Online Appendices

A Atlantic cod

Figure A1 shows how cod looks like. Cod in Norwegian sea is Atlantic cod, scientific name *Gadus morhua*. They can live for 25 years and usually attain sexual maturity between two and four years old. They can grow to 1.3m and 40kg (88lbs). Atlantic cod is one of the most heavily fished species. It was fished for a thousand years by north European fishers who followed it across the North Atlantic Ocean to North America. It supported the US and Canada fishing economy until 1992, when fishing cod was limited. Several cod stocks collapsed in the 1990s (declined by more than 95% of maximum historical biomass) and have failed to fully recover even with the cessation of fishing.[22]

Figure A2 illustrates the distribution area and spawning area in Norwegian sea. The amount (numbers and biomass) increases from south to north, and around 75% lives north of the 62 latitude (the fishing areas that are studied in this paper).[23] The cod spawns in most of the fjords or in fjord arms in bigger fjord systems (within 200km from the coast).

(a) cod

(b) A cod can weigh up to 40kg (88lbs)

Figure A1: Cod

A.1 Notes and Extensions

The method to estimate economies of scale using an estimated production function (Proposition 1) relies on Assumptions 1–4. This section concludes the theoretical foundation of economies of scale by discussing caveats and extensions if these assumptions are relaxed.

[22] See Frank et al. (2005) and NOAA, https://www.fisheries.noaa.gov/species/atlantic-cod

[23] See the description by the Institute of Marine Research, https://www.hi.no/en/hi/temasider/species/costal-cod--north-of-the-62-latitude.

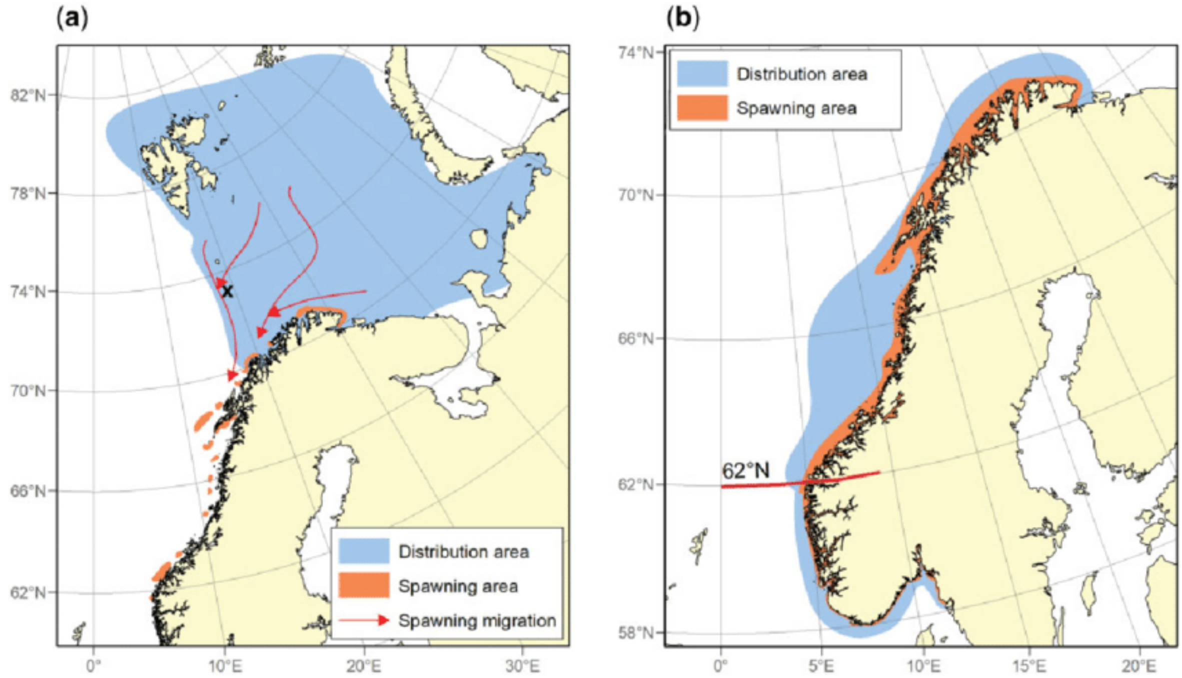


Figure A2: Cod fishery for the area north of 62°N

A.1.1 Elasticities If Input Markets Have Market Power

Assumption 1 implies a perfectly competitive input market. I now discuss the relation between output elasticity of cost and input elasticity of output if input price depends on the input usage of the firms. In this case, the cost minimization problem in the production stage will be:

$$C_{it}(q_{it}) = \min_{\boldsymbol{X}_{it}} \sum_{X \in \mathbb{X}} W_{it}^X(X_{it})X_{it} \text{ subject to } q_{it} \leq Q_{it}(\boldsymbol{X}_{it}), \tag{9}$$

where $W_{it}^X(\cdot)$ is the input price function of the X-input use. The Lagrangian function of the cost-minimization problem is

$$\mathcal{L}_{it} = \sum_{X \in \mathbb{X}} W_{it}^X(X_{it})X_{it} + \lambda_{it}(q - Q_{it}(\boldsymbol{X}_{it})). \tag{10}$$

The first-order condition for any input $X \in \mathbb{X}$ is

$$\frac{\partial \mathcal{L}_{it}}{\partial X_{it}} = W_{it}^{X\prime} X_{it} + W_{it}^X - \lambda_{it} \cdot \frac{\partial Q_{it}}{\partial X_{it}} = 0. \tag{11}$$

Summing this relation for all inputs and making a few algebra transformation, we arrive in:

$$\phi_{it} = \left(1 + \sum_{X \in \mathbb{X}} \eta_X \cdot \frac{W_{it}^X X_{it}}{C_{it}}\right) \left(\sum_{X \in \mathbb{X}} \theta_{it}^X\right)^{-1}, \tag{12}$$

where η_X is the price elasticity of demand for input X, i.e. $\eta_X \equiv \frac{dW^X}{dX} \cdot \frac{X}{W^X}$.

So, the output elasticity of cost is the ratio of average price elasticity of input demand, weighted by the share of input cost in total cost, to total input elasticities of output.

