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ARTICLE

On the productivity and technical efficiency of the Puerto Rican queen conch *Aliger gigas* fishery

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Abstract

Objective: This study examines the productivity and technical efficiency (TE) of diving operations that target queen conches *Aliger gigas* in the Commonwealth of Puerto Rico, the largest producer of queen conches in the United States. Currently, there is a proposal to list queen conch as threatened under the Endangered Species Act (ESA).

Methods: We use stochastic production frontier methods to investigate the relationship between catch and fishing inputs and the technical performance of diving operations.

Result: Our results show that the fleet could increase its catches, on average, by 30% (and, thus, increase its income) by using existing fishing inputs and technology more efficiently. We find that the potential to expand catches was slightly higher from increasing the crew size than from extending the length of the fishing trip. The study also finds considerable heterogeneity across coastal regions and operation sizes. Overall, operations on the east and west coasts and those having three or more crew members were more efficient. Operations that use a single gear and specialize on few species (revenue concentration) were associated with higher levels of TE. We also find that diving operations exhibit decreasing returns to scale.

Conclusion: The potential ESA listing of the queen conch poses a dilemma because increasing the efficiency of the fleet may continue to compromise the sustainability of the resource. While a threatened designation does not necessarily result in additional trade or harvest restrictions, further actions may be advisable given the many threats, such as overutilization, habitat loss, coastal pollution, and disruptive environmental change that queen conch populations face. Our model suggests that reducing the size of the crew and/or the length of the trip may increase efficiency, but these restrictions may not be advisable on safety grounds. Thus, management agencies may want to reassess existing trip limits and the length of the closed season and explore the use of closed areas.

KEYWORDS

Puerto Rico, queen conch, small-scale fisheries, stochastic frontier

INTRODUCTION

The queen conch *Aliger gigas* fishery is the quintessential Caribbean fishery.[1,2] This fishery has supported the livelihoods of coastal communities throughout the region for centuries (Brownell and Stevely 1981; Theile 2001; Farmer and Doerr 2022; Stoner and Appeldoorn 2022). Since the 1970s, a growing international demand for queen conches has put increased pressure on local stocks, forcing many Caribbean countries to impose stringent regulations, including gear restrictions, catch and export quotas, and complete fishing moratoria (Brownell and Stevely 1981; Theile 2001; Stoner and Appeldoorn 2022). Queen conch stocks are highly susceptible to overexploitation due to their unique life history characteristics, which include late maturity, slow motility, and the formation of feeding and breeding aggregations in shallow coastal habitats (<30 m; Stoner and Appeldoorn 2022). These characteristics make them easy and profitable targets for fishers. Additionally, queen conches need direct contact to breed, so when their populations become sparse, they have difficulty in finding mates and reproducing. Thus, intensive harvesting can lead not only to local depletion but also potentially to the collapse of native populations.[3] In 1992, the Convention on International Trade in Endangered Species of Wild Fauna and Flora listed the queen conch in Appendix II (Theile 2005).[4]

In 2012, renewed worries about declining queen conch populations within the species' range prompted a number of lawsuits that compelled the National Oceanic and Atmospheric Administration (NOAA) to conduct a comprehensive review of its status. The review determined that queen conches face a high level of extinction risk in the foreseeable future (about 30 years) unless several threats, such as overfishing, inadequate regulations, and climate change, among others, are addressed (Horn et al. 2022). As result, NOAA proposed to list the queen conch as a threatened species under the Endangered Species Act (ESA) in late 2022. The ESA protects endangered and threatened species from extinction throughout all or a significant portion of their range, as it prohibits importing, exporting, taking, possessing, selling, and transporting of the species.

This study examines the productivity and technical efficiency (TE) of diving operations that target queen conches in the Commonwealth of Puerto Rico, the largest producer of queen conches in the United States. Puerto Rico and the U.S. Virgin Islands are the only two jurisdictions in the United States that have queen conch fisheries.[5] Understanding the efficiency with which small-scale fishers turn fishing inputs into catch is important because it can provide useful insights into the biological and economic performance of management proposals (Sesabo and Tol 2007; Pham et al. 2014; Oliveira et al. 2016; Agar et al. 2017; Quijano et al. 2018; Van Nguyen et al. 2019; Álvarez et al. 2020; Jueseah et al. 2021; Solís et al. 2021). This article is organized as follows: after a brief description of the fishery, we describe the data and model. We then present and discuss the main results of the analysis. The article concludes with a summary of the main findings and policy implications.

Impact statement

The Commonwealth of Puerto Rico is the largest producer of queen conch in the United States. If queen conch becomes listed as threatened under the Endangered Species Act, managers may have to revisit its management. Understanding the drivers of the productivity and technical efficiency of small-scale fleets can yield valuable insights into the biological and economic performance of management proposals.

