Sharma & Leung (1998, the Hawaiian long-line fishery), Kirkley, Squires & Strand (1998, mid-Atlantic sea scallop fishery), Squires & Kirkley (1999, Pacific Coast trawl fishery), Binh, D'Haese, Speelman & D'Haese (2010, Mekong River Delta fishery), Guttormsen & Roll (2011, Norwegian groundfish fishery) and Álvarez, Couce & Trujillo (2020, Gran Canaria artisanal fishery), to name a few. There are many interesting hypotheses that can be investigated with knowledge of vessel level inefficiency. For example, both Kirkley et al.

[1] (Solís et al. 2015a) provide an overview of empirical studies examining capacity in fisheries.

(1998) and Alvarez and Schmidt (2006) study the "good captain hypothesis". A key finding from Alvarez and Schmidt (2006) is that the level of data aggregation (using trip level versus season or year averaged level) plays a role in how much "luck" (noise) or "skill" (technical efficiency) reveals itself. This result has important implications for the level of data aggregation as it pertains to the ratio of variances between noise and efficiency.

A common feature of many of the studies of TE of vessels that have access to panel data is that they do not include vessel specific fixed effects. Some notable exceptions include (Reimer et al. 2017) who use Greene's (2005) "true" fixed effects stochastic panel data frontier model to estimate a hyperbolic distance function and (Huang et al. 2018) who include vessel specific fixed effects in a multi-output stochastic production frontier. To our knowledge, there has yet to be an attempt in the fisheries literature to decompose unobserved vessel specific heterogeneity into idiosyncratic heterogeneity and time-invariant (persistent) technical efficiency (Kumbhakar et al. 2014).

A final important aspect of empirical specification of the fishing technology, and one that we will speak to, is the ability to measure excess capacity in limited access privilege programs, such as IFQs Reimer et al. (2017).[2] The estimation of excess capacity is one that requires delicacy; as noted by Kirkley, Paul & Squires (2004, pg. 272) "Effectively dealing with excess capacity in a given fishery, however, requires both establishing the extent of the problem by estimating the magnitude of excess capacity, and determining how particular boats in the fleet contribute to this capacity, rather than arbitrarily imposing a particular capacity reduction."

The setting of arbitrary levels is fraught with issues pertaining to measurement of capacity. Certainly for any given quota, it is an easy exercise to assess how many fewer vessels could meet such quota if they increased inputs, days at sea or technical efficiency. However, what an analysis of this sort misses is how best to measure capacity that maximizes the value of quota relative to the dockside prices that vessels receive when they offload their catch. This is, to our knowledge, an unexplored issue in the assessment of capacity utilization literature but one that deserves further attention.

This analysis re-evaluates the efficacy of the red snapper and grouper-tilefish IFQ programs to reduce overcapacity which have been in place since 2007 and 2010, respectively. Using recently developed generalized panel data stochastic frontier methods, we estimate an output-oriented distance function to measure both time-varying and time-constant vessel efficiency for both the red snapper and grouper-tilefish fisheries of the Gulf of Mexico from 2002 to 2018.

There are several major findings from our analysis. First, we estimated that 20% of the red snapper IFQ fleet, had it operated at full efficiency, could have harvested the red snapper quota, and that, 57% of the Gulf reef fish IFQ fleet, had it operated at full efficiency, could have harvested the combined red snapper and grouper-tilefish quotas in the early stages of the program (2011–2016). Second, time varying technical efficiency increased post-IFQ. In the case of the red snapper fishery it grew by 6% and in the case of the Gulf reef fish fishery it increased by 5%. Third, fleet capacity increased by 35% in the red snapper fishery and by 7% in the Gulf reef fish IFQ fishery, post-IFQ. Finally, the fleet as a whole has enjoyed increasing returns to scale throughout the sample period with a noticeable improvement after the IFQ was in place.

[2] Earlier work studying excess capacity include (Pascoe and Coglan 2000; Felthoven 2002; Felthoven et al. 2009) and (Horrace and Schnier 2010).

2 Gulf of Mexico Red Snapper and Grouper-Tilefish Fisheries

There are two IFQ programs in the Gulf of Mexico. The red snapper program and the grouper-tilefish program, which has five share categories: red grouper, gag, other shallow-water groupers, deep-water groupers, and tilefishes (SERO 2019a, b). In 2018, the commercial fleet landed about 6.3 million pounds (gutted weight) of red snapper worth $30 million (USD) in dockside revenues and 4.3 million pounds of grouper-tilefish worth $20.4 million (USD) in dockside revenues (SERO 2019a, b). Red grouper makes about half of the grouper-tilefish landings and revenues. Vertical line and longline vessels are the main gears that participate in these programs. Although, most of the vessels jointly catch species from both programs within a trip, vertical line vessels catch most of the red snapper and longline vessels catch most of the grouper-tilefish species, particularly red grouper. The contemporary federal commercial management history of these fisheries can be divided into a "command and control" period and an IFQ (or catch share) period.

2.1 The Red Snapper Fishery

Here we provide a brief overview of the Gulf of Mexico red snapper fishery.[3] The command and control period (1984–2006) began with the adoption of the GOMR FMP in 1984. This FMP aimed to attain the greatest overall benefit to the nation by increasing the yield of the reef fish fishery, minimizing user conflicts in near shore waters, and protecting juvenile reef fish and their habitats (Waters 2001).

Ensuing management measures that sought to protect the red snapper stock included minimum size limits and quotas; however, stock assessments concluded that the stock was in worse condition than expected, resulting in tighter regulations (Table 1). These more stringent regulations included quota reductions, reef fish permit moratoria, and red snapper trip limit endorsements (200 or 2,000 lbs. depending on the vessel's catch history). Despite these new regulations, fishing derby conditions developed and quotas began to be met progressively sooner. Subsequently, the Council extended the resultant fishing season by splitting the quota into 2 seasons (Spring and Fall) and establishing 10/15-day fishing mini-seasons. (Waters 2001) reports that these management measures were not only biologically ineffective because of quota overages and high discard rates but also were economically wasteful because they resulted in excessive capital investments (i.e., overcapacity), short fishing seasons, market gluts, depressed prices, high harvesting costs, and unsafe fishing practices. To reverse these unintended consequences the Council adopted an IFQ (or catch share) program.

The catch share period (2007-present) began on January 1, 2007. The intent of the IFQ program was to reduce overcapacity and to eliminate, to the extent possible, the problems associated with derby fishing in the red snapper commercial fishery. The 5-year review of this IFQ program concluded that the program had mixed success (Gulf of Mexico Fishery Management Council 2013). The program successfully mitigated derby-fishing behavior and prevented quota overages, but overcapacity remained high as one-fifth of the fleet could harvest the commercial quota. The 5-year review also suggested that further policy interventions may be required to curb overcapacity and to reduce discarding in the eastern Gulf (even though

[3] Detailed accounts of the management history of the red snapper fishery can be found in Waters (2001), Hood et al. (2007), Agar et al. (2014), and SERO (2019b).