A.1.2 The Case of Dynamic Inputs

This extension relaxes Assumption 2 and quantifies the cost elasticity when an input has adjustment costs and dynamic implications on future cost values. Consider the classical cost minimization in a dynamic context in which capital K_{it} is dynamic and adjusted by endogenous investment level $I_{i,t-1}$ whereas labor L_{it} is variable. So, the capital evolves as $K_{it} = \delta K_{i,t-1} + I_{i,t-1}$ and the adjustment cost depends on both investment level and the capital state, $A(I_{i,t-1}, K_{i,t-1})$. For simplicity, I drop the notation i in this section. The dynamic cost minimization problem is

$$V(K_{t-1}, \Omega_t) = \min_{I_{t-1}, L_t} rI_{t-1} + wL_t + A(I_{t-1}, K_{t-1}) + \beta E[V(K_t, \Omega_{t+1})|\Omega_t], \tag{13}$$

$$\text{subject to } \; Q(K_t, L_t) \geq q_t, \tag{14}$$

$$K_t = \delta K_{t-1} + I_{t-1}. \tag{15}$$

Note that we can rewrite this problem into

$$V(K_{t-1}, \Omega_t) = \min_{I_{t-1}, L_t} r \cdot (K_t - \delta K_{t-1}) + w \cdot L_t + A(K_t - \delta K_{t-1}, K_{t-1}) + \beta E[V(K_t, \Omega_{t+1})|\Omega_t].$$

So, we can consider an equivalent problem with endogenous choices of capital and labor:

$$\begin{aligned} V(K_{t-1}, \Omega_t) &= \min_{K_t, L_t} rK_t + wL_t + \mathcal{A}(K_t, K_{t-1}) + \beta E[V(K_t, \Omega_{t+1})|\Omega_t], \\ \text{subject to } \; & Q(K_t, L_t) \geq q_t. \end{aligned} \tag{16}$$

Lemma 1 (The dynamic version of the summed output elasticities of inputs)**.** *In a dynamic cost minimization with adjustment costs such that $\mathcal{A}(K^*_{t+1}, K^*_t) = K^*_t \cdot \frac{\partial \mathcal{A}}{\partial K_{t+1}} + K^*_t \cdot \frac{\partial \mathcal{A}}{\partial K_t}$, we have*

$$\frac{AVC_t + E[AAC_{t+1}|\Omega_t]}{MC_t} = \theta_{L_t} + \theta_{K_t},$$

$$\textit{where } \; AVC_t = \frac{rK_t + wL_t}{Q_t},$$

$$AAC_{t+1} = \frac{\mathcal{A}(K_{t+1}, K_t)}{Q_t}.$$

Note that $AVC_t = E[AVC_t|\Omega_t]$ and $MC_t = E[MC_t|\Omega_t]$. Intuitively, we have a dynamic equivalent version for the Proposition 1: The sum of all input elasticities of output is the ratio of expected average cost to marginal cost, as defined by the ratio of total variable cost and expected adjustment cost to marginal cost.

A.1.3 Compatibility of Profit Maximization and Cost Minimization

I now show that the cost minimization behavior of firms—Assumption 3—does not preclude the profit maximization behavior, which is often the assumed goal of the firms. Indeed, the two behaviors are compatible in a variety of market structures: perfect competition, Cournot competition, Cournot competition in the presence of bargaining power stemming from output size, price differentiation due to output-independent quality adjustment, and co-influence of output and input in a generalized cost function. To see why, let me first describe the two decision making processes of a firm.

Definition 1. The input choice problem of a firm to maximize its profit is

$$\text{[Problem 1:]} \quad \max_{\boldsymbol{X}_{it}} \mathcal{P}_{it}(Q_{it}(\boldsymbol{X}_{it})) \cdot Q_{it}(\boldsymbol{X}_{it}) - \mathcal{G}(\boldsymbol{X}_{it}),$$

where $\mathcal{P}_{it}(\cdot)$ is the firm individual output price function, $Q_{it}(\boldsymbol{X}_{it})$ is the production function, $\mathcal{G}(\cdot)$ is the generalized cost function.

Definition 2. The two-step decision problem where the firm decides output level to maximize profits in the first stage and decides inputs to minimize production cost of producing the targeted output in the second stage is

$$\begin{aligned} \text{[Problem 2:]} \quad & \max_{q_{it}} \ \mathcal{P}_{it}(q_{it}) \cdot q_{it} - C(q_{it}) \text{ in stage 1, and} \\ & C(q_{it}) = \min_{\boldsymbol{X}_{it}} \ \mathcal{G}(\boldsymbol{X}_{it}) \text{ subject to } Q_{it}(\boldsymbol{X}_{it}) \geq q_{it} \text{ in stage 2.} \end{aligned}$$

Proposition 3 (Compatibility of profit maximization and cost minimization)**.** *Assume differentiability, concavity of profit function, and convexity of cost function. Problem 1 and Problem 2 are equivalent for the following market environments:*

i) Perfect competition in the output market.

ii) Cournot competition in the output market.

iii) Bargaining power stemming from output size. That is, $\mathcal{P}_{it}(q_{it}) = P(\mathcal{Q}(q_{it}), q_{it})$.

iv) Price differentiation stemming from an endogenous effort that affect quality but not quantity. That is, $\mathcal{P}_{it} = P(\mathcal{Q}(q_{it}), q_{it}, H(e_{it}))$ and $\mathcal{G}(\cdot) = \mathcal{G}(\boldsymbol{X}_{it}, e_{it})$, where e_{it} is the endogenous efforts.

v) Co-influence of output and input in cost function. That is, $\mathcal{G}(\cdot) = G(Q_{it}(\boldsymbol{X}_{it}), \boldsymbol{X}_{it})$.

If firms can differentiate their prices by allocating inputs to directly adjust product quality $H(\boldsymbol{X}_{it})$, i.e. $\mathcal{P}_{it} = P(\mathcal{Q}(q_{it}), q_{it}, H(\boldsymbol{X}_{it}))$, then the two problems are not equivalent in general.

Appendix B shows the proof. The main intuition is that the cost minimization problem lies in the production stage rather than being a whole single goal of the firm. The cost minimization problem aims to design inputs to produce the targeted output rather than to design the output that minimizes cost.

Proposition 3 also contributes to the production function literature that has traditionally assumed perfect competition in the output market to use the proxy variable approach to estimate a production function Olley and Pakes (1996); Levinsohn and Petrin (2003); Ackerberg, Caves and Frazer (2015); Doraszelski and Jaumandreu (2018); Gandhi, Navarro and Rivers (2020). I show that such assumption is only a special case and stronger than assuming cost minimization behavior in the input choice stage and profit maximization in the output choice stage.

A.1.4 Relation to Markups

Although I am the first that derives elasticities of costs to measure economies of scale and shows how to estimate it, I am not the first that exploits the cost-minimization condition of the input allocation problem. Indeed, an emerging literature on IO and macroeconomics has used this condition to estimate markups. This approach has been called production approach to distinguish it from the demand approach. In the demand approach championed by Bresnahan (1989) and Berry, Levinsohn and Pakes (1995), the markup estimation relies on assumptions on utility maximizing behavior of consumers and on how firms compete (for example, Bertrand-Nash price competition or Cournot quantity competition). This demand approach requires data on (at least) product market shares and product characteristics. In contrast, the production approach, established by De Loecker and Warzynski (2012), is posited on the cost minimization by producers and requires data on individual firm output, input, and a variable input's expenditure share in revenue. Examples of applications of this production approach include Braguinsky et al. (2015); De Loecker et al. (2016); De Loecker, Eeckhout and Unger (2020). I now discuss the relation between my output elasticity of cost and the markup in this production approach literature.

