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ARTICLE

Profits, prices and productivity in a common pool fishery

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Abstract

Profitability change for any firm depends on both price and productivity change. Because most firms have little influence on prices in either output or input markets, oftentimes productivity change is thought to be the most relevant determinant of profitability change. When firms produce a product by harvesting or extracting government-regulated natural resource stocks, it is important for regulators to understand how their decisions influence firm profitability and its underlying drivers. In this study, we use a recently developed index number decomposition method to identify the drivers of profitability, price, and productivity change for vessels operating in the U.S. northeast scallop fishery. Our main finding is that increases in profitability over the period 1996 to 2015 were primarily due to increases in prices for scallops, combined with favorable biomass change. Fishing vessels were able to get higher prices for their harvest because of an innovative spatial harvest strategy, which resulted in catches of large, premium-priced scallops. Remarkably, this system resulted in both an increase in vessels harvesting scallops and large increases in profitability.

KEYWORDS

data envelopment analysis, efficiency, fishery, productivity, profitability

JEL CLASSIFICATION

D24, Q22

1 | INTRODUCTION

The majority of the world's wild harvested seafood resides in the Exclusive Economic Zones (EEZs) of coastal states, where governments regulate commercial fishing in order to conserve fishery biomass for future generations and to achieve other societal goals. Regulators typically limit catch (output controls), input usage (effort controls), or a combination of the two (Clark, 1990; Squires, 1987). Regardless of which management approach is used, regulators invariably like to measure different dimensions of commercial fleet performance to assess how their management strategies are affecting the fleets they are regulating. Common performance criteria include revenue per unit effort, revenue per active vessel, and revenue per vessel day (Murphy et al., 2012; Murphy et al., 2015; Rountree et al., 1998), along with a broader suite of measures covering community well-being, share prices, and income concentration (Clay et al., 2014).

There have been numerous studies worldwide focused on profitability changes in response to specific fishery management practices (Dupont et al., 2005; Ekerhovd and Gordon, 2020; Fox et al., 2003; Walden, 2013; Walden and Kitts, 2014). All of these studies utilized vessel-level data to measure profitability change. It is possible to decompose vessel-level measures of profitability change into productivity and price change components (Dupont et al., 2005; Grifell-Tatjé and Lovell, 2015; O'Donnell, 2018). Such decompositions can help answer important questions about the impact of regulatory changes on fishing operations. For example, did profitability increase due to increases in landings brought about by a policy change or an external factor, such as reduced fuel prices? Did profitability decrease because outputs declined or was it declining output prices? In natural resource industries where government regulators manage a common pool resource, decomposing profitability change provides important feedback about the impact of management policies on firms that are actively harvesting the resource.

Profitability, or return to the dollar, in U.S. fisheries is not measured on a regular basis, largely because data on input prices and quantities are missing (Walden and Kitts, 2014). In this paper, we measure profitability change in the northeast U.S. scallop fishery over the period 1996 to 2015. We then adopt recent advances in index number methods to decompose profitability change into measures of price change and productivity change. Productivity change is then further decomposed into a measure of technical and environmental change, and two measures of efficiency change. Our measure of technical and environmental change is innovative as it accounts for two different environmental variables; to our knowledge, this has not been done before in productivity studies centered on commercial fishing vessels.

We focus on the northeast U.S. scallop fishery for two reasons. First, it is an extremely valuable fishery. Examination of 2017 revenue totals from all U.S. marine fisheries showed scallops as the fifth most valuable species in terms of ex-vessel revenue (https://www.fisheries.noaa.gov/foss, Accessed March 9, 2021). Second, because since 2004 the fishery has been managed through what perhaps can best be described as an "industrial policy" arrangement rather than a catch share system. We describe it in this manner because the per-vessel harvests and areas where vessels can fish are strictly controlled by government regulators through either direct harvest limits or limits on fishing time. Amendment 10, implemented in 2004, instituted a spatial-management program where specific fishing areas were designated for rotational management, similar to what might be found in crop farming; harvest levels of scallops in those areas are strictly controlled. Amendment 10 also left in place a non-transferrable effort control system for areas outside the spatial-management areas where inputs are strictly regulated. This type of management system is unique in the U.S., as it combines a system of area closures, similar to a crop rotation system, with both an effort control system and an individual trip quota system. We seek to determine whether there was an increase in profitability given the highly regulated nature of this fishery, and if so, what were the drivers of profitability change? The time period chosen for our study includes years prior to the start of Amendment 10 when the novel spatial-management program for controlling fishing mortality was enacted.

Vessels operating in the northeast U.S. scallop fishery are more highly regulated than if they were operating in a catch share system, and we expected there would be limited opportunities to increase profitability. However, we found that this was not the case. After implementation of Amendment 10 in 2004, profitability increased in eight out of the following 11 years, although it declined in only thre years. Our results show that profitability increased due to both price and productivity increases, both of which can be associated with the area management program. We attribute the increases in prices to an improvement in the price of large scallops after implementation of the spatial-management program. We also find that the productivity increases were highly correlated with biomass increases. Our study demonstrates the importance of domestic harvest prices and management strategies, which influence those prices and improve profitability. One of the lessons learned is that, by delaying harvests, scallops can mature to a size that can command premium prices and yield increased revenues. In turn, adoption of such price- and revenue-augmenting strategies can improve industry profitability.

2 | SCALLOP MANAGEMENT

The sea scallop fishery is currently one of the most valuable commercial fisheries on the U.S. Atlantic coast, with recent ex-vessel value exceeding $400 million per year (NEFMC, 2015). Scallops are primarily caught in the waters of Georges Bank (GB), Southern New England (SNE), and the Mid-Atlantic Bight (MAB) with dredge gear, although some vessels use bottom trawls. Virtually all sea scallops are shucked at sea and are often graded into size categories (based on number of scallops per pound) on the vessel (Georgianna et al., 2017). Minimal shore-side processing occurs after landing.

Until 1994, the scallop fishery was an open-access fishery primarily regulated with a minimum size (meat count) standard. In 1994, a limited-access (LA) program was implemented in conjunction with a Days-at-Sea (DAS) effort control program that restricted total fishing time. The scallop fishery has a long history of spatially explicit fishing regulations, with tremendous variation from year-to-year. Three large areas in GB/SNE (Nantucket Lightship, Closed Area I, and Closed area II) were closed to commercial bottom-tending gear, including dredges and bottom trawls, to rebuild depleted stocks of groundfish in 1994. Two additional areas in the MAB (Hudson Canyon and Virginia Beach) were closed in 1999 to allow high abundances of juvenile scallops to mature. Sizable amounts of large scallops were later found in some of these closed areas, and beginning in 1999, the LA fleet was allowed to fish in a portion of the closed areas (64 Federal Register 31,144; 65 Federal Register 37,903). From 1999–2003, individual vessels were allowed to take a limited number of trips into these access areas; these trips were associated with a possession limit and time spent at sea counted against a vessel's annual days-at-sea allocation. In 2004, Amendment 10 formalized the spatial-management strategy in which parts of the fishing grounds with high amounts of juvenile scallops are closed to allow biomass to grow. When opened as "access areas," scallop vessels can fish a limited number of trips, with a possession limit. Two additional areas (Elephant Trunk and Delmarva) were added to the program at this time, and one (Virginia Beach) was removed from the program because the closure did not produce increases in local scallop biomass. From 2004–2006, vessels could end a trip early and take a subsequent partial trip with a slight penalty. Because the penalty was removed in 2006, the trip allocations have functioned as an individual quota. By 2012, allocated DAS had been cut by almost 50% relative to the 2004 level in response to increases in landings per trip and mandates to not exceed catch limits (NEFMC, 2015). Currently, LA vessels are allocated trips, with a possession limit, to specific access areas each fishing year and days-at-sea (DAS) for use in other regions (known as open areas). LA vessels fishing in open areas (i.e. not access areas) are not subject to a possession limit. LA vessels are not allowed to transfer DAS or stack multiple DAS allocations on a single vessel; the LA fleet has been nearly constant in size over time. Under the formal spatial-management program, fishing in the access areas no longer requires using open-area DAS, and allocated DAS were decreased by an additional 50% to account for this (Table 1).