Table 1 Regulatory History of the Commercial Gulf of Mexico Red Snapper Fishery. mp gw stands for Millions of Pounds, Gutted Weight

Year	Season Length (days)	Quota (mp gw)	Harvest (mp gw)	Size Limit (in.)	Management Actions
1984	365	–	–	13	Reef Fish FMP
1990	365	2.79	2.40	13	Amendment 1: Established commercial quota, bottom longlines prohibited within 50 fathoms west of Cape San Blas, FL and within 20 fathoms elsewhere
1991	236	1.84	2.02	13	Reduced TAC
1992	95	1.84	2.81	13	Emergency rule: Ap. 3 - May 14 1,000 lb. trip limit, Moratorium on new reef fish permits, Establishment of 2,000 lb. and 200 lb. trip limit endorsements based on historical participation
1993	94	2.76	3.08	13	One trip per day limit, Endorsement extension
1994	77	2.76	2.93	14	Raised minimum size over next 5 years,Established Class 1 and Class 2 licenses, Extended reef fish permit moratorium
1995	52	2.76	2.65	15	Season opened Feb. 28
1996	87	4.19	3.90	15	TAC increased Quota split into Spring and Fall seasons Endorsement extension
1997	73	4.19	4.34	15	Fall season started Sept. 2 for 1st 15 days/month until quota met
1998	72	4.19	4.22	15	Fall season started Sept. 1, 1st 10 days/month Establishment of permanent red snapper Class 1 and Class 2 licenses (2,000 and 200 lb.), Spring season allocated 2/3 quota, started Feb. 1,
1999	70	4.19	4.40	15	Spring season reduced from 15 to 10 days/month
2000	66	4.19	4.36	15	Spring season opened on Feb. 1 for 10 days each month until spring quota reached (2/3 quota), Fall season open Oct. 1 for 10 days each month until remaining quota reached Extended permit moratorium for 5 more years
2001	79	4.19	4.18	15	None
2002	91	4.19	4.32	15	None
2003	94	4.19	3.99	15	
2004	105	4.19	4.21	15	
2005	131	4.19	3.69	15	Extended reef fish permit moratorium indefinitely
2006	126	4.19	4.21	15	
2007	365	2.99	2.87	13	Amendment 26: Implemented commercial RS-IFQ program, reduced quota, mid-year quota increase, reduced size limit
2008	366	2.30	2.24	13	

Table 1 (continued)

Year	Season Length (days)	Quota (mp gw)	Harvest (mp gw)	Size Limit (in.)	Management Actions
2009	365	2.30	2.24	13	
2010	365	3.19	3.06	13	Mid-year quota increase. Area closures due to Deepwater Horizon oil spill
2011	365	3.30	3.24	13	Mid-year quota increase
2012	366	3.71	3.64	13	Mid-year quota increase
2013	365	5.05	4.91	13	Mid-year quota increases
2014	365	5.05	5.02	13	
2015	365	6.57	6.47	13	Mid-year quota increase
2016	366	6.10	6.06	13	
2017	365	6.31	6.29	13	Mid-year quota increase
2018	365	6.31	6.29	13	

Source: SERO (2019b)

overall discarding had decreased) because of insufficient allocation (leased quota) and also because of the recovery (and eastern expansion) of the red snapper resource (Agar et al. 2014).

2.2 The Grouper-Tilefish Fishery

The command and control period (1984–2010) began with the adoption of the GOMRF FMP in 1984, which sought to protect reef fish population and imposed gear restrictions. Like the red snapper fishery, the grouper-tilefish fishery has a long and complex management history of progressively stricter regulations. We do not examine its management history in detail because the program contains 13 individual species, which would make the discussion unwieldy. Readers interested in the details of the grouper-tilefish management history are referred to the appendix of SERO (2019a).

Similar to red snapper fishery, the Council managed the grouper-tilefish fishery with permit limits, annual quotas (initially aggregate quotas but later individual species quotas), trip limits (6,000 lb. g.w.), minimum size limits, seasonal closures, and area-gear restrictions. The shift from aggregate to individual level quotas in some cases was driven by the poor condition of the stock (e.g., gag grouper). Starting in 2004, the grouper-tilefish fishery experienced frequent closures earlier in the year. For example, between 2004 and 2009, the deep-water grouper and tilefish fishing seasons went from a year-round season to an average season of 162 and 211 days, respectively (SERO 2019a). The deep-water grouper and tilefish fisheries also experienced quota overages.

In 2010, the catch era began with the implementation of Amendment 29 to GOMRF FMP, which established the grouper-tilefish IFQ program to mitigate derby-fishing conditions and reduce overcapacity in the commercial fleets. The 5-year review of this latter program also indicated that the program had been successful at mitigating derby-fishing conditions but additional work was required to curb overcapacity and reduce discard mortality (Gulf of Mexico Fishery Management Council 2018).

3 Methodology

3.1 Empirical Model

To assess characteristics of the production process of the IFQ fleet, we deploy a stochastic output distance frontier (ODF). The ODF measures the maximum amount by which an output vector can be proportionally expanded holding an input vector fixed. One of the most common empirical forms for the ODF is the translog (TL) functional form. The TL represents a global second order approximation to the true ODF and is represented as:

$$\begin{aligned} \ln D_{it} = \beta_0 + \sum_{m=1}^{M} \left(\beta_m + \rho_m t\right) \ln y_{mit} + 0.5 \sum_{p=1}^{M} \sum_{m=1}^{M} \beta_{mp} \ln y_{mit} \ln y_{pit} \\ + \sum_{k=1}^{K} \left(\delta_k + v_k t\right) \ln x_{kit} + 0.5 \sum_{k=1}^{K} \sum_{l=1}^{K} \delta_{kl} \ln x_{kit} \ln x_{lit} + \sum_{m=1}^{M} \sum_{k=1}^{K} \gamma_{mk} \ln y_{mit} \ln x_{kit}, \end{aligned} \quad (1)$$

where D_{it} is the output distance, y_{mit} is the m^{th} output level and x_{kit} is the k^{th} input level for vessel i fishing in period t for $i = 1, \ldots, n$ and $t = 1, \ldots, T$. Axiomatically, the ODF is homogeneous of degree 1 which allows normalization by one output. The ODF is also symmetric in the cross terms such that $\beta_{mp} = \beta_{pm}$ and $\delta_{kl} = \delta_{lk}$. Once the normalizations have been taken into account, and rearranging, we have

$$\begin{aligned} -\ln y_{1it} = \beta_0 &+ \sum_{m=2}^{M} \left(\beta_m + \rho_m t\right) \ln \tilde{y}_{mit} + 0.5 \sum_{p=2}^{M} \sum_{m=2}^{M} \beta_{mp} \ln \tilde{y}_{mit} \ln \tilde{y}_{pit} \\ &+ \sum_{k=1}^{K} \left(\delta_k + \nu_k t\right) \ln x_{kit} + 0.5 \sum_{k=1}^{K} \sum_{l=1}^{K} \delta_{kl} \ln x_{kit} \ln x_{lit} \\ &+ \sum_{m=2}^{M} \sum_{k=1}^{K} \gamma_{mk} \ln \tilde{y}_{mit} \ln x_{kit} - \ln D_{it}, \end{aligned} \tag{2}$$

where $\tilde{y}_{mit} = y_{mit}/y_{1it}$. Given that $D_{it} \leq 1$ it follows that $\ln D_{it} \leq 0$. This implies that we can set $u_{it} = -\ln D_{it}$. Adding in a stochastic noise term, v_{it} along with vessel specific heterogeneity, τ_i, we have our final, panel stochastic ODF:

$$\begin{aligned} -\ln y_{1it} = \beta_0 &+ \sum_{m=2}^{M} \left(\beta_m + \rho_m t\right) \ln \tilde{y}_{mit} + 0.5 \sum_{p=2}^{M} \sum_{m=2}^{M} \beta_{mp} \ln \tilde{y}_{mit} \ln \tilde{y}_{pit} \\ &+ \sum_{k=1}^{K} \left(\delta_k + \nu_k t\right) \ln x_{kit} + 0.5 \sum_{k=1}^{K} \sum_{l=1}^{K} \delta_{kl} \ln x_{kit} \ln x_{lit} \\ &+ \sum_{m=2}^{M} \sum_{k=1}^{K} \gamma_{mk} \ln \tilde{y}_{mit} \ln x_{kit} + \kappa z_{it} + v_{it} + u_{it} + \tau_i, \end{aligned} \tag{3}$$

where z_{it} is a set of controls that also impact the distance frontier. This has all the makings of a standard stochastic cost frontier: for a fixed level of outputs $\tilde{y}_{2it}, \ldots, \tilde{y}_{Mit}$ and inputs, time-varying vessel inefficiency decreases how much output can be produced. Note this happens radially, so that all outputs are decreased by the same relative amount.