Let me begin with the review of the production approach. The production approach to estimate markups also relies on the cost minimizing problem. However, De Loecker and Warzynski (2012) rewrite the first order condition into

$$\frac{W_{it}X_{it}}{P_{it}Q_{it}} \cdot \frac{P_{it}}{\lambda_{it}} = \frac{\partial Q_{it}}{\partial X_{it}} \cdot \frac{X_{it}}{Q_{it}}, \tag{17}$$

where P_{it} is the output price. Hence, the markup ratio $\mu \equiv \frac{P_{it}}{\lambda_{it}}$ can be calculated through:

$$\mu_{it} = \frac{\theta_{it}^X}{\alpha_{it}^X}, \tag{18}$$

where α_{it}^X is the share of expenditure on input X in total sales, i.e. $\alpha_{it}^X \equiv \frac{W_{it}X_{it}}{P_{it}Q_{it}}$. Using this relation, De Loecker and Warzynski (2012) show firm-level markups can be inferred using production data. Specifically, one would need (i) data on output and input to estimate the production function and the output elasticity of one (or more) variable input(s) θ_{it}^X and (ii) data on expenditure share α_{it}^X, which is often available in the financial statement of the firms.

To think about the relation between output elasticity of cost ϕ and markup μ, we now can use Proposition 1 and equation (18) to get

$$\sum_{X \in \mathbb{X}} \theta_{it}^X = \sum_{X \in \mathbb{X}} \mu_{it} \alpha_{it}^X = \mu_{it} \sum_{X \in \mathbb{X}} \alpha_{it}^X = \mu_{it} \cdot \frac{C_{it}(Q_{it})}{P_{it} Q_{it}} \tag{19}$$

$$\Longrightarrow \phi_{it} \cdot \mu_{it} = \frac{PQ}{C} \tag{20}$$

However, I want to emphasize that this relation in fact exists *without* the cost minimization assumption. Indeed, for every differentiable cost function, we have $\phi \cdot \mu = \frac{dC}{dQ} \cdot \frac{Q}{C} \cdot \frac{P}{dC/dQ} = \frac{PQ}{C} \equiv \frac{revenue}{cost}$, where $\mu \equiv \frac{P}{MC}$ is the markup. So, it is the relation between ϕ and θ or between μ and θ that requires the cost minimizing behavior in the input choice decision.

In my application of examining economies of scale to study cap and trade in fishery, I could have estimated the markup using the above approach, but I unfortunately do not observe the revenue cost ratio nor the revenue share of expenditure on input.

B Cost minimization and profit maximization

Proof of proposition 3. First, consider the Cournot competition. The profit maximization problem is

$$\max_{\boldsymbol{X}_{it}} P(\mathcal{Q}(Q_{it}(\boldsymbol{X}_{it}))) \cdot Q_{it}(\boldsymbol{X}_{it}) - G(\boldsymbol{X}_{it}),$$

where $Q_{it}(\boldsymbol{X}_{it})$ is the production function that defines the output quantity the firm can produce with such input use. The profit equals the revenue, which is the product of market price and the firm's output, subtracted by the cost $G(\cdot)$ the firm pays for their input uses. In the Cournot market environment, the market price depends on the total output of all firms in the market $\mathcal{Q}$. Of course, we have $\frac{d\mathcal{Q}}{dQ_{it}} = 1$, because $\mathcal{Q}$ is the industry output. Assume differentiability for all functions and concavity of the profit function, the optimal input use to maximize profits satisfies the following first order condition:

$$P' \cdot \frac{\partial Q}{\partial X} \cdot Q + P \cdot \frac{\partial Q}{\partial X} - \frac{\partial G}{\partial X} = 0.$$

Now, consider the alternative two-step decision process. In the first stage, the firm decides the output level that maximizes the following profits:

$$\max_{q_{it}} P(\mathcal{Q}(q_{it})) \cdot q_{it} - C(q_{it}),$$

where $C(q_{it})$ is the cost of producing q_{it} units of output. In the second stage, the firm decides the input use to minimize this cost of producing q_{it}. That is,

$$\min_{\boldsymbol{X}_{it}} G(\boldsymbol{X}_{it}) \text{ subject to } Q_{it}(\boldsymbol{X}_{it}) \geq q_{it}.$$

The optimal output and input levels in the two-step decision process satisfy the following first order conditions:

$$\begin{aligned} P' \cdot q + P - C' &= 0, \\ \frac{\partial G}{\partial X_{it}} - \lambda \frac{\partial Q_{it}}{\partial X_{it}} &= 0, \\ Q_{it}(\boldsymbol{X}_{it}) &= q_{it} \text{ (assumming interior solutions)}, \end{aligned}$$

where λ is the multiplier associated with the targeted output constraint. Notice that the marginal cost C' is the shadow price of output constraint λ. The three conditions imply $P' \cdot Q + P - \frac{\partial G/\partial X}{\partial Q/\partial X} = 0$, which is equivalent to the first order condition of the profit-maximizing input-choice problem. Hence, the two decision problems, input choice to maximize profits and 2-step decision to maximize profits and minimize production cost, are equivalent in the Cournot market environment.

Now, consider the case where price is endogenous in output due to bargaining power. The profit maximization problem is

$$\max_{\boldsymbol{X}_{it}} P(\mathcal{Q}(Q_{it}(\boldsymbol{X}_{it})), Q_{it}(\boldsymbol{X}_{it})) \cdot Q_{it}(\boldsymbol{X}_{it}) - G(\boldsymbol{X}_{it}).$$

The profit-maximizing input must satisfy

$$\left(P_1 \cdot \frac{\partial \mathcal{Q}}{\partial X} + P_2 \cdot \frac{\partial Q}{\partial X}\right) \cdot Q + P \cdot \frac{\partial Q}{\partial X} - \frac{\partial G}{\partial X} = 0,$$

where P_1, P_2 denote partial derivatives: $P_1 = \frac{\partial P}{\partial \mathcal{Q}}, P_2 = \frac{\partial P}{\partial Q}$.

Consider the two-step decision

$$\max_{q_{it}} P(\mathcal{Q}(q_{it}), q_{it}) \cdot q_{it} - C(q_{it}) \text{ in stage 1, and}$$

$$C(q_{it}) = \min_{\boldsymbol{X}_{it}} G(\boldsymbol{X}_{it}) \text{ subject to } Q_{it}(\boldsymbol{X}_{it}) \geq q_{it} \text{ in stage 2.}$$

The optimal output and input in the two-step decision must satisfy

$$\begin{aligned}(P_1 + P_2) \cdot q + P - \frac{dC}{dq} &= 0,\\ \frac{\partial G}{\partial X} - \lambda \frac{\partial Q}{\partial X} &= 0,\\ Q(\boldsymbol{X}) &= q.\end{aligned}$$

Because the marginal cost is the shadow price $\frac{dC}{dq} = \lambda$, the three above conditions imply the first-order-condition of the profit-maximization problem. So, the two decision problems are equivalent in the presence of bargaining power.