FISHERY BACKGROUND

The Commonwealth of Puerto Rico is an archipelago located in the northeast Caribbean Sea and is made up of the main island of Puerto Rico and several smaller islands, including Vieques, Culebra, Mona, and Desecheo (Figure 1). The archipelago has an area of 9104 km^2 (3515 mi^2). Small-scale fisheries play an important role, supporting hundreds of fishers throughout the Commonwealth (Suárez-Caabro 1979; Gutiérrez-Sánchez 1982; Pérez 2005; Griffith et al. 2007; Valdés-Pizzini 2011; Agar et al. 2020).

[1] *Aliger gigas*, originally known as *Strombus gigas* or more recently as *Lobatus gigas*, is commonly known as the queen conch.

[2] Fishers mainly harvest queen conches for their meat, but some also sell their shells as curio and tourist souvenirs (Theile 2001; Horn et al. 2022). Queen conches can produce valuable pearls, but these are extremely rare (Agar and Shivlani 2017).

[3] Genetic work suggests that queen conches do not form a single panmictic population in the greater Caribbean (Stoner and Appeldoorn 2022; Vaz et al. 2022). For instance, Truelove et al. (2017) reported finding several regionally isolated queen conch populations throughout the region.

[4] Appendix II includes species that are not necessarily threatened with extinction but may become so unless trade is closely controlled (More information available at https://cites.org/eng/app/appendices.php).

[5] The State of Florida banned the commercial and recreational harvest of queen conches in 1986.

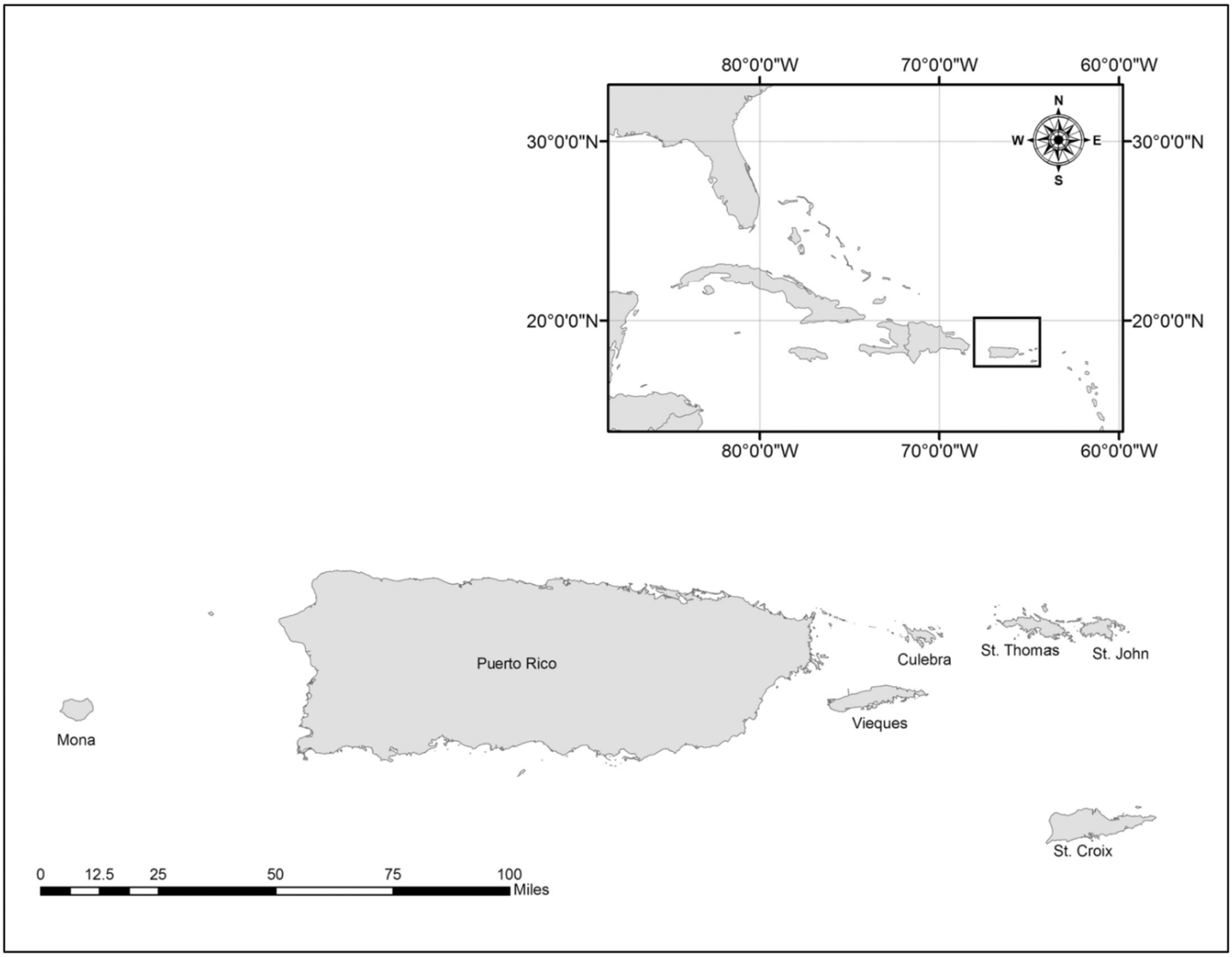

FIGURE 1 Map of the Commonwealth of Puerto Rico (1 mile = 1.61 km).