Landings of scallops in the mid-1990s were low due to low biomass and restrictive fishing regulations designed to allow the scallop biomass to grow. Over the period 1996 to 1999, the DAS allocation was cut by one-third as part of a plan to rebuild depleted stocks of sea scallops. Prior to the 1994 closures of many fishing grounds, the scallop fishery was experiencing "growth overfishing," in which there is excess harvest of small individuals before they reach the economically optimal size

TABLE 1 Vessel numbers, characteristics, scallop landings, and revenue 1996–2015 in our sample for the northeast scallop fishery 1996–2015

Year	Vessel count	Mean length	Mean horse-power	Mean age	Mean crew size	Mean days at sea	Mean capital cost	Mean daily cost	Premium scallop mean pounds	Market scallop mean pounds	Mean scallop revenue
1996	199	84	872	19	6	144	65,519	1918	11,995	56,712	416,143
1997	188	83	838	20	6	139	63,121	1867	9921	47,578	403,889
1998	189	84	850	21	6	126	58,822	1770	8541	41,991	338,315
1999	206	84	860	22	6	92	60,819	1908	13,640	71,022	492,112
2000	225	83	855	23	7	102	61,760	2065	22,778	107,631	673,485
2001	247	83	830	24	7	108	58,173	2026	25,417	143,013	627,579
2002	261	82	798	25	7	111	56,376	2022	33,334	140,944	691,343
2003	290	82	791	24	7	108	50,857	2001	28,002	149,189	781,848
2004	306	82	811	24	7	86	48,382	1895	35,001	129,590	867,467
2005	327	81	769	24	6	77	45,877	1725	23,110	110,469	1,039,406
2006	338	81	764	24	7	81	47,076	1860	25,826	115,079	912,811
2007	344	81	759	24	6	91	46,388	1910	29,902	115,822	971,232
2008	338	81	773	24	6	64	49,795	2039	30,469	88,454	832,772
2009	341	81	770	24	7	75	48,751	1637	32,472	104,268	887,302
2010	342	81	777	25	7	76	43,047	1981	29,520	110,573	1,126,538
2011	340	81	775	26	7	68	40,945	2311	30,963	114,507	1,451,345
2012	338	81	783	26	7	69	37,782	2686	27,775	115,953	1,407,680
2013	335	82	784	27	6	54	37,842	2121	21,687	80,757	1,175,388
2014	336	81	771	28	6	45	36,364	2048	18,277	59,421	971,667
2015	293	81	777	28	6	47	36,357	1692	17,410	59,319	936,369

(Edwards, 2005; Repetto, 2001). The spatial-management system addresses "growth overfishing," biomass has increased (Hart and Rago, 2006), and there is a substantial price premium for large scallops (Ardini and Lee (2018).

By 2004 scallop biomass had dramatically increased from historical lows, and GB/SNE biomass had grown faster and to higher levels than the MAB biomass (Hart and Rago, 2006). Biomass is currently historically high; however, MAB biomass has declined recently as a result of (planned) high levels of catch and lower than expected reproduction. In 2013, the biomasses in GB and MAB regions were 14 and 7 times greater than the respective biomasses in 1993 (Northeast Fisheries Science Center, 2015). Landings have remained at historically high levels, varying from 41–64 million pounds, before declining in 2013 and 2014.

3 | METHODS

Measuring profitability change for commercial fishing vessels is a reasonably simple exercise: Profitability is merely the ratio of total revenue to total cost, and profitability change for a fishing vessel is simply the ratio of profitability in one period to profitability in another period. However, policy makers and others are often interested in understanding the reasons profitability has changed. At a minimum, profitability change can be broken down into two parts, one that measures output and input price change, and the other which measures productivity change. The price component is often referred to as the "terms of trade," or "price recovery" component (Grifell-Tatjé and Lovell, 2015; O'Donnell, 2012). By breaking profitability change into these two parts, decision makers can learn whether increasing (decreasing) profitability was caused by increasing (decreasing) output prices, decreasing (increasing) input prices, increasing (decreasing) productivity, or a combination of all three. Additionally, the productivity change term can be decomposed into numerous parts, including measures of technical change and efficiency change (Grifell-Tatjé and Lovell, 2015). The goal of these decompositions is to give a more complete picture of the reasons why profitability has changed. This can inform managers and policy makers about the impacts of their decisions.

Our analysis of profitability change involves four steps. The first step involves measuring changes in total factor productivity (TFP). The second step involves measuring changes in the terms of trade (TT). The third step involves decomposing profitability change into the product of our measure of TFP change and our measure of change in the TT. The final step involves decomposing our measure of TFP change into measures of technical and environmental change, and various types of efficiency change.

3.1 | Measuring changes in TFP

Measures of TFP change are measures of total output quantity change divided by measures of total input quantity change (Jorgenson and Griliches, 1967; Nadiri, 1970; O'Donnell, 2018; Prescott, 1998). In order to measure output quantity change, let $q_{it} = (q_{1it}, \ldots, q_{Nit})'$ denote the output vector of vessel i in period t. An index that compares the outputs of vessel i in period t with the outputs of vessel h in period s using the latter as a reference point is any variable of the form $QI(q_{hs}, q_{it}) = Q(q_{it})/Q(q_{hs})$ where $Q(\ldots)$ is any nonnegative, nondecreasing, linearly homogenous aggregator function (O'Donnell, 2012, 2018). Any index of this type is proper in the sense that, if outputs are positive, then it satisfies the six output-index axioms listed in O'Donnell (2018, p. 94): weak monotonicity, homogeneity type I, homogeneity type II, proportionality, time–space reversal, and transitivity. The weak monotonicity axiom says that the index cannot decrease if there is an increase in any element of the comparison vector (i.e., with any increase in q_{it}). Homogeneity type I says that if the comparison vector is multiplied by a given number then the index will increase by that number. Homogeneity type II says that if both the comparison and reference vectors are each multiplied by the same number, then the index will not change. The proportionality axiom says that if the comparison vector is proportional to the reference vector, then the index will equal the factor of proportionality. The time–space reversal axiom says that the index that compares the comparison vector with the reference vector is the reciprocal of the index that compares the reference vector with the comparison vector (i.e., when the roles of the comparison and reference vectors are reversed). The final axiom, transitivity, says that the index number obtained when comparing any two vectors directly must equal the index number obtained when the comparison is made via a third vector.

On the input side, let $x_{it} = (x_{1it}, \ldots, x_{Mit})'$ denote the input vector of vessel i in period t. A proper index that compares x_{it} with x_{hs} using the latter as a reference point is any variable of the form $XI(x_{hs}, x_{it}) = X(x_{it})/X(x_{hs})$ where $X(\ldots)$ is another nonnegative, nondecreasing, linearly homogenous aggregator function (O'Donnell, 2012, 2018). Again, any index of this type is proper in the sense that, if inputs are positive, then it satisfies the six input-index axioms listed in O'Donnell (2018, p. 105).

We are now in a position to construct a TFP index (TFPI). A proper index that compares the TFP of vessel i in period t with the TFP of vessel h in period s using the latter as a reference point is any variable of the form $TFPI(x_{hs}, q_{hs}, x_{it}, q_{it}) = QI(q_{hs}, q_{it})/XI(x_{hs}, x_{it})$ where $QI(\ldots)$ is any proper output index and $XI(\ldots)$ is any proper input index (O'Donnell, 2018, p. 105). Equivalently, $TFPI(x_{hs}, q_{hs}, x_{it}, q_{it}) = \frac{TFP(x_{it}, q_{it})}{TFP(x_{hs}, q_{hs})}$ where $TFP(x_{it}, q_{it}) \propto Q(q_{it})/X(x_{it})$ is the TFP of vessel i in period t. If outputs and inputs are positive, then all TFPIs of this type satisfy the six productivity-index axioms listed in O'Donnell (2018, p. 115).