Consider the third situation in which price is endogenous in product quality H and the quality can be adjusted by effort e_{it}. Then the equivalent two-step decision is

$$\begin{aligned}\max_{q_{it}, e_{it}} P(\mathcal{Q}(q_{it}), q_{it}, H(e_{it})) \cdot q_{it} - C(q_{it}, e_{it}) \text{ in stage 1, and}\\ C(q_{it}, e_{it}) = \min_{\boldsymbol{X}_{it}} G(\boldsymbol{X}_{it}, e_{it}) \text{ subject to } Q_{it}(\boldsymbol{X}_{it}) \geq q_{it} \text{ in stage 2.}\end{aligned}$$

The reason is the optimal output, effort, and input must satisfy

$$\begin{aligned}(P_1 + P_2) \cdot q + P - C_1 &= 0,\\ P_3 \cdot q - C_2 &= 0,\\ \frac{\partial G}{\partial X} - \lambda \frac{\partial Q}{\partial X} &= 0.\end{aligned}$$

Because $\frac{\partial C}{\partial q} = \lambda$ and $\frac{\partial C}{\partial e} = \frac{\partial G}{\partial e}$, the three above conditions imply the two first-order conditions that input and effort in the profit-maximization problem satisfy.

However, in a price-differentiation environment where the firm can use its production input to adjust product quality, the two problems, profit-maximizing input choice and two-step decision, are not equivalent in general. That is, consider the case $P_{it} = P(\mathcal{Q}(Q_{it}), Q_{it}, H(\boldsymbol{X}_{it}))$, where product quality $H(\cdot)$ can be directly adjusted by the production input factors $\boldsymbol{X}_{it}$. In this environment, there does not exist an equivalent two-step decision with the cost-minimizing input choice in the second stage, unless the quality function $H(\cdot)$ satisfies a set of conditions in relation to the price function and the production function $Q(\cdot)$.

Finally, consider the flexible form of the cost function in which output and input are interdependent. In this environment, the profit-maximizing input-choice problem is

$$\max_{\boldsymbol{X}_{it}} P(\mathcal{Q}(Q_{it}(\boldsymbol{X}_{it})), Q_{it}(\boldsymbol{X}_{it})) \cdot Q_{it}(\boldsymbol{X}_{it}) - G(Q_{it}(\boldsymbol{X}_{it}), \boldsymbol{X}_{it}).$$

The input choice must satisfy

$$\left(P_1 \cdot \frac{\partial Q}{\partial X} + P_2 \cdot \frac{\partial Q}{\partial X}\right) \cdot Q - P \cdot \frac{\partial Q}{\partial X} - \frac{\partial G}{\partial Q} \cdot \frac{\partial Q}{\partial X} - \frac{\partial G}{\partial X} = 0.$$

The equivalent two-step decision is

$$\begin{aligned} &\max_{q_{it}} P(\mathcal{Q}(q_{it}), q_{it}) \cdot q_{it} - C(q_{it}) \text{ in stage 1, and} \\ C(q_{it}) = &\min_{\boldsymbol{X}_{it}} G(q_{it}, \boldsymbol{X}_{it}) \text{ subject to } Q_{it}(\boldsymbol{X}_{it}) \geq q_{it} \text{ in stage 2,} \end{aligned}$$

where the output and input must satisfy

$$\begin{aligned} (P_1 + P_2) \cdot q + P - C' &= 0, \\ \frac{\partial G}{\partial X} - \lambda \cdot \frac{\partial Q}{\partial X} &= 0, \\ Q(\boldsymbol{X}) &= q. \end{aligned}$$

Because $\frac{dC}{dq} = \frac{\partial G}{\partial q} + \lambda$, these three conditions imply the first-order condition of the profit maximizing problem. Hence, the two problems are equivalent.

C The Case of Dynamic Inputs

Proof of Lemma 1

Proof. Consider the dynamic problem (16), the FOCs with respect to L_t, K_t are:

$$w = \lambda \cdot \frac{\partial Q}{\partial L_t} \Longrightarrow \frac{w \cdot L_t}{\lambda \cdot Q} = \frac{\partial Q}{\partial L_t} \cdot \frac{L_t}{Q} = \theta_{L_t} \tag{21}$$

$$r + \frac{\partial \mathcal{A}(K_t, K_{t-1})}{\partial K_t} + \beta E\left[\frac{\partial V(K_t, \Omega_{t+1})}{\partial K_t} | \Omega_t\right] = \lambda \cdot \frac{\partial Q}{\partial K_t} \tag{22}$$

Apply the Envelope theorem to calculate the derivative of value function:

$$\frac{\partial V(K_t, \Omega_{t+1})}{\partial K_t} = \frac{\partial \mathcal{A}(K_{t+1}, K_t)}{\partial K_t}. \tag{23}$$

Substitute this in the FOC wrt K_t to get the Euler equation for the dynamic capital:

$$r + \frac{\partial \mathcal{A}(K_t, K_{t-1})}{\partial K_t} + \beta E\left[\frac{\partial \mathcal{A}(K_{t+1}, K_t)}{\partial K_t} | \Omega_t\right] = \lambda \cdot \frac{\partial Q}{\partial K_t} \tag{24}$$

Multiply both sides by $\frac{K_t}{Q(K_t,L_t)\cdot\lambda}$ at optimal levels K_t^*:

$$\Longrightarrow K_t^* \cdot \left(r + \frac{\partial \mathcal{A}(K_t, K_{t-1})}{\partial K_t} + \beta E\left[\frac{\partial \mathcal{A}(K_{t+1}, K_t)}{\partial K_t} |\Omega_t \right] \right) / (Q \cdot \lambda) = \frac{\partial Q}{\partial K_t} \cdot \frac{K_t}{Q} \equiv \theta_{K_t}|_{K_t^*},$$

$$\Longrightarrow \frac{K_t^* \cdot r + K_t^* \cdot \mathcal{A}_1 + \beta \cdot K_t^* \cdot E[\mathcal{A}_2|\Omega_t]}{Q \cdot \lambda} = \theta_{K_t}|_{K_t^*}, \tag{25}$$

where $\mathcal{A}_1$ and $\mathcal{A}_2$ denote the first and second derivatives of $\mathcal{A}$.