For the red snapper IFQ model, we have four outputs (red snapper, other snappers, grouper-tilefish species, and a miscellaneous or residual group), one quasi-fixed input (vessel length) and two variable inputs (days fished and crew size). Here z_{it} includes quarter dummies ($Q4$ is the baseline), regional landing location (county-level) dummies, biomass estimates for red snapper, red grouper, gag and yellowedge grouper as well as IFQ implementation dummies for red snapper (2007–2018) and grouper-tilefish (2010–2018). For the Gulf reef fish IFQ model (i.e., red snapper with grouper-tilefish) we employ a similar model with the exception that instead of four species groupings we only have three: red snapper with grouper-tilefish, other snappers and the residual group.

We enhance the model by allowing for both vessel specific heterogeneity as well as time constant vessel inefficiency. This is achieved by writing $\alpha_i = c_i + \tau_i$, where c_i captures vessel heterogeneity and τ_i captures time invariant, or persistent, inefficiency. Recognizing this distinction in unobservable heterogeneity is important as it is likely that there exist differences across vessels participating in the IFQ that do not vary over time (like innate skipper skill) as well as persistent habits that vessels may exhibit which lead to lower catch rates than otherwise expected. We assume that $\tau_i \geq 0$ to capture this. Given that our time span covers 17 years for the red snapper fishery, learning is likely to occur. This is captured in u_{it}. Here if $u_{it} \leq u_{it+1}\ \forall t$ then time-varying inefficiency is decaying over time, and one reason for this can be learning on behalf of the skipper. τ_i has no time component so this acts to quantify unobservable skill in fishing, i.e. persistent inefficiency.

3.2 Estimation

Assuming that x_{kit} and α_i are uncorrelated, the OLS estimator applied to the empirical model in (3) is consistent, but inefficient. Further, while OLS estimation is simple, it does not offer the ability to recover estimates of unobserved heterogeneity or output efficiency. A simple, multi-step procedure originally proposed in Kumbhakar et al. (2014) is available to estimate the stochastic ODF for specification given in (3), known as plug-in likelihood estimation (see Andor and Parmeter 2017). To aid in describing how we recover estimates of inefficiency (both time-varying and persistent) we first rewrite the normalized stochastic ODF as

$$
\begin{aligned}
-\ln y_{1it} = \beta_0^* &+ \sum_{m=2}^{M}\left(\beta_m + \rho_m t\right)\ln \tilde{y}_{mit} + 0.5\sum_{p=2}^{M}\sum_{m=2}^{M}\beta_{mp}\ln \tilde{y}_{mit}\ln \tilde{y}_{pit} \\
&+ \sum_{k=1}^{K}\left(\delta_k + \nu_k t\right)\ln x_{kit} + 0.5\sum_{k=1}^{K}\sum_{l=1}^{K}\delta_{kl}\ln x_{kit}\ln x_{lit} \\
&+ \sum_{m=2}^{M}\sum_{k=1}^{K}\gamma_{mk}\ln \tilde{y}_{mit}\ln x_{kit} + \varepsilon_{it}^* + \alpha_i^*.
\end{aligned} \tag{4}
$$

where $\beta_0^* = \beta_0 + E[\tau_i] + E[u_{it}]$; $\alpha_i^* = c_i + \tau_i - E[\tau_i]$; and $\varepsilon_{it}^* = v_{it} + u_{it} - E[u_{it}]$. With this specification both α_i^* and ε_{it}^* are zero mean and constant variance random variables. Additionally, we assume that v_{it} is i.i.d. $N(0, \sigma_v^2)$ and u_{it} is i.i.d. $N_+(0, \sigma_u^2)$ while c_i is i.i.d. $N(0, \sigma_c^2)$, τ_i is i.i.d. $N_+(0, \sigma_\tau^2)$. The parameters of the model are estimated in three steps. We discuss estimation of this model under the random effects (RE) framework.

Step 1 Estimate the parameters of the stochastic ODF in (4) using a random effects panel data estimator. These estimates are then used to generate predicted values of α_i^* and ε_{it}^*, denoted by $\widehat{\alpha}_i^*$ and $\widehat{\varepsilon}_{it}^*$. No distributional assumptions are required to estimate the parameters of the output distance function.

Step 2 Time-varying technical inefficiency, u_{it}, is estimated using the information contained in $\hat{\varepsilon}_{it}^*$ from Step 1. Under the assumption of Half-Normal, we have $\varepsilon_{it}^* = v_{it} + u_{it} - \sqrt{2/\pi}\,\sigma_u$. The parameters for the distributions of v and u can be estimated using maximum likelihood or method of moments. Doing so allows predictions of time-varying technical efficiency $E\left[e^{-u_{it}}|\varepsilon_{it}^*\right]$ to be constructed, which (Kumbhakar et al. 2018) term relenting technical efficiency, though we will use the term time-varying efficiency here (TVE).

Step 3 Estimate τ_i following a similar strategy as in Step 2. For this we use $\widehat{\alpha}_i^*$ from Step 1. Again, based on the common distributional assumptions, $\alpha_i^* = c_i + \tau_i - \sqrt{2/\pi}\,\sigma_\tau$ can be estimated using maximum likelihood. Estimates of the persistent technical inefficiency (PTE) component, can be obtained from $E\left[e^{-\tau_i}|\alpha_i^*\right]$. Overall technical efficiency (OTE) is then constructed as the product of PTE and TVE, OTE = PTE×TVE.

An alternative multi-step approach based on corrected OLS (COLS) follows from Kumbhakar and Lien (2018). Rather than performing maximum likelihood estimation in steps 2 and 3, method of moments are deployed to recover estimates of the unknown distributional parameters. A benefit of this approach is that a modified likelihood function is not needed and these estimators can be constructed with a few lines of code in any matrix oriented statistical software. To see this, note that under the distributional assumptions of Normal and

Half Normal which is used to construct the composite α_i or ε_{it}, the variance parameters can be constructed using the second and third moments of these terms. That is, for the second and third moments of, say, $\widehat{\zeta}_{it}$:

$$\widehat{m}_2(\widehat{\zeta}) = (nT)^{-1} \sum_{i=1}^{n} \sum_{t=1}^{T} \widehat{\zeta}_{it}^2 \tag{5}$$

and

$$\widehat{m}_3(\widehat{\zeta}) = (nT)^{-1} \sum_{i=1}^{n} \sum_{t=1}^{T} \widehat{\zeta}_{it}^3, \tag{6}$$

the variance components can be estimated via:

$$\widehat{\sigma}_u^2 = \max\left\{0, \left[\sqrt{\frac{\pi}{2}}\left(\frac{\pi}{\pi-4}\right)\widehat{m}_3(\widehat{\varepsilon}^*)\right]^{2/3}\right\} \tag{7}$$

$$\widehat{\sigma}_v^2 = \widehat{m}_2(\widehat{\varepsilon}^*) - \left(\frac{\pi-2}{\pi}\right)\widehat{\sigma}_u^2. \tag{8}$$