Many Puerto Rican fishers pursue a livelihood strategy of occupational multiplicity, which combines fishing with other informal and formal wage labor activities (Pérez 2005; Griffith et al. 2007; García-Quijano 2009; Matos-Caraballo and Agar 2011). Some fishers, particularly older individuals, further supplement their income with government assistance (Pérez 2005).

In 2019, Puerto Rican fishers landed about 1.13 million kg (2.5 million lb) of finfish and shellfish worth about US$12 million. The queen conch supports the second most valuable fishery in terms of revenue (17%) after the Caribbean spiny lobster *Panulirus argus* (27%). The queen conch fishery is mainly prosecuted using scuba. Diving operations typically fish for 6–7 h/day and have two to three crew members (Agar and Shivlani 2017). The Puerto Rican queen conch fishery is a "regulated open-access" fishery, meaning that fishers must pay a nominal fee for a fishing license (and queen conch endorsement) to participate in the fishery.

The queen conch fishery is regulated with an annual catch quota. Fishing for queen conches in federal waters (16.7–370.4 km [9–200 nautical miles]) is prohibited except in portions of Lang Bank off the island of St. Croix in the U.S. Virgin Islands. Fishers operating in Commonwealth waters are subject to a daily commercial quota of 150 conches/licensed fisher up to a maximum of 300 conches/vessel. Since 2013, Puerto Rican fishers have been allowed to shuck conches underwater, whereas previously they had to land the conches in the shell. In Commonwealth waters, there is a closed season for the queen conch, which runs from August 1 to October 31; the timing of the closure was set to coincide with the peak of the reproductive season. In addition, there is a sales ban to help with the enforcement of the closure and to allow fishers and dealers to exhaust their inventories. The sales ban begins 1 week after the start of the closure and lasts until the closure ends. Other Commonwealth regulations include minimum size limits (length of 228.6 mm [9 in] or lip width of 9.525 mm [0.375 in]) and gear bans (i.e., hookah).

DATA AND METHODS

Data

The data set used was built based on data from two sources. The National Oceanic and Atmospheric Administration provided us with logbook data that contained trip-level information, including landings, gear type, fishing effort, crew size, landing sites, and dockside prices. Logbooks document that scuba divers catch a variety of species using different fishing equipment (e.g., queen conches are caught manually, Caribbean spiny lobsters are caught by using snares, and reef fishes are caught by using spear guns). Depending on the target species, fishers tend to report their gear differently in their logbooks even though they are all using scuba. When fishing for queen conches, divers tend to record scuba diving as their main gear, whereas when fishing for Caribbean spiny lobsters, they tend to record snares as their main gear. Scuba divers fishing for reef fishes tend to record spear fishing as their main gear. Most divers may take multiple gears during a trip since they do not want to forgo the chance to catch other species opportunistically.

In this study, we focused on those trips taken in Commonwealth waters where scuba diving accounted for the plurality of the revenues. Logbooks show that most (>90%) of the queen conch is caught using scuba. After deleting observations with missing or incomplete values and outliers, we were left with unbalanced panel data consisting of 58,124 trips taken by 814 unique captains over an 8-year span (2012–2019). The panel showed that divers were highly specialized, with approximately 89% of the trips having a reported catch of only queen conches; another 6% of the trips had a reported harvest of both queen conches and Caribbean spiny lobsters, and the remaining trips had a reported catch of queen conches, Caribbean spiny lobsters, and reef fish. Data on climatic variables were obtained from the NOAA National Centers for Environmental Information website (https://www.ncei.noaa.gov/).

Stochastic production frontier

We examined the TE of the dive fleet that mainly targets the queen conch in Commonwealth waters using stochastic production frontier (SPF) methods.[6] Stochastic production frontiers are useful tools for examining the relationship between catch and fishing inputs and the technical performance of fishing vessels. The SPFs map the "best practice" or efficient frontier (i.e., the maximum potential catch), which provides a benchmark against which to compare the TE of individual vessels. Production levels below the frontier yield a measure of relative inefficiency. Stochastic production frontiers deem individual producers to be inefficient when their realized output deviates from the maximum possible output level (the best practice frontier; Kumbhakar et al. 2015). In contrast, traditional production functions measure the average output as a function of a given level of inputs, assuming that all producers are equally efficient. Another attractive feature of SPFs is that they do not require behavioral assumptions about the economic motivation of the fishers (e.g., profit maximization; Kumbhakar et al. 2015).