Different TFPIs are distinguished by the different aggregator functions that are used to construct the output and input indexes. The choice of aggregator functions (and therefore output, input and TFP indexes) is entirely a matter of taste. In this study, we measure output and input quantity change using Lowe indexes. Lowe quantity indexes use linear functions as aggregator functions, with average market prices used as weights. To be more specific, the Lowe output and input aggregator functions are $Q(q_{it}) \propto \overline{p}' q_{it}$ and $X(x_{it}) \propto \overline{w}' x_{it}$, where $\overline{p}$ is a vector of average output prices and $\overline{w}$ is a vector of average input prices (O'Donnell, 2012). The associated Lowe index that compares q_{it} with q_{hs} using the latter as a reference point is $QI^L(q_{hs}, q_{it}) = \overline{p}' q_{it}/\overline{p}' q_{hs}$. Similarly, the Lowe index that compares x_{it} with x_{hs} using the latter as a reference point is $XI^L(x_{hs}, x_{it}) = \overline{w}' x_{it}/\overline{w}' x_{hs}$. Finally, the Lowe index that compares the TFP of vessel i in period t with the TFP of vessel h in period s using the latter as a reference point is

$$TFPI^L(x_{hs}, q_{hs}, x_{it}, q_{it}) = \left(\frac{\overline{p}' q_{it}}{\overline{p}' q_{hs}}\right) / \left(\frac{\overline{w}' x_{it}}{\overline{w}' x_{hs}}\right) \quad (1)$$

Other well-known known measures of TFP change include Fisher, Tornqvist, EKS, CCD, and Malmquist indexes (Balk, 2008). However, these indexes are not proper measures of TFP change because they cannot generally be written as proper output quantity indexes divided by proper input quantity indexes (O'Donnell, 2018, Section 3.3.6).

3.2 | Measuring changes in the terms of trade

Measures of change in the TT are measures of output price change divided by measures of input price change. In this study, we measure price changes by deflating changes in revenues and costs by proper output and input quantity indexes. On the output side, the revenue received by vessel i in period t is $R_{it} = p_{it}' q_{it}$, where p_{it} denotes the vector of output prices received. A so-called implicit output price index that compares p_{it} with p_{hs} using the latter as a reference point is any variable of the form $PI(p_{hs}, p_{it}, \ldots) = RI(p_{hs}, q_{hs}, p_{it}, q_{it})/QI(q_{hs}, q_{it})$ where $RI(p_{hs}, q_{hs}, p_{it}, q_{it}) = R_{it}/R_{hs}$ is a simple revenue index and $QI(\ldots)$ is a proper output index. Similarly, on the input side, the input cost incurred by vessel i in period t is $C_{it} = w_{it}' x_{it}$ where w_{it} denotes the vector of input prices paid. An implicit input price index that compares w_{it} with w_{hs} using the latter as a reference point is any variable of the form $WI(w_{hs}, w_{it}, \ldots) = CI(w_{hs}, x_{hs}, w_{it}, x_{it}) / XI(x_{hs}, x_{it})$ where $CI(w_{hs}, x_{hs}, w_{it}, x_{it}) = C_{it}/C_{hs}$ is a simple cost index and $XI(\ldots)$ is a proper input index. Finally, an implicit terms-of-trade index (TTI) that compares the output and input prices of vessel i in period t with the output and input prices of vessel h in period s using the latter prices as a reference point is any variable of the form $TTI(w_{hs}, p_{hs}, p_{hs}, p_{it}, \ldots) = PI(p_{hs}, p_{it}, \ldots) / WI(w_{hs}, w_{it}, \ldots)$. In this study, we measure output and input quantity change using Lowe indexes. The associated Lowe implicit output and input price indices are $PI^L(p_{hs}, p_{it}, \ldots) = (p_{it}' q_{it} / p_{hs}' q_{hs}) / (\overline{p}' q_{it} / \overline{p}' q_{hs})$ and $WI^L(w_{hs}, w_{it}, \ldots) = (w_{it}' x_{it} / w_{hs}' x_{hs}) / (\overline{w}' x_{it} / \overline{w}' x_{hs})$. Thus, the Lowe implicit TTI is

$$TTI^L(w_{hs}, p_{hs}, w_{it}, p_{it}, \ldots) = \frac{p_{it}' q_{it} / p_{hs}' q_{hs}}{\overline{p}' q_{it} / \overline{p}' q_{hs}} \times \frac{\overline{w}' x_{it} / \overline{w}' x_{hs}}{w_{it}' x_{it} / w_{hs}' x_{hs}} \tag{2}$$

This index indicates how the output to input price ratio for vessel i in period t compares to that of vessel h in period s. A value greater than one means that vessel i in period t had a higher output to input price ratio than the reference vessel (vessel h in period s). This could be due to higher output prices, lower input prices, or a combination of both (note that in competitive input and output markets, these prices are beyond the control of a single firm).

3.3 | Decomposing profitability change

The profitability of vessel i in period t is simply revenue divided by cost: $PROF_{it} = R_{it}/C_{it}$. The index that compares the profitability of vessel i in period t with the profitability of vessel h in period s is $PROFI_{hsit} = \frac{PROF_{it}}{PROF_{hs}} = \frac{R_{it}/C_{it}}{R_{hs}/C_{hs}}$. This can be decomposed into the product of an implicit TTI and an associated TFPI. For example, in our study we measure output and input quantity change using Lowe indexes. In this case, the index that compares the profitability of vessel i in period t with the profitability of vessel h in period s can be decomposed as

$$PROFI_{hsit} = TTI^L(p_{hs}, p_{it}, w_{hs}, w_{it}, \ldots) \times TFPI^L(x_{hs}, q_{hs}, x_{it}, q_{it}) \tag{3}$$

where $TTI^L(\ldots)$ is the Lowe implicit TTI defined by (2) and $TFPI^L(\ldots)$ is the Lowe TFPI defined by (1). By examining both the TTI and the TFPI, profitability change can be attributed to changes in the terms of trade, changes in productivity, or a mix of both. For example, the TFPI can be less than (greater than) one, but profitability can be greater than (less than) one due to a TTI, which is greater than (less than) one. In other words, productivity may have declined but profitability could still have risen because a rise in the TTI has more than offset the decline in the TFPI. Further investigation of the TTI can be undertaken to determine if the change was due to rising (declining) output prices or input prices by examining the implicit output and input price indexes.

3.4 | Decomposing TFP change

It is generally accepted that productivity change is due to a combination of technical change and various types of efficiency change (e.g., Färe et al., 1994; O'Donnell, 2018). In our analysis, we are interested in more than just technical change and efficiency change: We are also interested in the effects of the production environment. Accounting for the production environment is important because vessels can move between fishing areas with different environmental characteristics (e.g., biomass levels). In order to make better decisions concerning fishing location choice, we need to understand the role of the production environment in determining TFP and do so by undertaking a series of decompositions of TFP.

We begin by letting $z_{it} = (z_{1it}, \ldots, z_{Jit})'$ denote a vector of variables that characterize the operating environment of vessel i in period t (e.g., the biomass level). We then follow O'Donnell (2018, p.201) and define the technical, scale, and mix efficiency (TSME) of vessel i in period t as:

$$TSME^t(x_{it}, q_{it}, z_{it}) = TFP(x_{it}, q_{it}) / TFP^t(z_{it}) \tag{4}$$

where $TFP^t(z_{it})$ denotes the maximum TFP that is possible in period t in an environment characterized by z_{it}. TSME is a measure of overall vessel performance that, by definition, takes a value less than or equal to one.[1] Importantly, we can rearrange Equation (4) and write TFP as the product of two components:

$$TFP(x_{it}, q_{it}) = TFP^t(z_{it}) \times TSME^t(x_{it}, q_{it}, z_{it}) \tag{5}$$

This equation says that observed TFP is a proportion (given by TSME) of the maximum TFP that is possible.

Next, we follow O'Donnell (2018, Section 5.7.5) and break the measure of TSME defined by (4) into an input-oriented measure of technical efficiency and an input-oriented measure of scale-and-mix efficiency. We use an input orientation because of the mixed nature of the regulations governing scallop fishing. In some areas, vessels are regulated in their use of inputs, specifically fishing time, gear, and crew size, whereas in other areas there are both output limits and input controls (limits on gear and crew size). Because output is limited in some areas, measuring efficiency from an input, rather than an output, orientation is more consistent with the way vessels operate in those areas. This is because output can only be expanded to a regulated maximum, but there are no restrictions on reducing inputs.