For estimation of the variance components of the time-constant components we would have

$$\widehat{\sigma}_\tau^2 = \max\left\{0, \left[\sqrt{\frac{\pi}{2}}\left(\frac{\pi}{\pi-4}\right)\widehat{m}_3(\widehat{\alpha}^*)\right]^{2/3}\right\} \tag{9}$$

$$\widehat{\sigma}_c^2 = \widehat{m}_2(\widehat{\alpha}^*) - \left(\frac{\pi-2}{\pi}\right)\widehat{\sigma}_\tau^2. \tag{10}$$

As in standard cross-sectional settings, if either $\widehat{\alpha}_i^*$ or $\widehat{\varepsilon}_{it}^*$ have the wrong skew, then the variance estimate of the corresponding inefficiency term will be zero (Olson et al. 1980). It is also possible to obtain negative variance estimates (what Olson et al. 1980 term a type 2 error) for the Normally distributed components, c_i and v_{it}, but this is rare empirically.

The three-step approach just described is inefficient relative to full maximum likelihood, yet is straightforward to implement. Previous research has shown that similar step-wise estimation strategies perform nearly identical to maximum likelihood in small samples (Olson et al. 1980; Coelli 1995; Andor and Parmeter 2017). This suggests that concerns over loss of efficiency in applying step-wise or corrected procedures may be overstated. Given this we elect to use the corrected procedure described above instead of full maximum likelihood for our empirical analysis.

4 Capacity, Overcapacity and Utilization

Before discussing the findings of this study it is useful to review the definitions of harvesting capacity, excess capacity and overcapacity. Following NMFS guidelines harvesting capacity is defined as the "maximum amount of fish that the fishing fleets could have reasonably expected to catch or land during the year under the normal and realistic operating conditions of each vessel, fully utilizing the machinery and equipment in place, and given the technology, the availability and skill of skippers and crew, the abundance of the stocks of fish, some or all fishery regulations, and other relevant constraints" (Terry et al. 2008). Further, NMFS defines excess capacity as the difference between harvesting capacity and estimated catch or landings and overcapacity as the difference between harvesting capacity and a short-term target catch level such as an annual catch limit or proxy (Terry et al. 2008).

This study adopts the definition of fishing capacity as the potential (maximal) output that a fishing fleet could harvest given the current stock of capital and other fixed inputs, the state of the technology and the available biomass (FAO 1998). With the notion of maximal output, estimation of capacity requires us to work with a stochastic production frontier (Parmeter and Kumbhakar 2014).

A standard approach to measuring capacity is, at the vessel level, determining maximum attainable output with the full utilization (unrestricted use) of variable inputs given the existing capital and other fixed factors of production. Felthoven et al. (2009) look at days at sea in their estimation of capacity.

To that end, several alternative approaches have been proposed to estimate capacity, including: (i) identifying the maximum observed variable input levels of all vessels with similar fixed input endowments (for instance comparing catch rates across vessels of the same length); (ii) identifying the theoretically maximum variable input usage levels; and (iii) increasing the observed variable input levels by an *ad hoc* amount, such as an increase of 25 or 50%. Here our approach to estimate capacity is more focused and, we believe, consistent with Terry et al. (2008). We hold inputs fixed at observed levels and ask what each vessel could catch if they were to eliminate both persistent and time-varying inefficiency. In some sense, we are moving vessels in the output direction radially to calculate capacity whereas other approaches move the vessels in the input direction to calculate capacity.

5 Data and Model Specification

The data used in this study were obtained from the National Marine Fisheries Service (NMFS) Southeast Coastal Fisheries Logbook Program and the Permits Information Management Systems (PIMS) databases. The logbook database contains detailed trip-level information on landings and fishing effort, and the PIMS database contains information on vessel characteristics.

To avoid potential biases due to heterogeneous fishing technologies, we modeled the vertical line and longline fleets separately. For the red snapper IFQ model we only included vertical line vessels that landed at least one pound of red snapper during the year, because this gear lands more than 80% of the red snapper in the entire database. For the Gulf reef fish IFQ model we included vertical line and longline vessels that landed at least one pound of red snapper or grouper-tilefish species during the year.

In the next two sections, we present the results of the red snapper and reef fish IFQ models.

Table 2 Descriptive statistics for the red snapper IFQ model

		Mean	St. Dev.	Min	Max
Red snapper (lbs.)	y_1	763.6	1,700.655	0	33,735
Other snapper (lbs.)	y_2	317.8	808.485	0	12,038
Grouper-tilefish (lbs.)	y_3	356.5	655.675	0	18,089
All other species (lbs.)	y_4	249.8	646.5	0	26,460
Vessel length (ft.)	x_1	37.7	9.7	18	78
Days away (count)	x_2	3.4	2.7	1	14
Crew size (count)	x_3	2.7	1.2	1	8
Red snapper biomass (mt.)	z_1	68,957.8	17,255	51,939.4	101,071
Gag biomass (mt.)	z_2	10,844	3,516.1	4,947	16,315
Red grouper biomass (mt.)	z_3	20,747	4,522.8	11,340	27,873
Yellowedge grouper biomass (mt.)	z_4	5,730.5	187.5	5,524.7	6,095.7

6 Red Snapper IFQ Model: Empirical Findings

6.1 Characteristics of the Technology

Following (Solís et al. 2015b) we study the five years prior to the implementation of the IFQ (2002–2006) along with the corresponding 12 years after (2007–2018). Those observations for which missing or incomplete input and/or output data were also excluded from the analysis resulting in an unbalanced panel data of 94,595 observations on 1306 distinct vessels.[4]

We did not aggregate to the quarter level as was done in Solís et al. (2015b) as this has the potential to obscure important trip information that can be hidden in the aggregation. For example, fisherman may make several trips in a quarter and in one trip may catch a substantial amount relative to their other trips. In sum their quarter level fishing may appear more robust given this one highly productive trip. By focusing on the trip level we can more aptly characterize performance for all trips taken by a vessel. By not aggregating we are left with the situation where some trips produced zero catch for a particular species. Those trips by vessels within a season that did not land red snapper were coded as landing 1 lb such that the subsequent logarithmic transformation was 0.[5]

Table 2 presents summary statistics for our inputs, outputs and biomass variables that are used to estimate the stochastic ODF for those vessels which landed red snapper caught with vertical lines. We can see immediately that for these vessels red snapper landings are, on average, more than double the catch of any other species. The largest vessel is 78 feet in length while the average vessel is roughly 40 feet in length with a crew size of three (exclusive of the captain). The vast majority of trips are under four days with an average of 3.4

[4] For reference, there were a total of 114,685 complete observations that reported red snapper landings regardless of fishing gear so limiting our analysis to vertical line covers roughly 82% of the trips where red snapper was caught.

[5] Certainly this empirical practice, while common in many applied production domains, is tenuous at best, but lacking a formal selection model, the other option is to focus our attention exclusively on those landings that reported red snapper. In this case we have 63,260 trip records, roughly two-thirds of our initial sample.