If the adjustment cost satisfies $\mathcal{A}(K_{t+1}^*, K_t^*) = K_t^* \cdot \mathcal{A}_1 + \beta \cdot K_t^* \cdot \mathcal{A}_2$, then

$$\frac{E[(K_t^* \cdot r + \mathcal{A}(K_{t+1}, K_t))|\Omega_t]}{Q} = \theta_{K_t}|_{K_t^*}. \tag{26}$$

Then sum the equalities (21) and (26) side by side, we get

$$E\left[\frac{AVC + AAC}{MC}\right] = \theta_{L_t} + \theta_{K_t}. \tag{27}$$

□

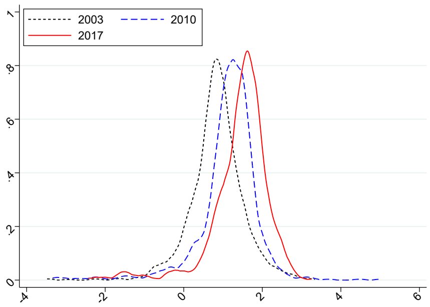
D Productivity and Cost Elasticity Using OLS with FEs and Dynamic Panel Approaches

Table D1: Summary statistics of estimates of cost indices by licensed length group

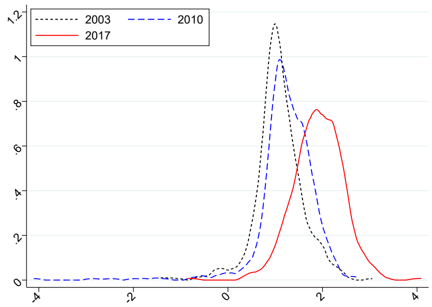
	Pre-trade-program					Post-trade-program				
	count	mean	sd	min	max	count	mean	sd	min	max
Panel A: Output elasticity of total costs, using the dynamic panel estimator for the production function										
0–10.9m	8,470	0.368	0.046	0.205	0.584	8,362	0.373	0.056	0.205	0.806
11–14.9m	3,590	0.429	0.058	0.249	0.660	3,637	0.445	0.071	0.225	0.790
15–20.9m	995	0.458	0.063	0.254	0.688	2,367	0.513	0.086	0.281	0.915
21–27.9m	433	0.463	0.066	0.300	0.734	1,016	0.532	0.095	0.326	1.005
Panel B: Output elasticity of total costs, using the OLS-FE estimator for the production function										
0–10.9m	8,470	0.387	0.054	0.205	0.651	8,362	0.393	0.066	0.205	0.969
11–14.9m	3590	0.456	0.070	0.249	0.741	3,637	0.476	0.085	0.224	0.934
15–20.9m	995	0.487	0.077	0.252	0.793	2,367	0.554	0.107	0.284	1.075
21–27.9m	433	0.485	0.079	0.298	0.824	1,016	0.567	0.119	0.323	1.217

Note: Pre-trade-program period and post-trade period for licensed groups 15–20.9m and 21–27.9m are 2001–2003 and 2005–2017. For licensed length group 11–14.9m, they are 2001–2007 and 2009–2017. Licensed length group 0–10.9m is not allowed to trade during 2001 and 2017, but we compare period 2001–2007 to period 2009–2017.

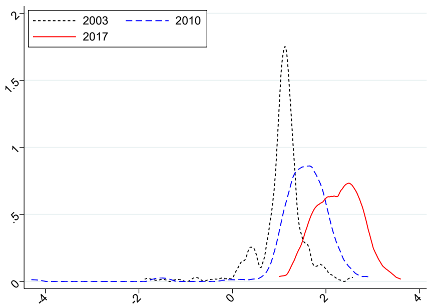
(a) productivity in licensed length 0–10.9m



(b) productivity in licensed length 11–14.9m



(c) productivity in licensed length 15–20.9m



(d) productivity in licensed length 21–27.9m

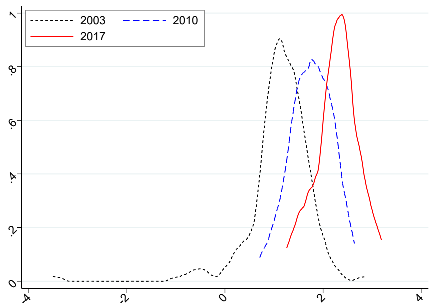
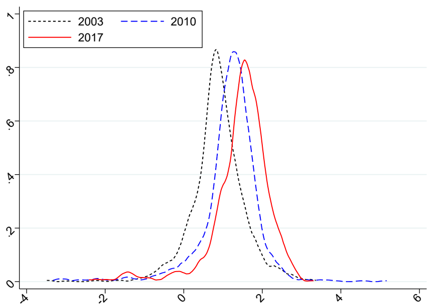
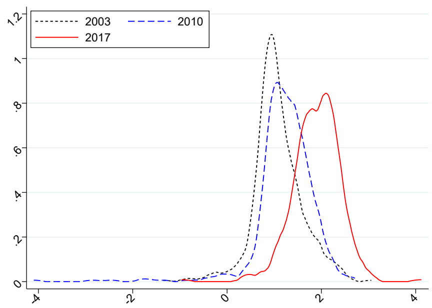


Figure D3: Distribution of productivity (from the OLS-with-FEs estimator)

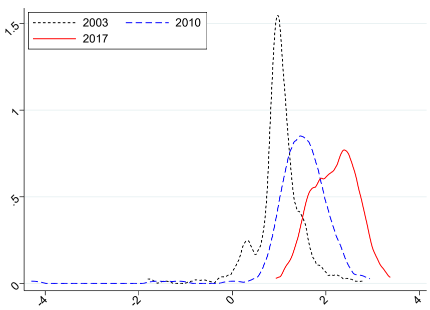
(a) productivity in licensed length 0–10.9m



(b) productivity in licensed length 11–14.9m



(c) productivity in licensed length 15–20.9m



(d) productivity in licensed length 21–27.9m

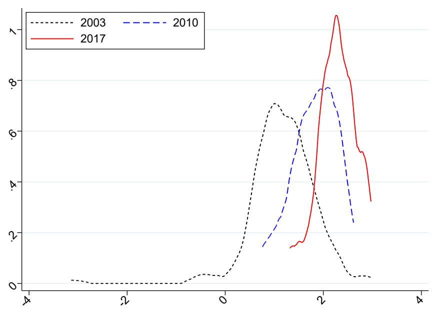
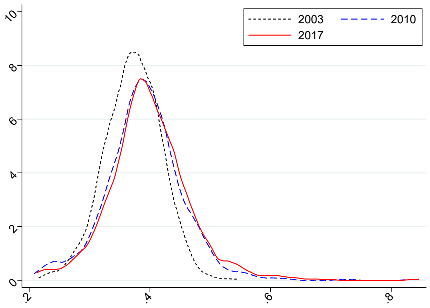
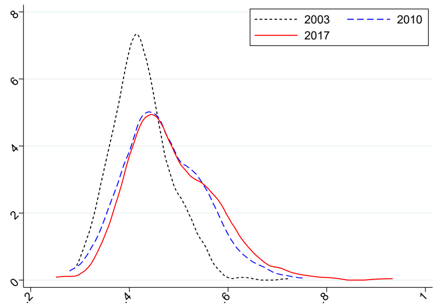