The input-oriented technical efficiency (ITE) of vessel i in period t is:

$$ITE^t(x_{it}, q_{it}, z_{it}) = 1/D_I^t(x_{it}, q_{it}, z_{it}) \tag{6}$$

where $D_I^t(x_{it}, q_{it}, z_{it})$ is an input distance function; it gives the smallest fraction of x_{it} that is capable of producing q_{it} using the technologies (i.e., techniques) available in period t in an environment characterized by z_{it}. This particular measure of ITE can be traced back at least as far as O'Donnell (2016, p. 331); it differs from the measures of ITE that are typically found elsewhere in the efficiency literature (e.g., Balk, 1998, Equation 2.1.5) in that it explicitly recognizes that changes in the operating environment may affect the amount of input required to produce a given level of output. Because our measure of ITE treats outputs and the ratio of inputs as given, it reveals the productivity gains the vessel could achieve by proportionally reducing all inputs. For example, an ITE score of 0.8 means the vessel could produce its observed outputs using only 80% of its inputs; if outputs remained unchanged, then the associated increase in productivity from this reduction in input usage would be $\frac{1}{0.8} - 1 = 0.25$, or 25%.

The input-oriented scale and mix efficiency (ISME) of vessel i in period t is

$$ISME^t(x_{it}, q_{it}, z_{it}) = TSME^t(x_{it}, q_{it}, z_{it}) / ITE^t(x_{it}, q_{it}, z_{it}) \tag{7}$$

[1] O'Donnell (2016) refers to TSME as firm efficiency (FE). Here we use the term TSME to remind us that the difference between observed TFP and the maximum possible TFP is, in fact, due to a combination of technical, scale, and mix efficiency. This TSME terminology is also used by O'Donnell (2018).

This measure of performance can be traced back at least as far as O'Donnell (2016, p. 332). Because it treats outputs as given but permits inputs to vary freely, it reveals the productivity gains the vessel could achieve through economies of scale and substitution. For example, an ISME score of 0.75 means that a technically efficient vessel could nevertheless change the scale of its operations and its output and/or input mix, and still increase its productivity by $\frac{1}{0.75} - 1 = 0.33$, or 33%.

Equations (5) and (7) can be used to decompose any proper TFP index into a measure of technical and environmental change and two measures of efficiency change. To be more specific, Equations (5) and (7) can be used to write

$$TFP\left(x_{it}, q_{it}\right) = TFP^t\left(z_{it}\right) \times ITE^t\left(x_{it}, q_{it}, z_{it}\right) \times ISME^t\left(x_{it}, q_{it}, z_{it}\right) \tag{8}$$

This equation holds for vessel i in period t. A similar equation holds for vessel h in period s. Dividing one equation by the other yields the following input-oriented decomposition of any proper TFP index (O'Donnell, 2018, p. 260):

$$TFPI\left(x_{hs}, q_{hs}, x_{it}, q_{it}\right) = \frac{TFP^t\left(z_{it}\right)}{TFP^s\left(z_{hs}\right)} \times \frac{ITE^t\left(x_{it}, q_{it}, z_{it}\right)}{ITE^s\left(x_{hs}, q_{hs}, z_{hs}\right)} \times \frac{ISME^t\left(x_{it}, q_{it}, z_{it}\right)}{ISME^s\left(x_{hs}, q_{hs}, z_{hs}\right)} \tag{9}$$

The first term on the right-hand side is an environment and technology index (ETI) (i.e., a measure of technical and environmental change). The second term is an input-oriented technical efficiency index (ITEI) (i.e., a measure of ITE change). The last term is an input-oriented scale-and-mix efficiency index (ISMEI) (i.e., a measure of ISME change). In this study, we estimate these components using data envelopment analysis (DEA) methods; details are provided in Appendix 1.

3.5 | Average measures of performance

The indexes defined up to this point allow us to compare the performance of vessel i in period t with the performance of a reference vessel h in a reference period s. However, we are also interested in comparing average levels of performance in different periods. In this paper, indexes that compare average performance in period t with average performance in a reference period s are obtained by dividing geometric averages of the index numbers in period t by geometric averages of the index numbers in period s. For example, the index that compares average TFP in period t with average TFP in period s is given by

$$TFPI_{st} = \left(\prod_{i=1}^{I_t} TFPI\left(x_{hs}, q_{hs}, x_{it}, q_{it}\right)\right)^{1/I_t} / \left(\prod_{i=1}^{I_s} TFPI\left(x_{hs}, q_{hs}, x_{is}, q_{is}\right)\right)^{1/I_s} \tag{10}$$

where I_t denotes the number of vessels in the dataset in period t. In our empirical application the reference period is 1996.

4 | DATA

We utilized a detailed spatially explicit dataset for our analysis, covering individual trips made by scallop dredge vessels to 12 specific fishing areas in three fishing zones during a 20-year time period (1996–2015). We began by aggregating individual trip data by year and fishing zone in such a way as to yield over 22,000 observations, with each observation comprising data on a given vessel operating in a given fishing area in a given year. We then reduced the number of observations by only including those vessels that had a steel hull and used scallop dredge gear in each time period, which resulted in a final dataset of 21,372 observations. The number of vessels in the final dataset each year varied between 188 (1997) and 344 (2007) (Table 1). Average vessel length was between 81 and 84 feet, with average length slightly declining between 1996 and 2005, and then stabilizing at 81 feet. Similarly, average vessel horsepower declined, from 872 in 1996 to 777 in 2015. However, average vessel age increased during the same time period, suggesting that the mix of vessels fishing for scallops changed over time rather than newer vessels being introduced to the fleet. Average crew size varied between six and seven, but the number of crew is limited to seven by regulation, unless fishing in an access area in which case vessels can carry eight crew. Average days at sea also substantially declined, from a high of 144 in 1996 to 47 in 2015. Average annual scallop landings in both market categories increased between 1996 and 2004 before declining to a low of 43,544 pounds in 2015. However, average scallop revenue per vessel substantially increased during the same time period, increasing from \$416.1 thousand (\$2009, GDPD implicit price deflator) to \$1.45 million in 2011 before declining to \$936 thousand in 2015. In 2015, the average scallop vessel was grossing 125% more revenue than in 1996, whereas fishing 78% fewer days and landing 12% more scallops. We are interested in associated changes in total output quantities, total input quantities, profitability, and TFP.

We use Lowe indexes to measure changes in $N = 4$ output variables and $M = 2$ input variables. Our indexes were computed using mean output and input prices from the years 2013–2015 as weights. The output variables were premium grade scallops landed (q_{1it}), medium grade scallops landed (q_{2it}), flatfish landed (q_{3it}), and other species landed (q_{4it}). Individual trips to each of our 12 areas were aggregated so that the quantities reflect total landings by a vessel from a specific area in a given year. The prices used (\$2009, GDPD implicit price deflator) were \$13.20 per pound of premium scallops landed, \$11.65 per pound for market scallops, \$2.21 per pound of yellowtail flounder landed, and \$2.16 per pound of other species. The input variables were days at sea (x_{1it}) and a measure of capital (x_{2it}). The measure of capital was the percent of time in a year spent by the vessel in a specific area. Because a vessel can fish several different areas, the sum of the capital measure across all areas in a given year will equal one. The input price for capital was the average user cost of capital calculated for the years 2013, 2014, and 2015 (\$36,854). For each vessel, the user cost of capital was calculated as (depreciation rate + opportunity cost of capital) times the vessel value. Depreciation was set at 5% and the opportunity cost of capital in each year was set equal to the BAA bond rate (https://fred.stlouisfed.org/series/BAA#0, accessed 11/10/2017). Vessel value was calculated based on shadow prices for vessel age, horsepower, and length published in Färe et al. (2017). The price for a day at sea (\$1953) was calculated based on the cost of fuel consumed and supplies used on fishing trips where there was an observer onboard recording these data. Because crew are typically paid a share of the proceeds from the sale of the catch, this daily operating cost from observer data was augmented with the daily opportunity cost of labor, which was approximated based on a wage rate from a similar occupation. For this study, labor cost was calculated using an average cost for labor per day in the construction trades obtained from the St. Louis Federal Reserve (https://fred.stlouisfed.org/series/AHECONS, accessed 7/9/2018).

Finally, we account for $J = 2$ environmental variables in our study: fishing zone (z_{1it}) and biomass (z_{2it}). The first of these variables is a categorical variable measuring the proximity of the fishing zone to shore (*1* = inshore; *2* = near offshore; *3* = distant offshore). The second variable is a measure of scallop density (biomass) within areas contained in each zone; this was estimated for each area based on yearly at-sea biomass surveys.