Table 3 Partial distance input/output elasticities and RTS pre- and post-IFQ: Assumes different technology pre- and post-IFQ for red snapper IFQ model. 1000 Bootstrap standard errors appear beneath each estimate in parentheses

	Whole Sample	Pre-IFQ	Post-IFQ	2007–2011	2012–2018
Output Elasticities					
Red Snapper	−0.275	−0.313	−0.250	−0.194	−0.280
	(0.001)	(0.002)	(0.001)	(0.002)	(0.002)
Other Snapper	−0.187	−0.185	−0.189	−0.185	−0.191
	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)
Grouper-Tilefish	−0.315	−0.279	−0.339	−0.376	−0.320
	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)
Other Species	−0.222	−0.224	−0.221	−0.244	−0.209
	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)
Input Elasticities					
Vessel Length	1.066	1.228	0.957	0.881	0.997
	(0.024)	(0.032)	(0.035)	(0.041)	(0.038)
Days Away	0.971	0.872	1.037	1.053	1.029
	(0.006)	(0.01)	(0.008)	(0.01)	(0.009)
Crew	0.403	0.401	0.403	0.470	0.368
	(0.01)	(0.018)	(0.012)	(0.016)	(0.014)
RTS	1.374	1.274	1.441	1.522	1.398
	(0.012)	(0.02)	(0.015)	(0.019)	(0.017)

days away. In general the characteristics of the fleet and fishery are similar to the snapshot of the fleet provided in Solís et al. (2015b) even when we extend those data to 2018.

Solís et al. (2015b) assumed that the ODF technology and TE were homogeneous for the fleet across the implementation of the IFQ. To test this we split our sample between pre- and post-IFQ and estimate separate stochastic ODF. We then use a heteroskedastic robust Wald test to assess if there are statistically meaningful differences between the two periods. We find at all conventional levels of significance that the pre- and post-IFQ periods do indeed display different technological features. Given this we assess the ODF in Equation (3) for the pre- and post-IFQ separately.

As translog model parameter estimates are notoriously difficult to interpret directly, model assessment typically relies on other alternatives. Table 3 presents input and output elasticities across the entire period along with returns to scale (RTS). We do not present the raw estimates from the translog ODF as any given parameter lacks direct economic interpretation. Rather, we focus on meaningful quantities that have direct economic relevance. We see that red snapper (y_1) and grouper-tilefish (y_3) have larger (in magnitude) output elasticities than the other categories, which is intuitive. Moreover, the output elasticity for red snapper decreased in magnitude between the pre- and post-IFQ periods by nearly 20%. Agar et al. (2014) report that after the adoption of IFQs, red snapper fishermen increased the duration of their trips and diversified their catch composition largely because of the elimination of trip limits and fishing mini-seasons.

Several other interesting features of the technology for the fleet are the fact that returns to scale are above one, suggesting the ability to scale up (by increasing crew size and days at sea). We do note that our estimates of RTS are lower than those reported in Solís, del Corral, Perruso & Agar (2015b, Table 4) as we treat vessel length as a quasi-fixed input whereas they treat it as a variable input. It appears here that the elasticity of vessel length (with respect to output) has decreased across the pre/post-IFQ split, although the last five years have seen a rise of the elasticity of vessel length quite close to one. This could be reflective of adaptation to the IFQ. It may capture the dramatic increase in red snapper quota during that period and the relative higher 'red snapper' share of total landings (see Table 11 on page 19 and Table 16 on page 24 of SERO 2019b). Additionally, catch responsiveness to changes in days at sea is twice as high as for changes in crew size. This is intuitive. Bringing additional crew will have less impact on the catch of a given trip than staying at sea for additional days. Given the fixed length of the vessel, additional crew could lead to overcrowding.

We deploy bootstrap sampling of the errors to assess the statistical significance of all of our estimates of returns to scale and input/output elasticities. We use a wild bootstrap algorithm with 1000 resamples. For each resample we reestimate the random effects model, again splitting the sample into pre- and post-IFQ periods, allowing the technology to differ. These standard errors are presented beneath each estimate in parentheses in Table 3. As is clear our measure of average elasticities of the fleet and scale are quite precise. We are dealing with nearly 100,000 observations so this is not surprising.

There is also a substantial impact of the IFQ on trip duration. The trip duration elasticity rose from 0.872 in the pre-IFQ period to 1.037 in the post-IFQ period probably because of the relaxation regulations such as trip limits and mini-seasons from the command and control period. All told, Table 3 suggests that there was a significant change in fleet behavior after the implementation of the IFQ program. The null hypothesis that technical inefficiency does not exist ($H_0 : \sigma_u = 0$) is rejected at the 1 per cent level favoring the adoption of a stochastic distance frontier over a standard distance function. The ratio of the standard deviation of u to that of v, λ, equals 1.887 prior to the implementation of the IFQ and 2.797 afterwards, indicating that skill (efficiency) is more important than random shocks in explaining production differences across fishing vessels.

To better assess the ability of vessels to increase red snapper landings we investigate time-varying inefficiency of the fleet in the pre- and post-IFQ periods. Figure 1 presents the kernel density plot of estimated time-varying inefficiency across the implementation of the IFQ. We see a rightward shift in the full distribution and a movement in the mean time-varying efficiency of roughly four percentage points (0.801 to 0.848).

Table 4 breaks down overall technical efficiency (OTE) by year as well as into its separate components: time-varying and persistent inefficiency (TVE and PE, respectively). Consistent with Figure 1 the fleet became more efficient over time. One empirical issue we encountered is that for the pre-IFQ sample, the random effects did not display appropriate skewness, so persistent efficiency was not identified; more specifically, the variance parameter is estimated to be zero, suggesting the lack of persistent inefficiency, the natural conclusion of which is that persistent efficiency is 1.[6] The common approach in this instance is to claim that persistent inefficiency is at or very near to 0, so time-varying and overall technical inefficiency are the same (Olson et al. 1980).

[6] This is a common issue in empirical work that typically results in researchers seeking alternative specifications to have the ability to present estimates on inefficiency. Another alternative is to use bootstrap bagging methods to construct confidence intervals for each vessel in each period.

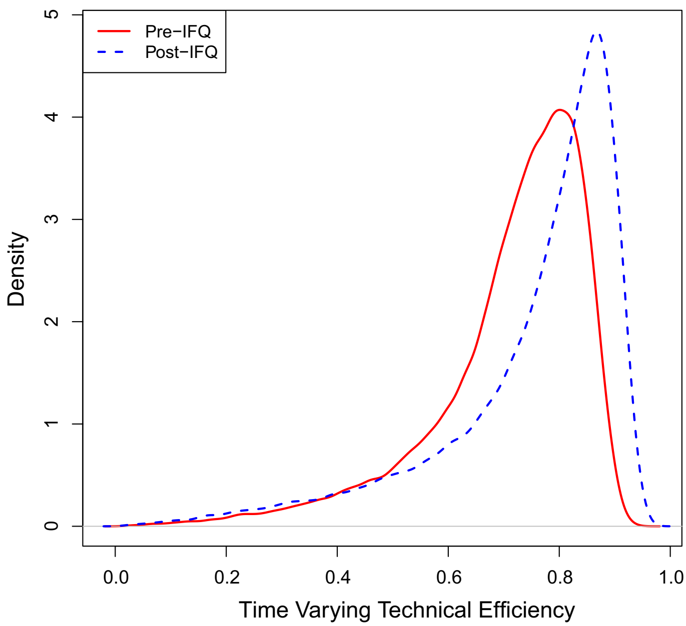

Fig. 1 Density plot of time-varying technical efficiency for Gulf of Mexico vessels, pre- and post-IFQ for the red snapper IFQ model