Figure D4: Distribution of productivity (from the dynamic panel estimator)

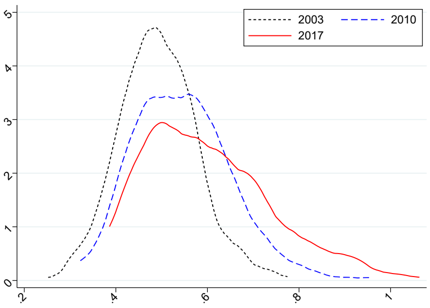
(a) elasticity of total costs, license 0–10.9m



(b) elasticity of total costs, license 11–14.9m



(c) elasticity of total costs, license 15–20.9m



(d) elasticity of total costs, license 21–27.9m

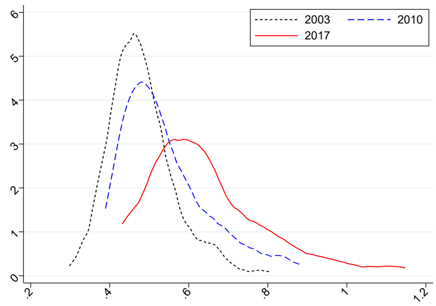
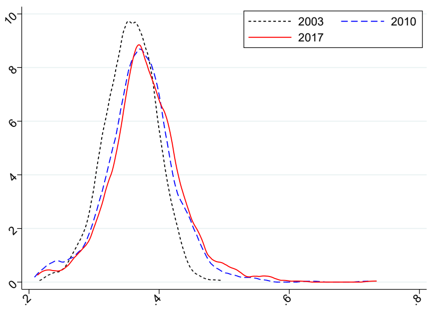
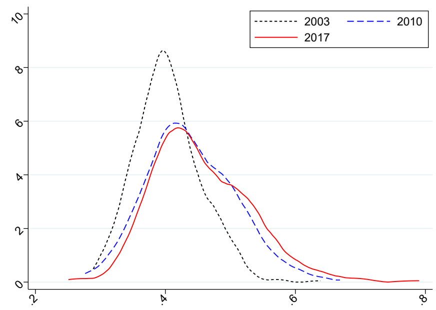


Figure D5: Distribution of output elasticity of total costs (implied from the OLS with FEs)

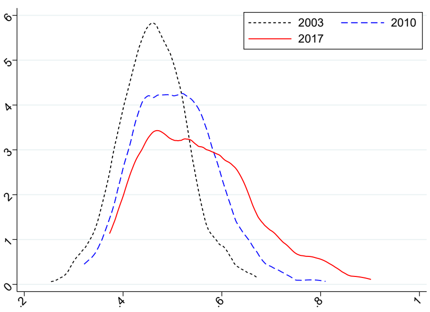
(a) elasticity of total costs, license 0–10.9m



(b) elasticity of total costs, license 11–14.9m



(c) elasticity of total costs, license 15–20.9m



(d) elasticity of total costs, license 21–27.9m

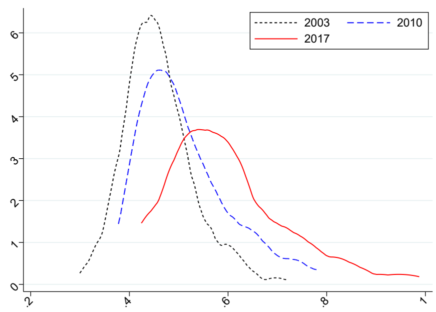


Figure D6: Distribution of output elasticity of total costs (from the dynamic panel estimator)

E Supplementary Event Studies and Diff-in-diff Results

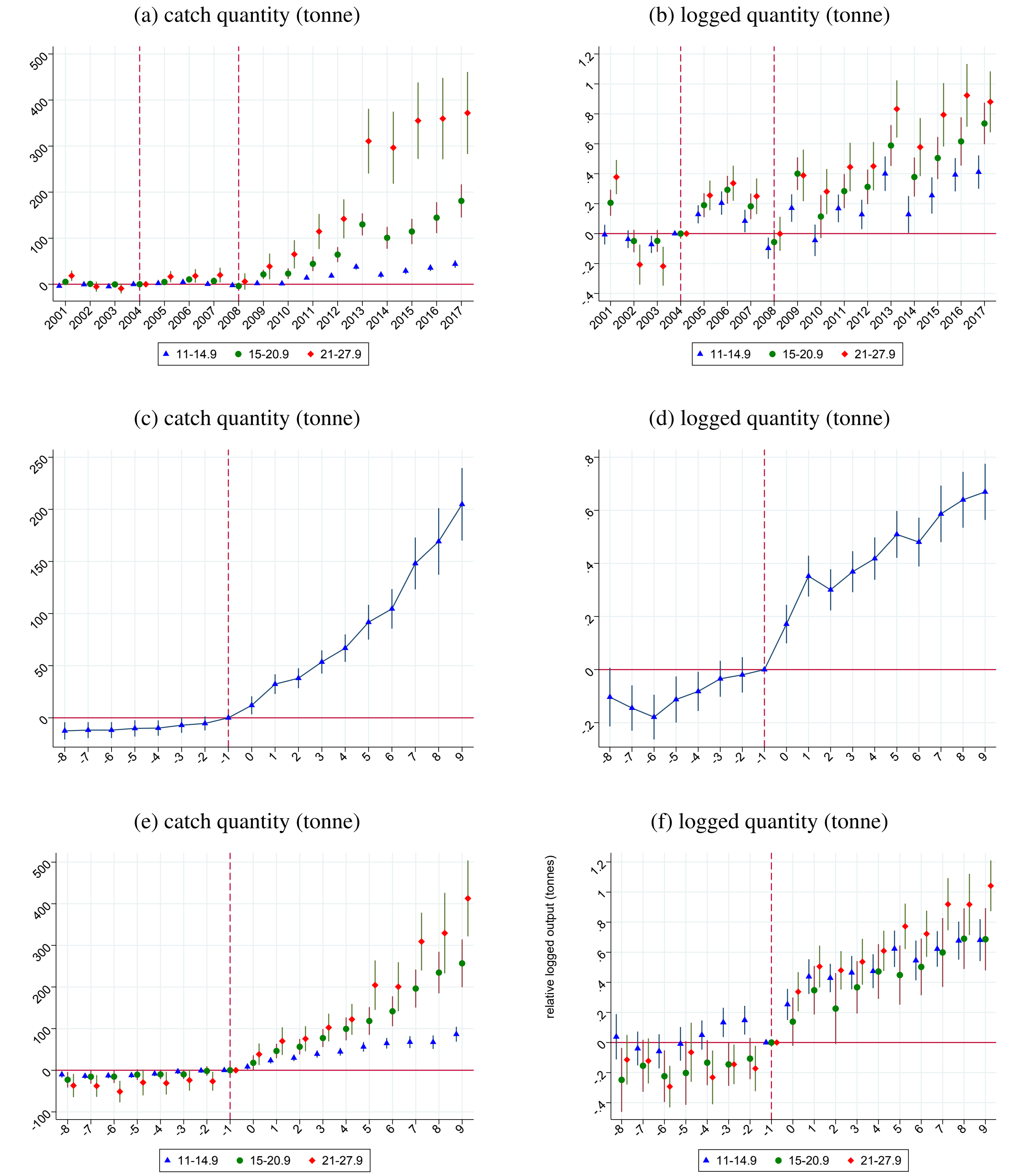


Figure E7: Impacts of the trading policy and quota acquisition on catch quantity and revenue