5 | RESULTS

We begin with profitability, which increased substantially between 1996 and 2015: The results reported in Table 2 and Figure 1 show that in 2015, average profitability was 6.339 times greater than in 1996. This increase can be broken down as follows: PROFI = TFPI × TTI = 2.561 × 2.476 = 6.339. This decomposition indicates that the increase in average profitability was driven by a 156.1% increase in average TFP and a 147.6% improvement in the average TT. This comparison masks variations in profitability and its components over the 20 year time period. Productivity peaked in 2012 (3.899), whereas the terms of trade reached a high in 2015 (2.476). After 2012, productivity declined but profitability still increased due to a better terms of trade. In some years, both the TTI and TFPI components increased (e.g., 2004), whereas in other periods both components declined (e.g., 2006, Table 2).

The years covered by this study can be broken into three distinct regulatory periods. The first period corresponds to the years 1996–1998, before the arrival of spatial management (effort control period), the second to the years 1999–2003 during the transition to spatial management (transition period), and the third from 2004–2015 after the passage of Amendment 10 (spatial-management period). During the effort-control period, a 14.4% fall in average TFP was exactly offset by a 16.8% improvement in the average TT, so average profitability remained unchanged. During the transition period, a 275.6% increase in average TFP was partially offset by a 37.8% deterioration in the average TT, resulting in a 133.4% increase in average profitability. Finally, during the spatial-management period, a 20.3% fall in average TFP was more than offset by a 141% improvement in the average TT, leading to a 171.6% increase in profitability.

There are few studies that examine changes in fishing performance over such a long time period. Several studies have looked at changes in profits in response to a regulatory change over a much shorter number of years. For example, in a study that used only three years of data, Dupont et al. (2005) found that, after implementing Individual Transferable Quotas (ITQs), profits in the Canadian Scotia-Fundy mobile gear fishery improved for large vessels but not for smaller vessels. The profit gain for the large vessel size class was 57% in the first year after ITQs were introduced (0.564/0.359). In another study that also used only three years of data, Fox et al. (2003) found that, after implementing an ITQ, profits in the British Columbia halibut fishery showed a large one-year

TABLE 2 Profitability index (PROFI), terms-of-trade index (TTI), and total factor productivity index (TFPI) for the northeast scallop fishery 1996–2015

Year	PROFI	TFPI	TTI
1996	1.000	1.000	1.000
1997	1.006	0.861	1.168
1998	1.000	0.856	1.168
1999	1.750	1.794	0.976
2000	2.369	2.775	0.854
2001	1.919	3.130	0.613
2002	2.046	3.077	0.665
2003	2.334	3.215	0.726
2004	3.617	3.787	0.955
2005	5.077	3.286	1.545
2006	3.742	3.162	1.183
2007	4.000	3.293	1.215
2008	3.973	3.414	1.164
2009	4.665	3.643	1.281
2010	5.255	3.631	1.447
2011	6.106	3.863	1.581
2012	5.426	3.899	1.392
2013	5.826	2.947	1.977
2014	6.297	2.756	2.285
2015	6.339	2.561	2.476

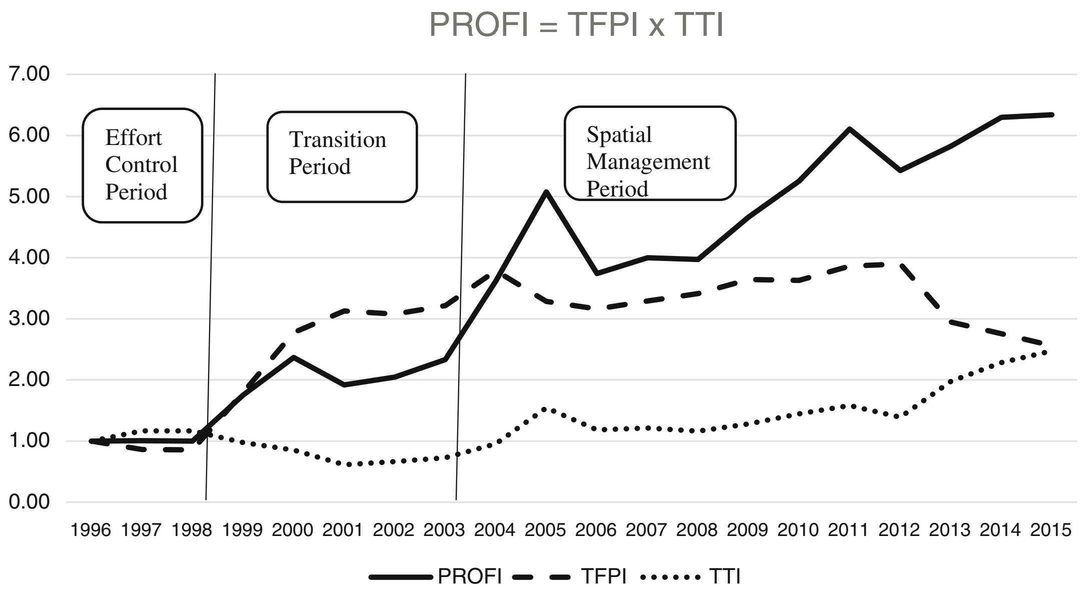

FIGURE 1 Profitability, productivity, and terms-of-trade for the northeast scallop fishery 1996–2015

gain (0.331/0.128–1 = 159%) with greater gains occurring among larger vessels. Results from our study, which cover a 20 year time period, show that after the first year of spatial management, profitability in the scallop fishery improved by 55% (3.62/2.34). In a study of the Norwegian Purse Seine fishery over a 20 year time period, Ekerhovd and Gordon (2020) found large increases in profits after moving to a fishery managed through individual vessel quotas (IVQs). They showed profits increasing nearly 5.9 times during the first 18 years in their series before dropping the last 2 years. This is similar to the profitability gains seen in our fishery (6.3 times over 20 years).

5.1 | Changes in the TTI

The TTI shows how output prices are changing in relation to input prices. A value greater than one means output prices have improved relative to input prices, compared to the reference period. A value less than one indicates an erosion of the ratio in relation to the reference period. The results reported in Table 3 and Figure 2 reveal that in 2015 the average TT was 147.6% higher than in 1996. This increase can be broken down as follows: TTI = PI/WI = 2.05/0.83 = 2.47. This decomposition indicates that the increase in the average TT was driven by a 105.4% increase in average output prices and a 17% fall in average input prices. Again, this comparison masks variations in the average TT and its components over the 20 year time period. Average output prices and the average TT increased in 1997, declined from 1998 to 2001, and then generally increased from 2001 to 2015. Average input prices were relatively flat until 2004, then increased until 2012, before declining during the last 3 years (Figure 2). During the effort-control period (1996–1998), average output prices increased by 7.8% and average input prices fell by 7.7%, resulting in a 16.8% improvement in the average terms of trade. During the transition period (1999–2003), average output prices fell by 32.4% and average input prices increased by 8.8%, resulting in a 37.8% deterioration in the average terms of trade. The decline in output prices in this period is consistent with a story of increasing volumes and stable demand; during the transition period, average output volume increased by 216.2%. Another factor that may have contributed to falling average output prices in this period was the inability of processors to fully adjust their production to account for increases in the availability of

TABLE 3 Terms-of-trade index (TTI), output price index (PI), input price index (WI), TFP index (TFPI), output quantity index (QI), and input quantity index (XI) for the northeast scallop fishery 1996–2015