Table 4 Technical efficiency scores for the red snapper fleet pre- and post-IFQ

	OTE	TVE	PE
2002	0.712	0.712	1.000
2003	0.714	0.714	1.000
2004	0.710	0.710	1.000
2005	0.714	0.714	1.000
2006	0.707	0.707	1.000
2007	0.593	0.742	0.799
2008	0.606	0.759	0.798
2009	0.599	0.753	0.796
2010	0.600	0.754	0.796
2011	0.598	0.752	0.795
2012	0.605	0.755	0.802
2013	0.610	0.758	0.804
2014	0.605	0.753	0.804
2015	0.597	0.744	0.803
2016	0.601	0.753	0.798
2017	0.598	0.749	0.798
2018	0.597	0.746	0.800
Entire	0.645	0.735	–
Pre – IFQ	0.711	0.711	–
Post – IFQ	0.601	0.751	0.800
2007–2011	0.599	0.752	0.797
2012–2018	0.602	0.751	0.802

Table 5 Annual red snapper fleet capacity measures pre- and post-IFQ

	Actual catch (mp)	C^{OTE}	C^{TVE}
2002	4225	6497	6497
2003	4083	6174	6174
2004	3714	5641	5641
2005	3334	4880	4880
2006	3999	6053	6053
2007	2580	4869	3981
2008	2079	3490	2906
2009	2088	3973	3262
2010	2742	5070	4158
2011	2937	5172	4305
2012	3391	6225	5230
2013	4311	7392	6224
2014	4548	8235	6836
2015	5874	10, 843	8970
2016	5501	9726	8083
2017	5748	10, 098	8422
2018	5656	10, 182	8509
Entire	4251	7286	6352
Pre – IFQ	3871	5849	5849
Post – IFQ	4410	7885	6562
2007–2011	2485	4515	3722
2012–2018	5785	10, 292	8590

6.2 Capacity of the Fleet

Table 5 details a year by year break down of the estimated capacity of the red snapper vertical line IFQ fleet. There are several striking features. First, consistent with Solís et al. (2015b), pre-IFQ red snapper catch and capacity levels are higher than those post-IFQ up to 2011 (the year their analysis ended). Second, we observe a noticeable increase in catches in the last few years of the analysis (2014 and onwards) in response to increased quota levels (Tables 5 and 6). Third, and most importantly, capacity levels were higher than catch totals and quota levels by a wide margin, indicating the presence of overcapacity.

Table 6 presents the observed vertical line fleet size and number of trips taken and the estimated smallest (fully efficient) fleet size and the minimum number (most productive) of trips that could have harvested the entire quota, had the fleet operated at full efficiency (OTE). This table shows that relative to the pre-IFQ period, both the number of fishing vessels and trips declined regardless whether or not they operated at full efficiency. It also shows the predicted (anticipated) quota utilization (i.e., catch/quota) had the observed fleet operated at OTE. As noted earlier, the actual fleet size and number of trips in the post-IFQ period, rose in response to increased quotas, particularly after 2014 (Table 6).

Tables 5 and 6 provides convincing evidence of the presence of excess capacity and over-capacity. Similar, to Solís et al. (2015b) we find that many vessels left the fishery after the implementation of the IFQ and that about 20% of the vertical line fleet (operating at full efficiency) could have harvested the entire quota. We note that a larger number of shorter

Table 6 Annual red snapper fleet size measures

Year	Quota (lbs.)	Fully efficient		Total				Quota utilization	
		Vessels	Trips	Vessels	Trips	% Vessels	% Trips	Actual	Predicted
2002	4, 189, 189	111	1297	430	8217	0.258	0.158	1.051	1.551
2003	4, 189, 189	115	1332	425	8134	0.271	0.164	1.025	1.474
2004	4, 189, 189	116	1443	439	8035	0.264	0.180	0.991	1.347
2005	4, 189, 189	127	1690	432	6863	0.294	0.246	0.864	1.165
2006	4, 189, 189	109	1390	394	6672	0.277	0.208	1.021	1.445
2007	2, 297, 297	68	203	291	3844	0.234	0.053	0.960	2.119
2008	2, 297, 297	77	351	279	3928	0.276	0.089	0.974	1.519
2009	2, 297, 297	57	229	286	4014	0.199	0.057	0.974	1.729
2010	2, 297, 297	44	176	334	3639	0.132	0.048	0.958	2.207
2011	3, 190, 991	75	367	319	4259	0.235	0.086	0.981	1.621
2012	3, 300, 901	45	252	316	4294	0.142	0.059	0.979	1.886
2013	3, 712, 613	49	270	313	4174	0.157	0.065	0.971	1.991
2014	5, 054, 054	62	362	346	4581	0.179	0.079	0.992	1.629
2015	5, 054, 054	49	269	345	5023	0.142	0.054	0.985	2.145
2016	6, 097, 297	63	448	352	5152	0.179	0.087	0.993	1.595
2017	6, 312, 613	67	488	369	5172	0.182	0.094	0.996	1.600
2018	6, 312, 613	68	431	376	4513	0.181	0.096	0.996	1.613

trips ensures fresher product, which is what has historically been demanded, promoting higher prices. Fewer trips means more product being landed at the same time, which can also lead to gluts and reduced prices.[7]

7 Gulf Reef Fish IFQ Model: Empirical Findings

Here we present the Gulf reef fish IFQ model, which combines the reported landings for red snapper and grouper-tilefish into a single species group category. We also include both longline and vertical line vessels. Excluding observations with missing fields resulted in an unbalanced panel data of 144,960 observations on 2,090 distinct vessels.

7.1 Characteristics of the technology

Table 7 presents summary statistics for inputs, outputs and biomass variables that are used to estimate the stochastic ODF for those vessels which landed either red snapper or grouper-tilefish with long or vertical lines. This table shows that, on average, IFQ species landings are more than four times higher than those from other species groupings. The largest vessel is 87 feet in length while the average vessel is roughly 38 feet in

[7] An alternative way to think about capacity would be the use of the vessels pre- and post-IFQ. This is an interesting extension which we leave for future research.

Table 7 Descriptive statistics for Gulf reef fish IFQ fishery

		Mean	St. Dev.	Min	Max
Red snapper/Grouper-Tilefish (lbs.)	y_1	1,261.6	2,042.5	0	39,352
Other snapper (lbs.)	y_2	221.1	683.4	0	12,038
All other species (lbs.)	y_3	301.3	753.8	0	51,794
Vessel length (ft.)	x_1	37.7	9.6	18	87
Days away (count)	x_2	3.9	3.3	1	14
Crew size (count)	x_3	2.6	1.1	1	8
Red snapper biomass (mt)	z_1	66,582.3	16,443.2	51,939.4	101,071
Gag biomass (mt.)	z_2	10,473.5	3,495.5	4,947	16,315
Red grouper biomass (mt.)	z_3	20,955.4	4,243.9	11,340	27,873
Yellowedge grouper biomass (mt.)	z_4	5,705.9	178.2	5,524.7	6,095.7

Table 8 Partial distance input/output elasticities and RTS pre- and post-IFQ for the Gulf reef fish IFQ fishery: Assumes different technology pre- and post-IFQ as well as across gear type

	Whole Sample	Pre-IFQ	Post-IFQ	2010–2014	2015–2018
Output Elasticities					
Red snapper/Grouper/Tilefish	−0.517	−0.511	−0.527	−0.509	−0.546
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)
Other snapper	−0.248	−0.267	−0.220	−0.232	−0.209
	(0.001)	(0.002)	(0.001)	(0.002)	(0.002)
All other species	−0.234	−0.222	−0.252	−0.259	−0.246
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Input elasticities					
Vessel length	0.974	0.913	1.066	0.944	1.185
	(0.019)	(0.025)	(0.026)	(0.025)	(0.035)
Days away	0.853	0.822	0.899	0.944	0.856
	(0.005)	(0.006)	(0.006)	(0.006)	(0.008)
Crew	0.366	0.363	0.371	0.368	0.374
	(0.008)	(0.01)	(0.01)	(0.011)	(0.013)
RTS	1.220	1.185	1.271	1.312	1.230
	(0.009)	(0.012)	(0.011)	(0.013)	(0.015)

length with a crew size of three (exclusive of the captain). The vast majority of trips are under four days with an average of 3.9 days away.