Note: Panels A and B plot the event study coefficients of ITT of the trading policy. Year 2004 and the non-tradable group (0–10.9m) are normalized. From 2004, the groups 15–20.9m and 21–27.9m may trade. From 2007, the group 11–14.9m may trade. Panels C–F plot the event study coefficients of ATT of quota acquisition, for years before and after the acquisition. Vessels in the non-tradable group and that are in the tradable group and do not trade are the base group.

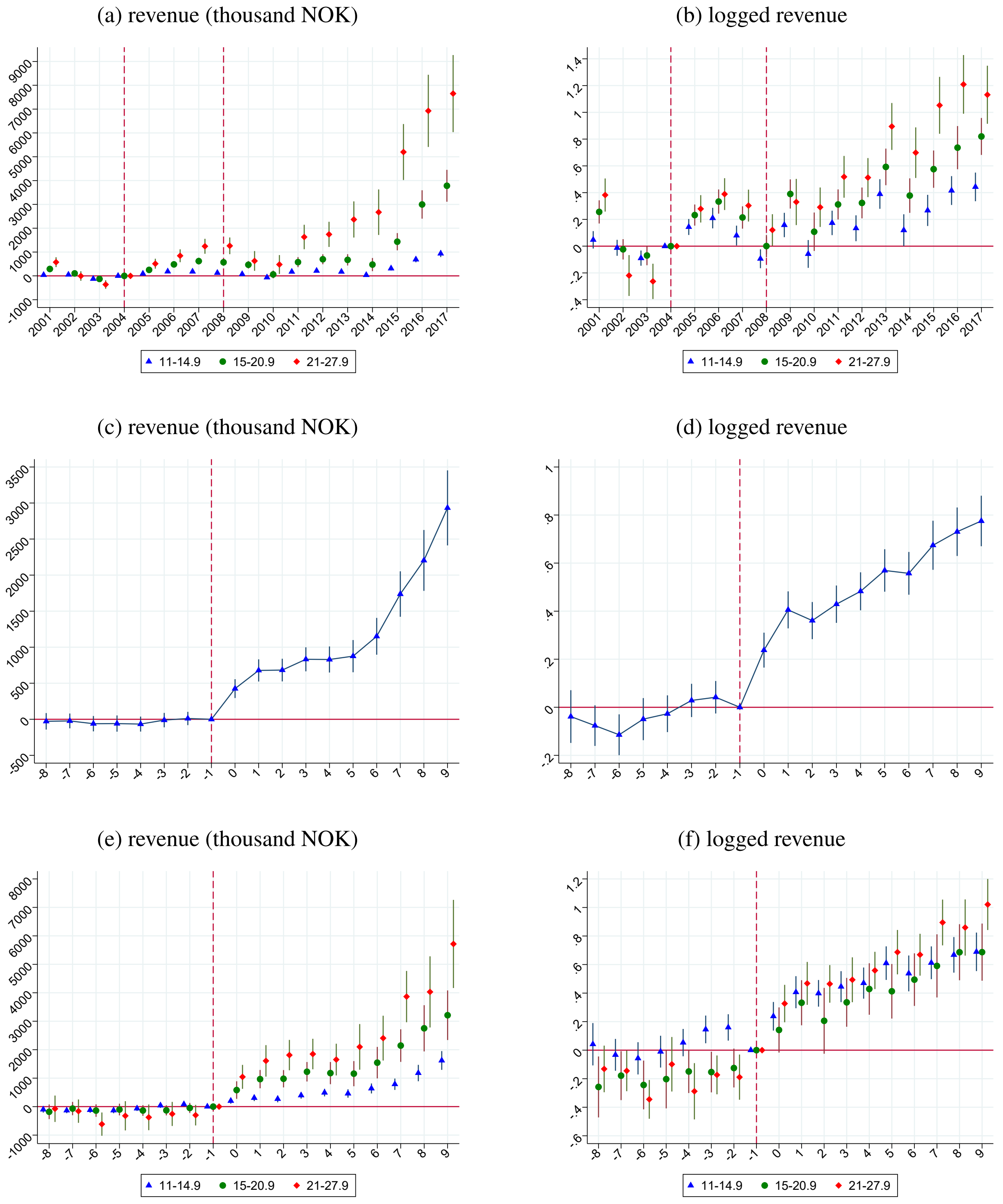


Figure E8: Impacts of the trading policy and quota acquisition on revenue

Note: Panels A and B plot the event study coefficients of ITT of the trading policy. Year 2004 and the non-tradable group (0–10.9m) are normalized. From 2004, the groups 15–20.9m and 21–27.9m may trade. From 2007, the group 11–14.9m may trade. Panels C–F plot the event study coefficients of ATT of quota acquisition, for years before and after the acquisition. Vessels in the non-tradable group and that are in the tradable group and do not trade are the base group.