Year	TTI	PI	WI	TFPI	QI	XI
1996	1.000	1.000	1.000	1.000	1.000	1.000
1997	1.168	1.138	0.974	0.861	0.933	1.083
1998	1.168	1.078	0.923	0.856	0.909	1.061
1999	0.976	0.983	1.007	1.794	1.339	0.746
2000	0.854	0.900	1.055	2.775	1.762	0.635
2001	0.613	0.635	1.035	3.130	2.480	0.792
2002	0.665	0.683	1.027	3.077	2.897	0.941
2003	0.726	0.729	1.004	3.215	2.874	0.894
2004	0.955	0.915	0.958	3.787	2.487	0.657
2005	1.545	1.357	0.878	3.286	1.711	0.521
2006	1.183	1.107	0.935	3.162	1.882	0.595
2007	1.215	1.144	0.942	3.293	1.716	0.521
2008	1.164	1.198	1.030	3.414	2.306	0.675
2009	1.281	1.111	0.867	3.643	2.217	0.609
2010	1.447	1.397	0.965	3.631	2.150	0.592
2011	1.581	1.707	1.080	3.863	1.863	0.482
2012	1.392	1.681	1.208	3.899	2.032	0.521
2013	1.977	1.948	0.986	2.947	1.590	0.539
2014	2.285	2.151	0.942	2.756	1.445	0.524
2015	2.476	2.054	0.830	2.561	1.550	0.605

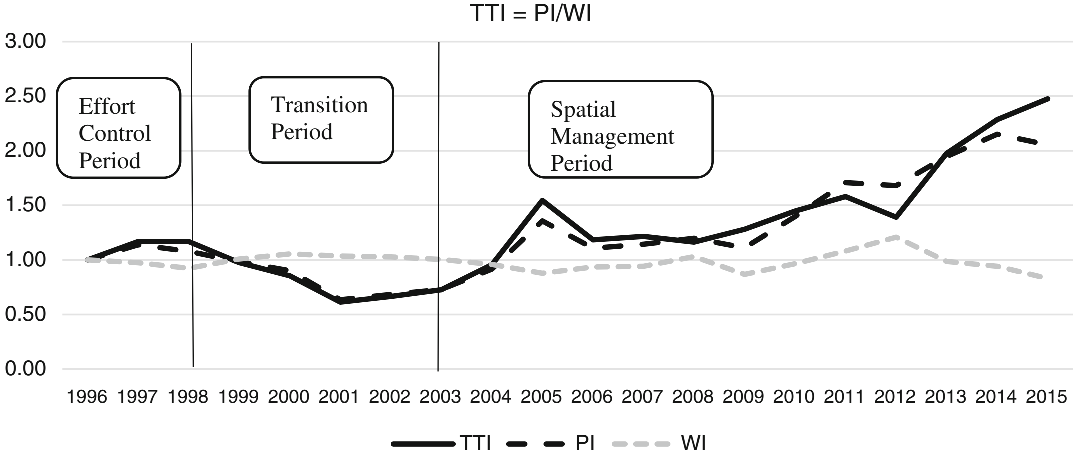

FIGURE 2 The terms-of-trade index (TTI), output (PI), and input (WI) price indices for the northeast scallop fishery 1996–2015

larger scallops or their inability to develop products that generated higher prices from a shift to bigger scallops during these years (Georgianna et al., 2017). Regardless of the reason, this trend reversed itself in the spatial management era (2004–2015). During this era, average output prices increased by 181.8% and average input prices fell by 17.3%, resulting in a 241% improvement in the average terms of trade. The increase in output prices in this era is consistent with a story of decreasing volumes and stable demand; during the spatial-management period, average output volume fell by 46.1%.

The increase in output prices after the implementation of spatial management was an important driver of increased profitability. Ekerhovd and Gordon (2020) also found in the Norwegian purse seine fishery that improved output prices were important in increasing profits. Examination of their figures shows an almost doubling of the mean output price index over a 20-year period. However, the two fisheries differ in the way they are managed. The Norwegian fishery uses individual vessel quotas, which can be consolidated and traded, whereas the scallop fishery is managed using more traditional spatially designated output and effort controls. In the case of the Norwegian fishery, part of the explanation for the price increase was technical change, specifically improved refrigeration, leading to improved prices. For the Northeast scallop fishery, improved prices have been attributable to processors increasing their demand for large premium scallops and driving up the ex-vessel price (Georgianna et al., 2017). The increase in the availability of large scallops was due to adoption of the spatial-management system, which addressed "growth overfishing." (Ardini and Lee, 2018; Hart and Rago, 2006). The important lesson here is that the northeast scallop fishery generated strong positive output price growth, which was comparable to a fishery managed through a market based mechanism (IVQs) over an equivalent length of time (i.e. 20 years).

5.2 | Changes in TFP

The results reported in Table 3 reveal that in 2015 average TFP was 156.1% higher than in 1996. This increase can be broken down as follows: TFPI = QI/XI = 1.55/0.605 = 2.56. This simple accounting decomposition indicates that the increase in the average TFP was driven by a 55% increase in average output volumes and a 39.5% fall in average input volumes. Again, this masks variations in the average volumes and TFP over the 20 year time period (Figure 3). TFP showed an increasing trend after 1998, reaching a maximum in 2012, before declining in the next three years. During the effort-control period (1996–1998), average output volumes fell by 9.1% and average input volumes increased by 6.1%, resulting in a 14.4% fall in average productivity. Most of the growth in TFP occurred in the transition period (1999–2003). During this period, average output volumes increased by 216.2% and average input volumes fell by 15.7%, resulting in a 275.6% increase in average productivity. Finally, during the spatial-management period (2004–2015), average output volumes fell by 46.1% and average input volumes fell by 32.3%, resulting in a 20.3% fall in average productivity.

Accounting decompositions of TFP into measures of output volume change and input volume change provide few, if any, insights into the economic drivers of TFP change. Although they might tell us that TFP increased because output volumes increased and input volumes fell, we are still left asking what has driven those changes in volumes. To find the answers, we must decompose changes in TFP into measures of technical, environmental and efficiency change.

The results reported in Table 4 and Figure 4 reveal that average TFP in 2015 was 156.1% higher than in 1996. An economic decomposition of this increase is the following: TFPI = ETI × ITEI × ISMEI = 6.5 × 0.518 × 0.76 = 2.56. This decomposition indicates that the effect of a 550% improvement in the average production environment and/or technologies (i.e., a massive outward shift in the production frontier) was partly offset by a 48.2% fall in average technical efficiency (i.e., an inability of fishers to use the available technologies to keep up with the outward-shifting frontier) and a 24% fall in average scale-and-mix efficiency (i.e., an inability of fishers to capture economies of scale and substitution). Again, this decomposition masks variations in the economic drivers of TFP change over the 20 year time period. During the effort-control period (1996–1998), a 7.5% improvement in the average environment and/or technologies was more than offset by a 13.9% fall in average technical efficiency and a 7.5% fall in average scale-and-mix efficiency, resulting in a 14.4% fall in average productivity. During the transition period (1999–2003), a 297.1% improvement in the average environment and/or technologies and a 0.7% increase in average technical efficiency

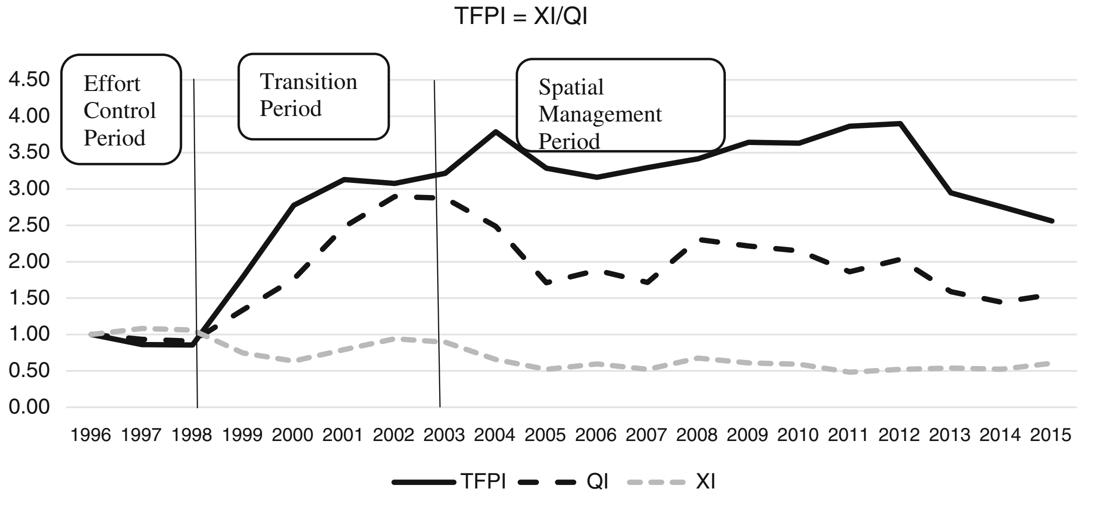

FIGURE 3 Total factor productivity index (TFPI), output (QI), and input quantity indices (XI) for the northeast scallop fishery 1996–2015