We modeled a trip-level SPF using a Cobb–Douglas specification because it is parsimonious in the number of parameters:

$$\ln(y_i) = \beta_0 + \sum_{j=1}^{n} \beta_j \ln(x_{ji}) + \sum_{k=1}^{m} \rho_k \mathbf{C}_{ki} + v_i - \mu_i, \quad (1)$$

where y_i is the total catch (kg [lb]; i.e., queen conches, Caribbean spiny lobsters, and miscellaneous reef fishes) of the ith vessel on a given trip, and x is a vector of two variable inputs: crew size (including the captain) and trip length (h).[7,8] The symbol **C** represents a vector of control variables that accounts for regulatory, geographical, resource, weather, and climatic factors. The seasonal closure dichotomous variable (i.e., dummy variable) was used to account for the 3-month harvest ban; this variable was set equal to 1 between August 1 and October 31 and was 0 otherwise. Dummy variables capture the impact of control variables as shifts in the production frontier (either upward or downward). They implicitly assume that the impact is identical across all fishers (Innes and Pascoe 2008). The βs and ρs are unknown parameters to be estimated.

We also included three coastal regional dummy variables (west, east, and south) to account for unobserved heterogeneity associated with geographic variations in access to the resource and species abundance, and seven annual dummy variables were included to control for intertemporal

[6]Although there are other approaches, such as data envelopment analysis, we used an SPF because it can deal with the randomness of the fishing process. The SPFs presume that deviations from the frontier are caused not only by inefficiency, but also by stochastic events, such as weather and luck. In addition, the parametric nature of the SPFs provides detailed knowledge about the relationship between catch and fishing inputs.

[7]Initially, we ran multiproduct distance frontier models, but they failed to converge—probably because of the large number of trips that did not jointly catch Caribbean spiny lobsters or reef fishes, as noted in the data description. Hence, we ended up aggregating all three groups into a single output, bearing in mind that the queen conch was the main source of revenue for these trips.

[8]The queen conch catch weight refers to meat weight since the shell remains underwater once the conch is shucked.

variations in resource availability. The dummy variables were benchmarked relative to the north coast in 2019. In addition, we accounted for weather and climate variability. We used a dummy variable to control for the rainy season (with a value of 1 for the period April–November and a value of 0 for the other months). Climatic variability was accounted for by using the Atlantic Multidecadal Oscillation (AMO) index, which captures sea surface temperature (SST) anomalies over the North Atlantic Ocean. A positive AMO phase corresponds with positive SST anomalies over most of the North Atlantic.

To isolate the stochastic and inefficiency effects in the SPF model, we made distributional assumptions about the terms of the composed error term, $\nu - \mu$. The term ν is assumed to be a two-sided random error with a normal distribution ($\nu \sim N[0, \sigma_{\nu}^2]$) that measures stochastic factors beyond the captain's control and underlying technology. These shocks can be either negative or positive, such as an unexpected bad weather event or a lucky fishing event. The term μ is assumed to have a one-sided, nonnegative component that measures the gap between observed and maximum feasible output (i.e., frontier) given the available inputs and underlying technology. The larger the value of μ, the greater is the level of inefficiency because it is more interior to the best practice frontier (Grafton et al. 2006).

Following Jondrow et al. (1982), the TE for the *i*th fishing operation was estimated as

$$\mathrm{TE}_j = \exp\left(-\mu_i\right), \quad (2)$$

where μ is the efficiency term as defined above. The TE for each vessel was calculated using the conditional mean of $\exp(-\mu)$, given the composed error term of the SPF model (Battese and Coelli 1988). Technical efficiency scores ranged between 0 and 1. A TE score of 1 indicates that fishing vessels are operating on the best practice frontier, whereas a TE score less than 1 indicates that the vessels are operating beneath the frontier. The TE scores are relative measures of managerial ability or fishing skill.

The maximum likelihood method developed by Battese and Coelli (1995) allowed us to estimate the determinants of technical inefficiency (TI) in a one-step procedure. Thus, TI could be estimated by incorporating the following expression into the frontier model shown in Equation (1):

$$\mu_j = \delta_0 + \sum_{n=1}^{k} \delta_n z_{nj} + \omega_j, \quad (3)$$

where μ_j is the TI, z_{nj} are variables that affect efficiency, δ_n are unknown parameters to be estimated, and ω_j is an error term.