Similar to our earlier analysis we allow the fishing technology to differ across the pre- and post-IFQ periods, using the 2010 grouper-tilefish IFQ as our cutoff. We also allow the technology to differ between longline and vertical line vessels.

Table 8 presents input and output elasticities across the entire period along with returns to scale. We do not present the raw estimates from the translog ODF as any given parameter lacks economic interpretation. Again, we focus on measures that have direct economic relevance. We see that red snapper/grouper-tilefish (y_1) have larger (in magnitude) output elasticities than the other categories, which is intuitive. Moreover,

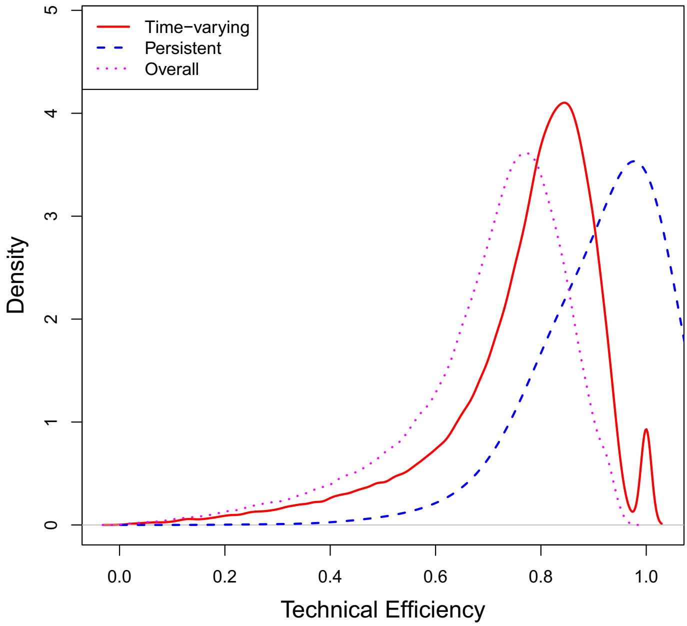

Fig. 2 Density plot of overall technical efficiency and its components for the Gulf reef fish IFQ fleet

the output elasticity for red snapper/grouper-tilefish increased in magnitude between the pre- and post-IFQ (in this case we use the year 2010 as that is when IFQs exists for all three species groups) but only minimally so.

Figure 2 presents the kernel density estimate of estimated technical efficiency both overall and in its constituent components: time-varying and persistent for the Gulf reef fish IFQ fleet. For the entire fleet over the full time period, we see that average persistent technical inefficiency is low (suggesting little time constant inefficiencies which pervade the fleet) while time-varying technical efficiency is lower than that for persistent technical efficiency. The spike that occurs at one occurs because we have several vessels that are found to be approximately fully efficient.

We also investigated a more nuanced depiction of time-varying technical efficiency of the Gulf reef fish fleet. Figure 3 presents the kernel density plot of estimated time-varying efficiency across gear type and pre/post adoption of the IFQ. We see a rightward shift in the estimated kernel densities for both vertical and longline fleets after the 2010 IFQ was implemented. The average technical efficiency moved up by almost 4 percentage points for vertical line vessels post-IFQ while it moved just over 9 percentage points for longline vessels. Moreover, the longline fleet appears to be more technically efficient than the vertical line fleet regardless of the IFQ.

Table 9 breaks down overall technical efficiency by year and into its separate components, time-varying and persistent. Consistent with Figure 2 the fleet became more efficient over time. One empirical issue we encountered is that for the pre-IFQ sample, the random effects did not display appropriate skewness, so persistent efficiency was not identified for the vertical line fleet. We did find persistent inefficiency in the longline fleet however.

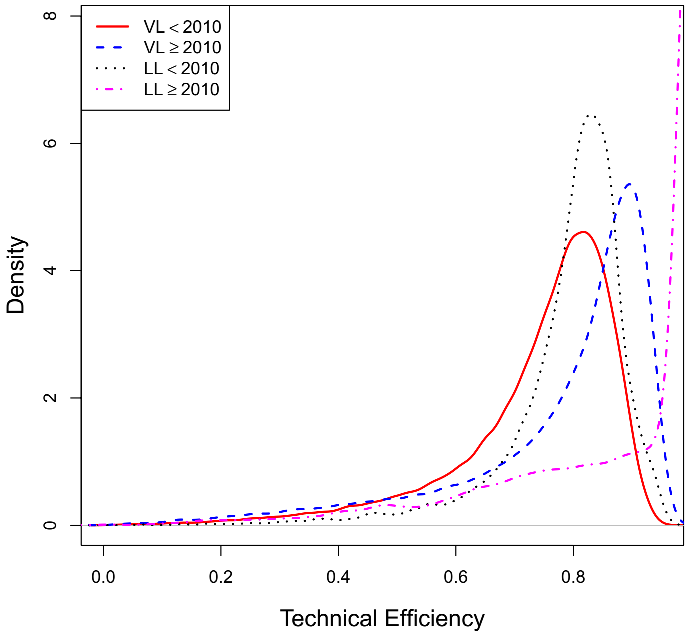

Fig. 3 Density plot of time-varying technical efficiency for Gulf reef fish IFQ fleet, pre- and post-IFQ by line type (Vertical Line – VL; Long Line – LL)

7.2 Capacity of the Fleet

Table 10 details a year by year break down of estimated excess capacity of the Gulf reef fish IFQ fleet. There are several striking features. First, reported landings had a near continuous decline from 2002 through 2010, rebounding after the IFQ went into effect. These reported landings again declined for the last two years for which we have full data (2017/2018). Second, looking over the pre-IFQ period, full fleet C^{OTE} is roughly 45% higher than reported landings, while for the second half of the post-IFQ the same measure is 62%. This level of excess capacity post-IFQ is consistent throughout the period (whether we look initially after the IFQ was implemented, 2010–2014, or later, 2015–2018). Finally, even though the average annual catch was *higher* prior to IFQ implementation, the fully efficient catch potential is roughly 7% higher after the IFQ goes into effect. This increased predicted catch potential is primarily driven by the last four years of catch data.

Table 11 also reveals several interesting features of the combined reef fish fishery. First, in the early days of the program (2011–2016) 57% of the fleet operating at full efficiency could not only have harvested the reported landings (77–95% of the quota) but also the entire quota. Second, beginning in 2017, the number of fully efficient vessels needed to harvest the entire quota rose to 100%. This is due to difference in the reported quota utilization of 60–70% relative to the predicted quota utilization of only 80–90%.