TABLE 4 Total factor productivity index (TFPI), environment and technology index (ETI), input-oriented technical efficiency index (ITEI), input scale-mix efficiency index (ISMEI), and biomass index (BI) 1996–2015 for the northeast scallop fishery 1996–2015

Year	TFPI	ETI	ITEI	ISMEI	BI
1996	1.000	1.000	1.000	1.000	1.000
1997	0.861	1.142	0.843	0.895	0.851
1998	0.856	1.075	0.861	0.925	0.832
1999	1.794	2.589	0.926	0.748	1.870
2000	2.775	4.446	0.957	0.652	6.599
2001	3.130	4.343	0.928	0.777	4.317
2002	3.077	4.531	0.852	0.797	4.780
2003	3.215	4.269	0.867	0.868	4.924
2004	3.787	4.419	0.843	1.016	5.710
2005	3.286	5.362	0.708	0.866	8.942
2006	3.162	5.242	0.711	0.848	7.433
2007	3.293	5.083	0.755	0.859	8.295
2008	3.414	5.562	0.689	0.891	9.562
2009	3.643	5.940	0.700	0.876	11.791
2010	3.631	5.681	0.683	0.935	12.454
2011	3.863	6.507	0.699	0.849	11.129
2012	3.899	7.062	0.665	0.830	9.128
2013	2.947	7.012	0.548	0.766	5.338
2014	2.756	6.973	0.481	0.821	6.272
2015	2.561	6.500	0.518	0.760	6.046

were only marginally offset by a 6% fall in average scale-and-mix efficiency, resulting in a 275.6% increase in average productivity. Finally, during the spatial-management period (2004–2015), a 52.3% improvement in the average environment and/or technologies was more than offset by a

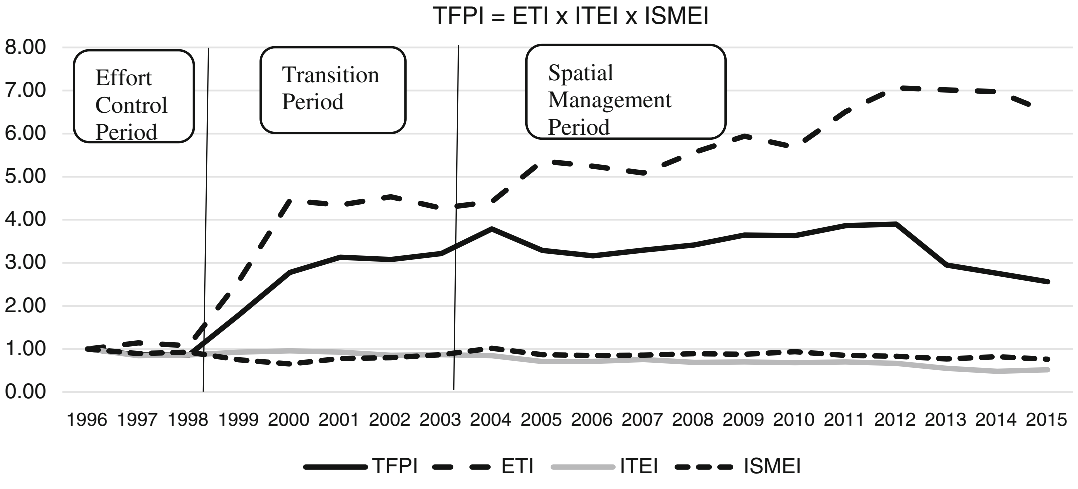

FIGURE 4 Productivity (TFPI), environmental and technical change (ETI), technical efficiency (ITEI), and input-scale-mix-efficiency (ISMEI) for the northeast scallop fishery 1996–2015

40.3% fall in average technical efficiency and a 12.4% fall average scale-and-mix efficiency, resulting in a 20.3% fall in average productivity.

Given that we use a proper productivity index, it is difficult to compare our results directly with the findings of other studies into fisheries productivity. Most other studies use either binary or chained Tornqvist indexes to measure changes in productivity (e.g., Ekerhovd and Gordon, 2020; Fox et al., 2003; Jin et al., 2002; Squires, 1992). Except in restrictive special cases, these indexes cannot be viewed as measures of output quantity change divided by measures of input quantity change: Unless revenue and cost shares are constant across both time and space, binary Tornqvist TFP indexes are not transitive (so they cannot be used to make multiple comparisons), and chained Tornqvist TFP indexes do not satisfy a proportionality axiom (so even if inputs and outputs in 2015 were exactly the same as they were in 1996, they would generally tell us that productivity had changed).

5.3 | Biomass

The results reported in Table 4 and Figure 4 indicate that the main driver of TFP change in our fishery over the sample period was the ETI component. We conjecture that changes in this component were driven by changes in the biomass, not technical progress. The role of biomass in commercial fishing vessel productivity change has been well documented (Jin et al., 2002; Squires, 1992; Walden et al., 2017). Ideally, we would like to "peel away" the change in biomass from the ETI and treat the biomass as another part of the TFPI decomposition. Unfortunately, there is no convenient way to do this using the DEA methodology we are using in our study. In order to examine the influence of biomass on the ETI, we chose to instead create a separate biomass index (BI) and then calculate Spearman's correlation coefficient between the BI and the ETI. Whereas Pearson's correlation coefficient measures the strength of linear relationships, Spearman's correlation coefficient measures the strength of monotonic relationships that can be either linear or nonlinear.

Our measure of the size of the biomass in a given year is simply the geometric mean of scallop densities in that year across all areas represented in our dataset. Our BI numbers are then obtained by simply dividing the size of the biomass in each year by the size of the biomass in the reference year, 1996. The BI numbers reported in Table 4 reveal that the biomass increased by 504.6% between

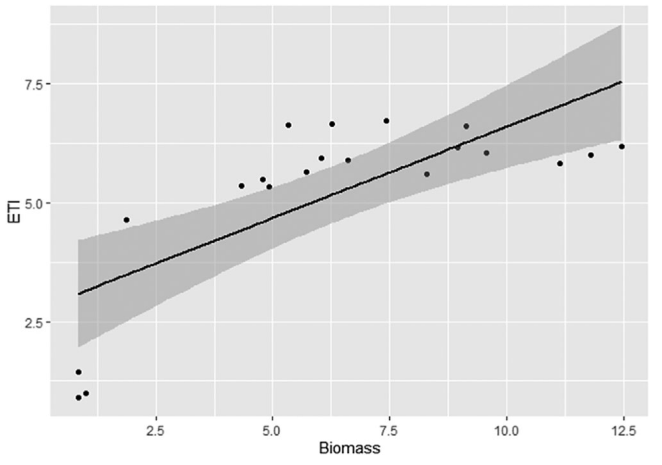

FIGURE 5 Scatterplot of ETI versus BI for the northeast scallop fishery 1996–2015

1996 and 2015. The minimum value of the BI was 0.832 in 1998, whereas the maximum value was 12.454 in 2010. During the effort-control period (1996–1998), the biomass decreased by 16.8%; during the transition time period (1999–2003), it increased by 4.924/1.870–1 = 163%; during the spatial-management era (2004–2015), it increased by 6.046/4.924–1 = 22.8%. Figure 5 suggests there is a strong monotonic (but nonlinear) relationship between the BI and ETI; the Spearman correlation coefficient between the two indices was 0.72.

6 | CONCLUSIONS

Vessels operating in the northeast scallop fishery between 1996 and 2015 were the beneficiaries of an accidental natural experiment, which made them substantially more profitable. Closing vast areas of Georges Bank in order to protect spawning stocks of groundfish species revealed the potential for scallops to grow free from fishing-induced mortality. Because larger scallops are able to command a higher price, fishing vessels benefitted from the implementation of a spatial-management system, which allocated individual quotas for vessels to harvest larger scallops from spatial-management areas. Together with additional effort controls for non-access area regions, vessels substantially increased their profitability.