Our TI model examined how specialization influences TE. Many studies have documented that catch (species) portfolios have become more specialized, raising questions about the ability of fishing communities to weather resource, market, and oceanographic shocks (Solís et al. 2020). We used the Berger–Parker (BP) metric to explore the impact of specialization on TE. The BP score is a dominance score that measures the proportional importance of the most valuable species (Magurran 1988). The BP scores were calculated as a ratio equal to N_{max}/N, where N_{max} is the revenue from the most valuable species and N is the total revenue. Berger–Parker scores range between close to 0 and 1. We also included a dummy variable equal to 1 for those trips that used a single gear (single gear = 1; 0 otherwise) and a linear time trend (t) to capture unobserved factors that influenced TE over time. Table 1 provides the descriptive statistics of the main variables used in the analysis. We also explored the importance of managerial skill relative to stochastic shocks (e.g., weather, luck, etc.) by estimating the parameter lambda (λ), which is the ratio of the standard error (SE) of the inefficiency term μ to the SE of the stochastic term ν (Kumbhakar et al. 2015).

RESULTS AND DISCUSSION

Model performance and production frontier

Table 2 presents the maximum likelihood estimates and corresponding SEs for both the SPF and TI models. All but one of the parameter estimates were statistically significant at least at the 0.10 significance level. The bottom of Table 2 shows the results of hypothesis tests that assessed the performance of the empirical model. The parameter λ (the ratio of the SE of μ to that of ν) was statistically significant at the 0.01 level, suggesting that fishing skill was more important than random shocks (or luck) in explaining differences in landing levels across trips (Table 2). In addition, the null hypothesis that inefficiency does not exist (H_o: $\lambda = 0$) could not be rejected at the 0.01 significance level. These results suggest that the adoption of the SPF method is more appropriate than the standard production function since TI is observable in the fishery (Herrero and Pascoe 2003; Solís et al. 2014).

With the SPF model, which examined the relationship between fishing inputs and landings, we found that the parameter estimates for trip duration and crew size were positive and statistically significant (Table 2). Since we implemented a Cobb–Douglas specification, these estimates can be interpreted as partial elasticities (or the responsiveness) of landings to a 1% change in the use of one input while the remaining inputs are held constant.

TABLE 1 Descriptive statistics of variables used in the analysis of the queen conch fishery in Puerto Rico. max, maximum; min, minimum; SD, standard deviation.

Variable	Description	Mean	SD	Min	Max
Catch (kg/trip)	Continuous	19.60	13.51	0.453	387.821
Trip duration (h/trip)	Continuous	3.797	4.044	1	8
Crew size (including captain)	Count	1.603	0.702	1	4
East coast	Dichotomous	0.197	0.397	0	1
West coast	Dichotomous	0.525	0.499	0	1
South coast	Dichotomous	0.232	0.422	0	1
North coast	Dichotomous	0.046	0.208	0	1
2012	Dichotomous	0.126	0.001	0	1
2013	Dichotomous	0.137	0.001	0	1
2014	Dichotomous	0.132	0.001	0	1
2015	Dichotomous	0.131	0.001	0	1
2016	Dichotomous	0.122	0.001	0	1
2017	Dichotomous	0.094	0.001	0	1
2018	Dichotomous	0.126	0.001	0	1
2019	Dichotomous	0.129	0.001	0	1
Single gear	Dichotomous	0.631	0.173	0	1
Berger–Parker index	Index	0.842	0.213	0.5	0.9

Thus, at the mean level of all inputs, a 1% increase in the duration of the trip will result in a 0.29% increase in landings. Perhaps more interesting is the magnitude of the elasticity of landings with respect to crew size (i.e., 0.33%), which indicates that the scope for expanding catches is slightly greater from increasing the size of the crew than from increasing the duration of the fishing trip. One plausible explanation for this result is that diving operations may find it more beneficial to add crew rather than increase the duration of the trip (and, thus, overall diving time) due to the risk of decompression sickness. Additionally, since the fishing activity and the processing (shucking) activity occur underwater, adding one more crew member (and their tanks) is unlikely to cause major overcrowding in the small craft.

The relatively minor difference in the magnitude of the input elasticities was somewhat unexpected, which lends weight to anecdotal accounts reporting that divers occasionally disregard the dangers of decompression sickness because of financial need. Agar and Shivlani (2017) report that Puerto Rican divers are more willing to take additional dives (or to prolong dives) if recent weather conditions have been poor or if their first tanks were unproductive. Agar and Shivlani (2017) also recount that the divers are often tempted to dive longer if they find productive aggregations toward the end of the trip, in some cases using a fourth tank to catch conches in 21.34–27.43-m (70–90-ft) depths.

The SPF model also revealed that the fishing operations experience decreasing returns to scale, meaning that a proportional increase in the use of all inputs results in a less-than-proportional increase in landings. In other words, a 10% increase in the use of all inputs will result in a 6.13% increase in catches (Table 2). Fousekis and Klonaris (2003) noted that fishing firms subjected to either increasing or decreasing returns to scale will exhibit scale inefficiencies, which manifest in the form of reduced productivity. Decreasing returns to scale imply that divers could increase their short-run productivity by cutting back on their fishing effort.