Table 9 Technical efficiency scores pre- and post-IFQ for full fleet and by gear type

	Full Fleet			Vertical line			Long line		
	OTE	TVE	PE	OTE	TVE	PE	OTE	TVE	PE
2002	0.733	0.745	0.986	0.737	0.737	1.000	0.711	0.797	0.892
2003	0.735	0.747	0.985	0.741	0.741	1.000	0.703	0.787	0.894
2004	0.737	0.749	0.985	0.742	0.742	1.000	0.707	0.791	0.894
2005	0.733	0.747	0.983	0.738	0.738	1.000	0.708	0.790	0.896
2006	0.735	0.749	0.982	0.740	0.740	1.000	0.711	0.791	0.899
2007	0.739	0.752	0.984	0.745	0.745	1.000	0.709	0.789	0.898
2008	0.731	0.744	0.985	0.734	0.734	1.000	0.715	0.793	0.902
2009	0.730	0.736	0.992	0.733	0.733	1.000	0.694	0.769	0.903
2010	0.627	0.778	0.804	0.608	0.767	0.793	0.808	0.886	0.912
2011	0.649	0.798	0.812	0.626	0.784	0.799	0.829	0.905	0.916
2012	0.647	0.789	0.817	0.625	0.776	0.804	0.815	0.889	0.917
2013	0.656	0.799	0.820	0.638	0.789	0.808	0.803	0.876	0.916
2014	0.648	0.794	0.815	0.632	0.787	0.804	0.788	0.862	0.915
2015	0.636	0.778	0.816	0.616	0.765	0.805	0.822	0.899	0.915
2016	0.641	0.786	0.814	0.621	0.774	0.803	0.813	0.891	0.912
2017	0.639	0.784	0.814	0.623	0.775	0.804	0.803	0.880	0.913
2018	0.636	0.780	0.813	0.615	0.767	0.802	0.831	0.910	0.914
Entire	0.697	0.763	0.916	0.691	0.754	0.918	0.741	0.821	0.902
Pre – IFQ	0.734	0.746	0.985	0.739	0.739	1.000	0.708	0.790	0.896
Post – IFQ	0.642	0.787	0.814	0.623	0.776	0.803	0.811	0.887	0.915
2010–2015	0.646	0.792	0.814	0.626	0.781	0.802	0.809	0.884	0.915
2015–2018	0.638	0.782	0.814	0.619	0.770	0.804	0.817	0.895	0.913

8 Conclusions

This study assessed the impact of the IFQ program on the TE and overcapacity of the red snapper IFQ and Gulf reef fish IFQ fisheries. Drawing on recent econometric developments that account for vessel-specific heterogeneity, we find that time-varying TE improved after the adoption of IFQ. In the red snapper fishery, time-varying TE rose by almost 6% (from 0.711 pre-IFQ to 0.751 post-IFQ) and in the Gulf reef fish fishery it increased by 5% (from 0.746 pre-IFQ to 0.787 post-IFQ). In contrast, overall TE declined post-IFQ in both fisheries; however, this result was affected by the inability of the model to capture persistent TE in the pre-IFQ periods.

We also find that fishing capacity increased in the red snapper IFQ fishery but results were mixed in the Gulf reef fish IFQ fishery. In the red snapper fishery, post-IFQ capacity increases ranged from 12% to 35% depending on the metric considered (i.e., existing practices vs. fully efficient practices). In contrast, in the Gulf reef fish IFQ fishery, post-IFQ capacity declined by 4% when using existing practices but rose by 7% when assumed that best practices were employed.

Perhaps, the most important finding from our analysis is that Gulf IFQ programs continue to have limited success alleviating overcapacity. For instance, in the red snapper fishery, after a 12-year period, we estimated 20% of the fleet could land the entire quota.

Table 10 Annual fleet capacity measures pre- and post-IFQ for the Gulf reef fish IFQ fishery

	Actual catch (mp)	C^{OTE}	C^{TVE}
2002	13, 374	19, 545	18, 803
2003	12, 525	18, 469	17, 724
2004	13, 043	18, 971	18, 142
2005	12, 030	17, 676	16, 916
2006	11, 236	16, 060	15, 417
2007	8692	12, 285	11, 783
2008	9225	13, 250	12, 692
2009	7544	11, 190	10, 868
2010	6446	11, 277	9578
2011	8630	13, 723	11, 887
2012	9900	16, 173	13, 988
2013	10, 112	15, 825	13, 777
2014	10, 916	17, 715	15, 385
2015	11, 262	19, 084	16, 386
2016	11, 021	17, 458	15, 065
2017	9556	15, 138	13, 054
2018	8701	13, 877	11, 955
Entire	10, 248	15, 748	14, 319
Pre – IFQ	10, 959	15, 931	15, 293
Post – IFQ	10, 541	17, 073	14, 740
2010–2014	9201	14, 943	12, 923
2015–2018	10, 135	16, 389	14, 115

Table 11 Annual fleet size measures

Year	Quota (lbs.)	Fully efficient		Total				Quota utilization	
		Vessels	Trips	Vessels	Trips	% Vessels	% Trips	Actual	Predicted
2010	12, 220, 991	482	5046	482	5046	1.000	1.000	0.613	0.923
2011	10, 830, 901	222	1450	470	5921	0.472	0.245	0.895	1.267
2012	11, 867, 613	223	1350	461	5944	0.484	0.227	0.935	1.363
2013	13, 510, 054	261	1917	445	5643	0.587	0.340	0.869	1.171
2014	13, 734, 054	224	1482	479	6233	0.468	0.238	0.949	1.290
2015	15, 437, 270	265	1854	469	6387	0.565	0.290	0.877	1.236
2016	16, 947, 297	390	3813	464	6465	0.841	0.590	0.774	1.030
2017	17, 162, 613	494	6213	494	6213	1.000	1.000	0.679	0.882
2018	17, 162, 613	486	5538	486	5538	1.000	1.000	0.616	0.809

As mentioned earlier, a similar result was reported by Solís et al. (2014), within the first 5-years of the introduction of the IFQ program. Our estimation of overcapacity in the Gulf reef fish IFQ fishery proved more difficult because the fleet did not regularly land the entire quota. Nonetheless, in the early days of the Gulf reef fish IFQ program

(2011–2016), we estimated that 57% of the fleet, employing fully efficient practices, could have landed the entire quota.

Research on the performance of Gulf IFQ programs including our own has shown that they have provided strong incentives to mitigate race to fish conditions, but their impact on (dis)investment behavior has been more circumscribed than anticipated. While our work did not explore the reasons behind the slow retirement of excess capital in these fisheries, a fruitful area for future research would be to use our estimates to motivate interventions to accelerate the transition to a fully rationalized fishery. Without being prescriptive, vessel and permit buybacks may offer a potential means to retire long-lived, redundant fishing capital and provide relief to those fishing communities impacted by consolidation. In addition, fishery managers may also want to consider folding non-IFQ reef fish species (e.g., vermilion snapper, gray triggerfish) into a Gulf-wide reef fish IFQ program to prevent spillovers since the IFQ fleet participates in both fisheries.

To conclude, we note that further methodological improvements can be made for these types of studies since in both the red snapper and reef fish IFQ models, data spanning over 17 years is quite lengthy to believe that substantial persistent inefficiency levels remain. Alternative panel data stochastic frontier models that model this persistent efficiency as a function of various vessel specific (time constant) information may prove useful (Amsler and Schmidt 2019). Additionally, the reliance on the translog functional form could also be relaxed in future work (Parmeter and Zelenyuk 2019) and time-varying inefficiency could be modeled completely independent of distributional assumptions (Zhou et al. 2020).

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