Our research demonstrates why profitability change is a more complete indicator of vessel performance than productivity change. Although productivity indices give managers important information about changes in response to regulatory actions, it is ultimately just a partial indicator of performance change. For example, between 2000 and 2001, average TFP in the northeast scallop fishery increased, and yet average profitability declined. Between 2012 and 2014, average profitability increased but average TFP declined. Based on TFP alone, managers would conclude that vessel performance improved between 2000 and 2001, even though profitability decreased. During the 2012–2014 period, an examination of TFP alone would lead managers to conclude that vessel performance declined, even though profitability increased. If profitability matters the most to vessels owners, then it would be a mistake to focus only on TFP as a performance indicator.

Our research also shows the importance of understanding the role of output and input prices in determining profitability change. Changes in the terms of trade (i.e., the ratio of output prices to input prices) have driven significant changes in profitability in the northeast scallop fishery. For example, in 2005, output prices and input prices all increased. However, output prices increased substantially more than input prices, and the resulting increase in the terms of trade drove an increase in profitability. For this fishery, our findings showed that changes in output prices were a key determinant of changes in profitability. For example, increases in average output prices over the period 2010–2015 were a major contributor to increases in both the terms of trade and profitability. At the end of the study period (2015), the terms of trade was 2.48 times higher than it had been in 1996. This is quite remarkable given the heavily regulated nature of the fishery.

Our research also shows that technical efficiency can be declining at the same time that TFP is increasing, due to the offsetting effects of technical and environmental change. Our results revealed that average technical efficiency of vessels in the northeast scallop fishery declined steadily over the study period, but these declines were more than offset by significant improvements in production environments and/or technologies. Focusing on technical efficiency alone as a performance measure would have given managers a misleading view of vessel performance. In the spatial-management system, vessels can carry an additional crew member to the rotational access areas. They may be spending additional time handling the scallops, as higher quality scallops command a premium price. Both of these factors may have contributed to the declines in technical efficiency. Another possibility is that bycatch issues with flatfish species changed the way vessels had to fish in access areas. Vessels faced bycatch limits for yellowtail flounder, which may have prevented them from fishing if the bycatch limit was exceeded or altered the way the vessels fished in the access areas. Scale-and-mix efficiency also contributed to productivity gains in some years, although the effects were small by comparison with the effects of changes in environments and/or technologies. Although improvements in technical efficiency would have increased TFP further, the gains in TFP were still impressive.

Because a fishing vessel harvests a resource whose size and condition is external to the vessel, the maximum TFP for that vessel in any given period is influenced by the biomass. For example, given the same biomass in Years 1 and 2, a vessel fishing in both years with the same amount of inputs and using the same fishing technology would be expected to produce the same amount of output. However, if the biomass doubled in Year 2, then, given the same inputs and the same fishing technology, a vessel should double its output and double its TFP. In this example, the increase in TFP is solely due to the higher biomass and nothing to do with the way the vessel is operated. From a public policy perspective, government decision makers need to understand how much productivity change occurs because government policies led to better use of capital and labor, or to technical progress, and how much occurs because of changes in the underlying resource stock.

Disentangling the impact of the biomass, which is an environmental variable external to the firm, on productivity is difficult using a DEA model. In this analysis, we created an environment and technical change index (ETI) to capture the influence of both biomass and technical change. In order to examine the influence of biomass on the ETI, we constructed a biomass index and computed the correlation between the biomass index and the ETI. Our results showed that biomass was highly correlated with the ETI. Along with visual plots, the high correlation coefficient supports the inference that biomass was a major component of the ETI and therefore a major driver of productivity change.

In our study, the decomposition of profitability showed that environmental and technical change in combination with improving output prices were the two most important factors determining increased profitability. By focusing harvests on large scallops and strictly managing quotas, prices paid for scallops have substantially increased. Policies that increase ex-vessel prices are rarely mentioned in a fishery management context, yet our research shows the importance of price-enhancing policies on profitability. One additional strategy that managers could have adopted to further increase profitability would be to allow vessels to consolidate their permits. For example, "permit stacking," where a vessel could buy or lease a permit from another fishing vessel, would have allowed vessels to make additional trips to the access areas where the large scallops commanding a price premium are located. Presumably, more profitable vessels could have leased permits from less profitable vessels, which would have concentrated revenue on fewer vessels and increased profitability for those vessels.

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APPENDIX 1. DEA MODELS

In this paper, the TFPI numbers are computed using Equation (1). An input-oriented decomposition of these numbers involves estimating the measures of TSME and ITE defined by Equations (4) and (6); in this Appendix we explain how to estimate these measures using DEA. After estimating TSME and ITE, Equation (7) can be used to compute ISME = TSME/ITE. Ratios of the ITE and ISME scores can then be used to compute the ITEI and ISMEI components in Equation (9). Finally, the ETI component in Equation (9) can be computed as a residual: ETI = TFPI/(ITEI x ISMEI). Researchers who are familiar with DEA models will observe that the DEA models we use to estimate TSME and ITE account for two environmental variables. This makes them slightly more complicated than the models typically found in the nonparametric efficiency literature. Our models also deal with the fact that one of our environmental variables is a categorical variable (z_{1it} = the fishing area in which vessel i operated in period t) and the other is a continuous variable (z_{2it}= the biomass in the area fished by vessel i in period t).

Estimating the measure of TSME defined by Equation (4) first involves estimating $TFP^t(z_{it})$. The DEA estimation problem can be written as

$$TFP^t(z_{it}) = Max_{q,x,\mu,\theta}\left\{Q(q) : q \leq \sum_{h=1}^{I}\sum_{r=1}^{t}\theta_{hr}d_{hrit}q_{hr}, \sum_{h=1}^{I}\sum_{r=1}^{t}\theta_{hr}d_{hrit}z_{2hr} \leq \mu z_{2it},\right.$$

$$\left. X(x) = 1, \sum_{h=1}^{I}\sum_{r=1}^{t}\theta_{hr}d_{hrit}x_{hr} \leq x, \sum_{h=1}^{I}\sum_{r=1}^{t}\theta_{hr}d_{hrit} = \mu, \theta_{hr} \geq 0 \forall h, r\right\}$$

where $d_{hrit} = I(z_{1hr} = z_{1it})$ is a dummy variable that takes the value 1 if vessel h in period r operated in the same fishing area as vessel i in period t (and zero otherwise).[2] This dummy variable has the effect of deleting from the dataset any observations on any vessels that did not operate in same fishing area as vessel i in period t. The reference set for vessel i in period t is all vessels fishing in the same area as vessel i in any time period up to and including period t. If fishing area was not

[2]This problem is derived from a fractional program that is slightly more general than (6.14) in O'Donnell (2018); it is slightly more general because it accounts for the fact that the first environmental variable is a categorical variable.

important, then this dummy variable could be deleted and the problem would reduce to problem (6.15) in O'Donnell (2018).

Estimating the measure of ITE defined by Equation (6) involves estimating the input distance function. The estimation problem can be written as

$$ITE^t\left(x_{it},q_{it},z_{it}\right) = Min_{\mu,\lambda}\left\{\mu : q_{it} \le \sum_{h=1}^{I}\sum_{r=1}^{t}\lambda_{hr}d_{hrit}q_{hr}, \sum_{h=1}^{I}\sum_{r=1}^{t}\lambda_{hr}d_{hrit}z_{2hr} \le z_{2it},\right.$$

$$\left.\sum_{h=1}^{I}\sum_{r=1}^{t}\lambda_{hr}d_{hrit}x_{hr} \le \mu x_{it}, \sum_{h=1}^{I}\sum_{r=1}^{t}\lambda_{hr}d_{hrit} = 1, \lambda_{hr} \ge 0 \forall h,r\right\}.$$

This problem has a similar mathematical structure, but not the same interpretation, as problem (32) in O'Donnell et al. (2017).[3] If fishing area was not important, then the dummy variable could be deleted and it would reduce to problem (6.9) in O'Donnell (2018).

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SUPPORTING INFORMATION

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[3]Problem (32) in O'Donnell et al. (2017) is a metafrontier problem used to estimate residual input-oriented technical efficiency (RITE) (rather than ITE). That problem has the same structure as the ITE problem presented here except that the summation over periods goes from $r = 1$ to T (instead of $r = 1$ to t).