The seasonal closure and rainy season were estimated to reduce catches by 9.6% and 2.7%, respectively.[9] The AMO index had a positive and statistically significant impact on catches—perhaps because, as Stoner and Appeldoorn (2022) suggested, positive SST anomalies may extend the spawning season (and, thus, aggregation), at least in some areas. The coastal region dummy variables, which captured variations in access to the resource and species abundance, were higher for the east and west coasts. These results are generally consistent with expectations based on the observed behavior of the fleet. The yearly dummy variables suggested that resource availability (relative to 2019 levels) rose in 2017 and 2018.

[9]The impact of a dummy variable on productivity was estimated using $(1-e^{\omega})\times 100$, where ω is the coefficient of the dummy variable.

TABLE 2 Parameter estimates for the stochastic production frontier (SPF) and technical inefficiency (TI) models of the queen conch fishery in Puerto Rico. AMO, Atlantic Multidecadal Oscillation; SE, standard error. $*p < 10\%$; $**p < 5\%$; $***p < 1\%$

Parameter	Coefficient	SE
SPF model		
Constant	3.145***	0.019
Crew size	0.328***	0.006
Trip duration	0.285***	0.009
Seasonal closure	−0.101***	0.006
Rainy season	−0.027***	0.005
AMO index	0.078***	0.002
West coast	0.238***	0.011
East coast	0.692***	0.007
South coast	0.202***	0.006
2012	−0.053***	0.012
2013	−0.073***	0.012
2014	0.008	0.011
2015	−0.023*	0.010
2016	−0.027**	0.010
2017	0.022*	0.010
2018	0.057***	0.009
TI model		
Constant	0.275***	0.042
Dominance index	−0.941***	0.020
Single gear	−0.054***	0.004
Time trend	0.064***	0.007
$\lambda = \sigma_{\mu/}\sigma_{\nu}$	3.754***	
$\sigma^2 = \sigma_{\nu}^2 + \sigma_{\mu}^2$	0.883***	
Log likelihood	−46,434.1	

Factors influencing technical inefficiency

Table 2 shows the results of the TI model, which examined factors that impacted efficiency (Table 2). Positive (negative) signs imply a negative (positive) impact on TE. Positive and statistically significant impacts of revenue dominance (BP score) and the use of a single gear on TE suggested the presence of specialization efficiencies. Trip-level specialization efficiencies may arise because when faced with limited underwater fishing time, divers find it more profitable to focus on a particular habitat–species combination. Agar and Shivlani (2017) report that divers fish over a wide range of habitat types depending on the species pursued. For instance, divers targeting queen conches harvest them on seagrass beds and sandy bottoms, whereas divers targeting Caribbean spiny lobsters and reef fishes catch them on hard bottoms and reef areas. However, many fishers target multiple species as a means to reduce financial risk. The time trend had a negative and statistically significant impact on TE. Although we are unsure about the possible causes for the negative sign of the time trend, it may reflect declining abundance, graying (aging) of the fleet, attachment to traditional fishing practices, and/or a disinclination to innovate. The absence of information on demographic, household, and vessel characteristics and stock abundance precluded us from identifying other important determinants of inefficiency, which merits further research.

Technical efficiency of the fleet

We used Equation (2) to compute the TE score for each trip. The mean TE score was 70%, indicating that the average diving operation could increase its catches by 30% by using the available inputs and existing technology more efficiently (Table 3). The estimated average TE score was slightly higher than those reported for other gears in Puerto Rico. For instance, Agar et al. (2017) reported that the mean TE score for the trap fishery was 64%; however, that estimate used gross revenues as the benchmark, whereas landings were examined in the present study.

We also found that there was a marked degree of heterogeneity across diving trips. Table 3 presents the breakdown of TE scores across select characteristics. On average, operations on the east and west coasts had higher TE scores. Average TE scores were also higher for those operations that had larger crew sizes (more than three crew members). Single-gear trips were about 27% more efficient that those using multiple gears (Table 3). Average TE scores peaked when trips lasted 5 h.

Figure 2 shows that the kernel distribution of TE scores was left (negatively) skewed. Figure 3 shows that most operations landed between 65% and 80% of their full potential. Figure 4 illustrates that the mean TE score slowly fell by 5.81% between 2012 and 2019. Figures 3 and 4 also show that a large number of observations exhibited very low levels of TE. Most of these extremely inefficient observations corresponded to operations that took short trips (≤1 h) and that were single manned, pointing to the presence of fishers who may occasionally dabble in diving to supplement their income. Valdés-Pizzini (2006) noted that scuba diving is popular among Puerto Rican fishers because of its low capital requirements, the year-round warm weather, the widely available facilities to service the gear, and the absence of catch and gear theft problems associated with other fishing gears, such as traps.

TABLE 3 Average technical efficiency scores by category for the queen conch fishery in Puerto Rico. max, maximum; min, minimum; SD, standard deviation.

Category	Mean	SD	Min	Max	Observations (%)
Entire sample	0.703	0.138	0.060	0.989	100.0
Coast					
East	0.759	0.134	0.323	0.915	25.6
West	0.703	0.160	0.070	0.984	48.1
South	0.671	0.141	0.094	0.989	20.7
North	0.594	0.127	0.060	0.970	5.6
Crew size					
1	0.578	0.102	0.205	0.773	51.9
2	0.692	0.140	0.060	0.983	34.5
3	0.709	0.138	0.070	0.989	13.4
4	0.733	0.1266	0.123	0.970	0.2
Trip duration (h/trip)					
1	0.532	0.163	0.217	0.647	0.7
2	0.613	0.183	0.106	0.938	1.3
3	0.695	0.131	0.070	0.956	2.4
4	0.722	0.138	0.102	0.983	21.4
5	0.759	0.184	0.305	0.968	26.6
6	0.706	0.131	0.069	0.983	29.3
7	0.702	0.195	0.333	0.961	6.2
8	0.682	0.151	0.060	0.989	12.0
Gear					
Single	0.793	0.078	0.401	0.989	56.2
Multiple	0.621	0.146	0.060	0.979	43.8

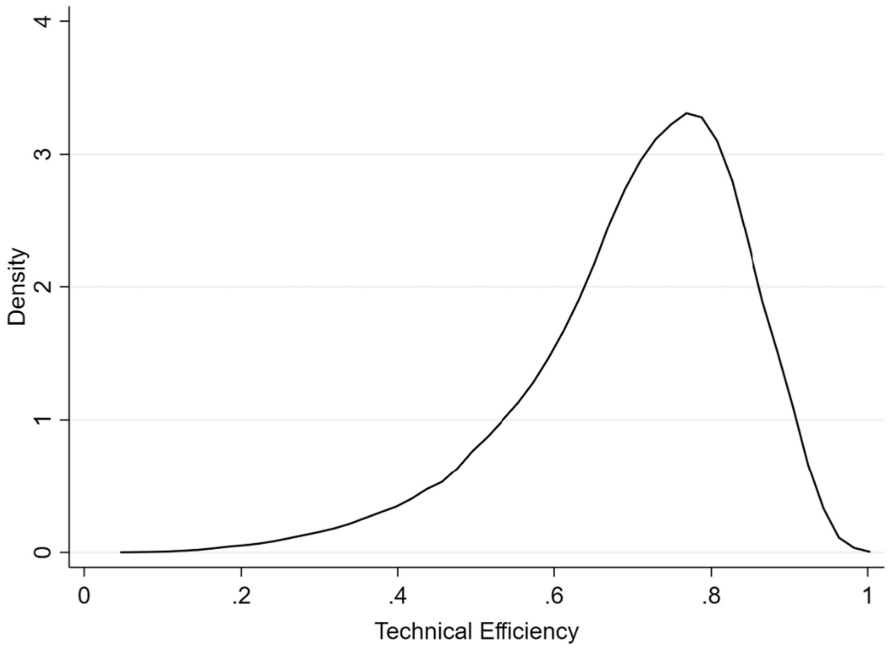

FIGURE 2 Kernel density of technical efficiency scores for the queen conch fishery in Puerto Rico. The figure shows that technical efficiency scores follow a left-skewed unimodal distribution. The long tail toward the left side captures the presence of a large number of inefficient diving trips in the sample.

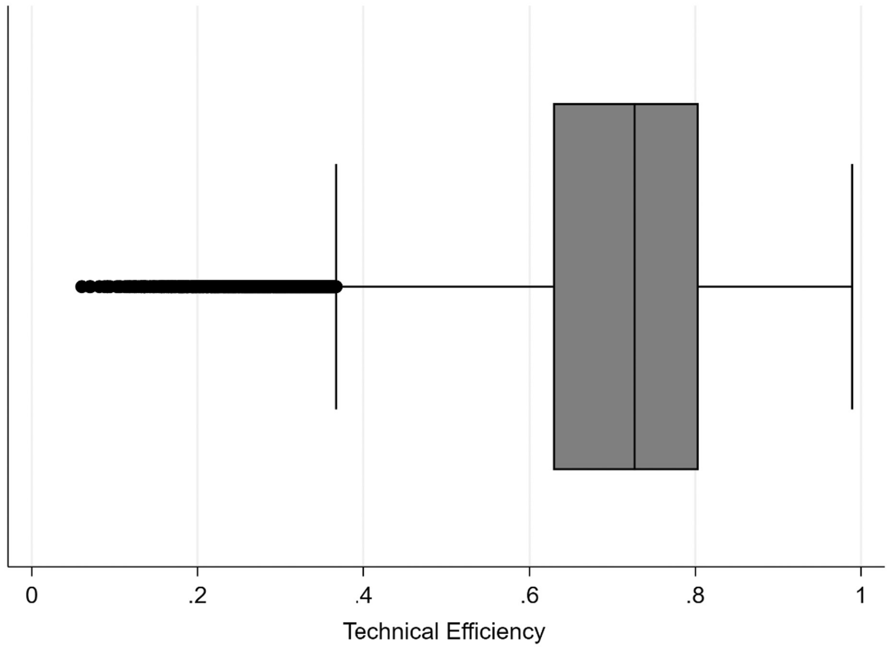

FIGURE 3 Box plot of technical efficiency scores for the queen conch fishery in Puerto Rico. The figure shows the distribution of technical efficiency scores across diving trips. The box, which captures the interquartile range (IQR), shows that the middle 50% of scores fall between 0.65 and 0.80, indicating that these trips landed between 65% and 80% of their full potential. The bottom and top of the box indicate the 25th and 75th quantiles, and the line inside the box represents the median score. The whiskers extend to the highest and lowest scores within 1.5 times the IQR from the box. The individual points beyond the whiskers represent the most inefficient trips, which landed less than 40% of their full potential.

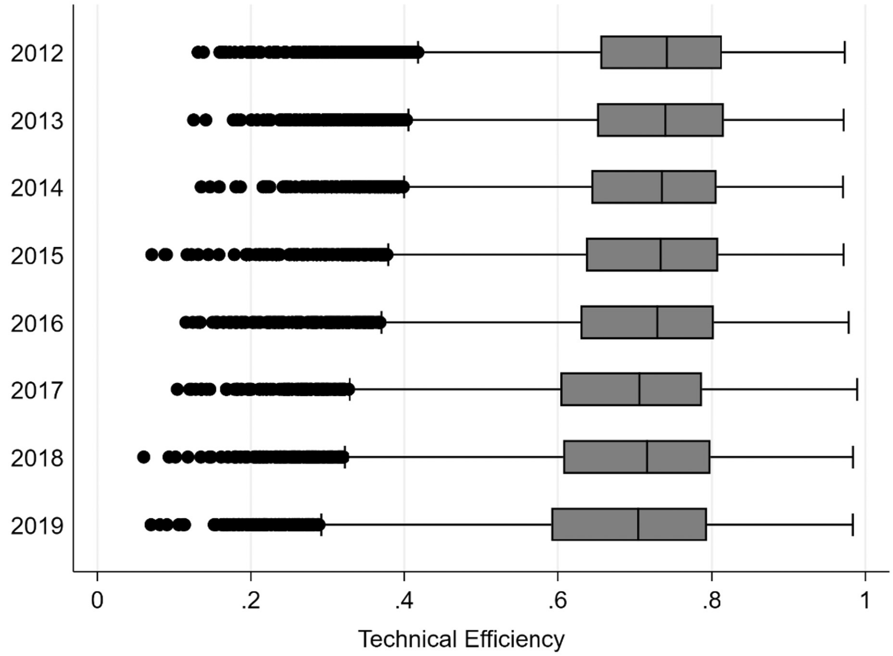

FIGURE 4 Distribution of technical efficiency scores by year for the queen conch fishery in Puerto Rico. The figure displays the distribution of technical efficiency scores across diving trips by year and shows that the mean score fell by almost 6% between 2012 and 2019. The figure also shows that the lowest quantile became more inefficient over time. See Figure 3 for definitions of the box plot elements.

CONCLUSIONS

The queen conch fishery faces numerous threats: most significantly, overutilization stemming from commercial, recreational, and subsistence fishing and illegal, unreported, and unregulated fishing (Horn et al. 2022). This growing concern over the health of queen conch populations led to a proposal to list the species for protection under the ESA. Our work suggests that by using existing fishing inputs and technology more effectively, the average small-scale diver could boost their catches by 30%, which would improve the welfare of small-scale fishing households. However, we observed considerable variation in TE levels across different coastal regions and operation sizes. Interestingly, our work found that the potential to expand catches was slightly higher from increasing the crew size than from extending the length of the fishing trip.

The potential ESA listing of the queen conch poses a dilemma because increasing the efficiency of the fleet may continue to compromise the sustainability of the resource. While being listed as a threatened species does not necessarily result in added trade or harvest restrictions, additional protective actions may be advisable for queen conch conservation given the other threats, such as habitat loss, coastal pollution, and disruptive environmental change. Although identifying superior interventions is outside the scope of this work and is best carried out while engaging stakeholders, our results suggest that simultaneously reducing the crew size and the length of the trip by 10% could lower landing levels by 6.13% but improve the efficiency of the diving operations due to the nature of the technology, which involves decreasing returns to scale. However, implementing these restrictions, either individually or in combination, may not be advisable on safety grounds. Consequently, fishery management agencies may want to reconsider current trip limits and the duration of the closed season as well as exploring the potential benefits of establishing closed areas to protect queen conch resources.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data used in this study are available from NOAA, but restrictions apply to access of confidential data pursuant to NOAA's policies.

ETHICS STATEMENT

The authors report following ethical guidelines and confirm that the current study did not involve human subjects or animal experiments.

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