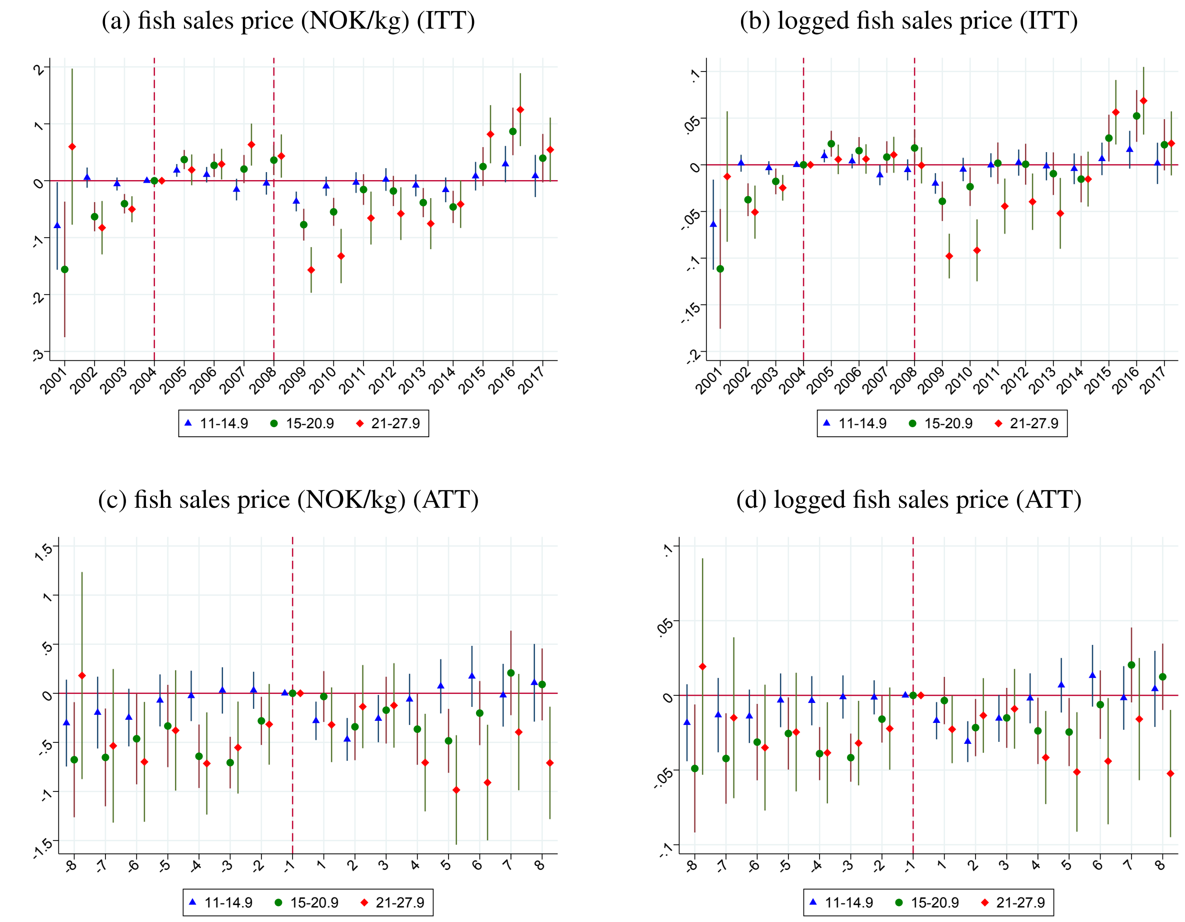


Figure E9: Event studies of ITT of trading policies and ATT of quota acquisition on trip-level transacted fish sales price

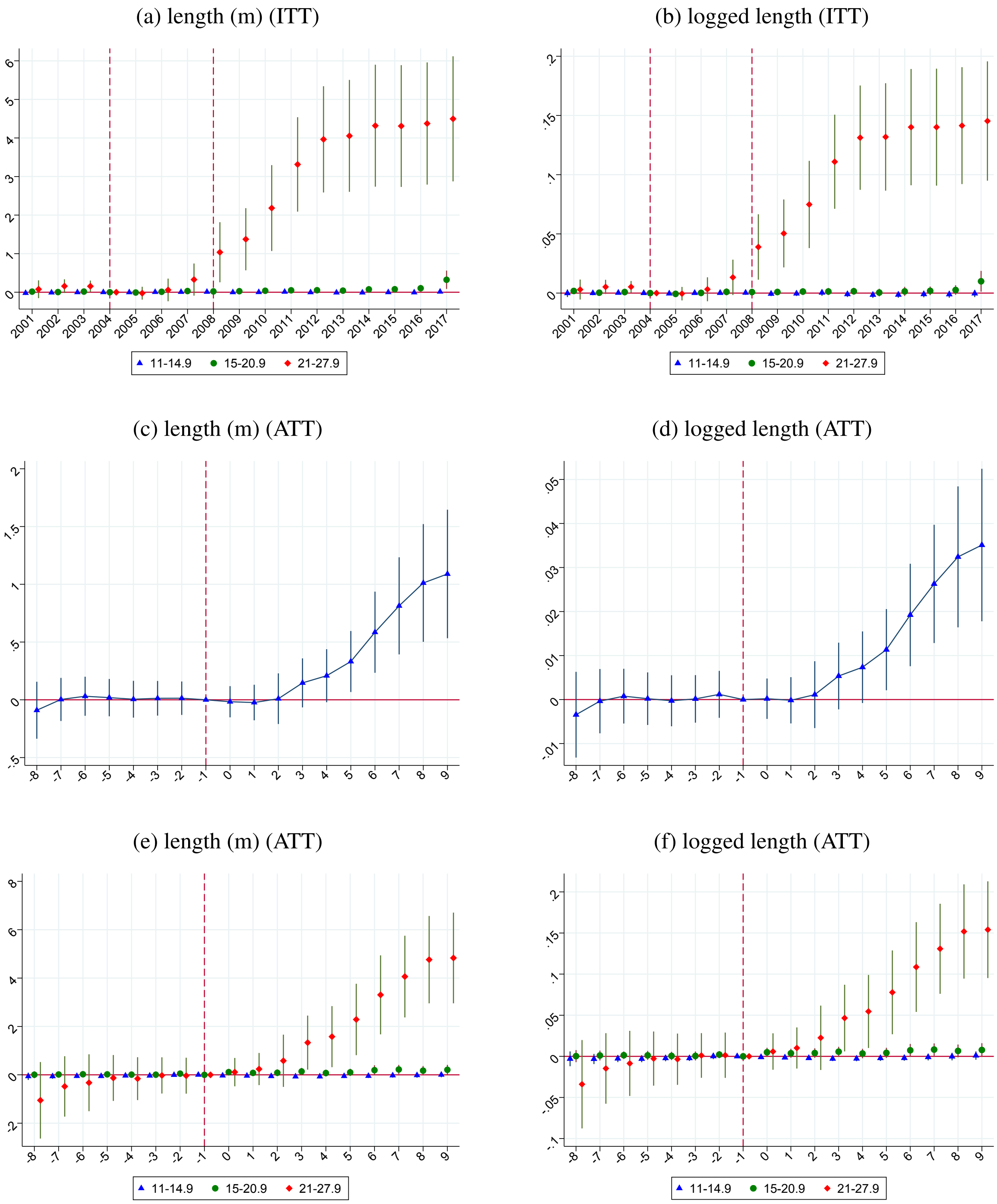


Figure E10: Impacts of the trading policy and quota acquisition on vessel actual length

Note: Panels A and B plot the event study coefficients of ITT of the trading policy. Year 2004 and the non-tradable group (0–10.9m) are normalized. From 2004, the groups 15–20.9m and 21–27.9m may trade. From 2007, the group 11–14.9m may trade. Panels C–F plot the event study coefficients of ATT of quota acquisition, for years before and after the acquisition. Vessels in the non-tradable group and that are in the tradable group and do not trade are the base group.

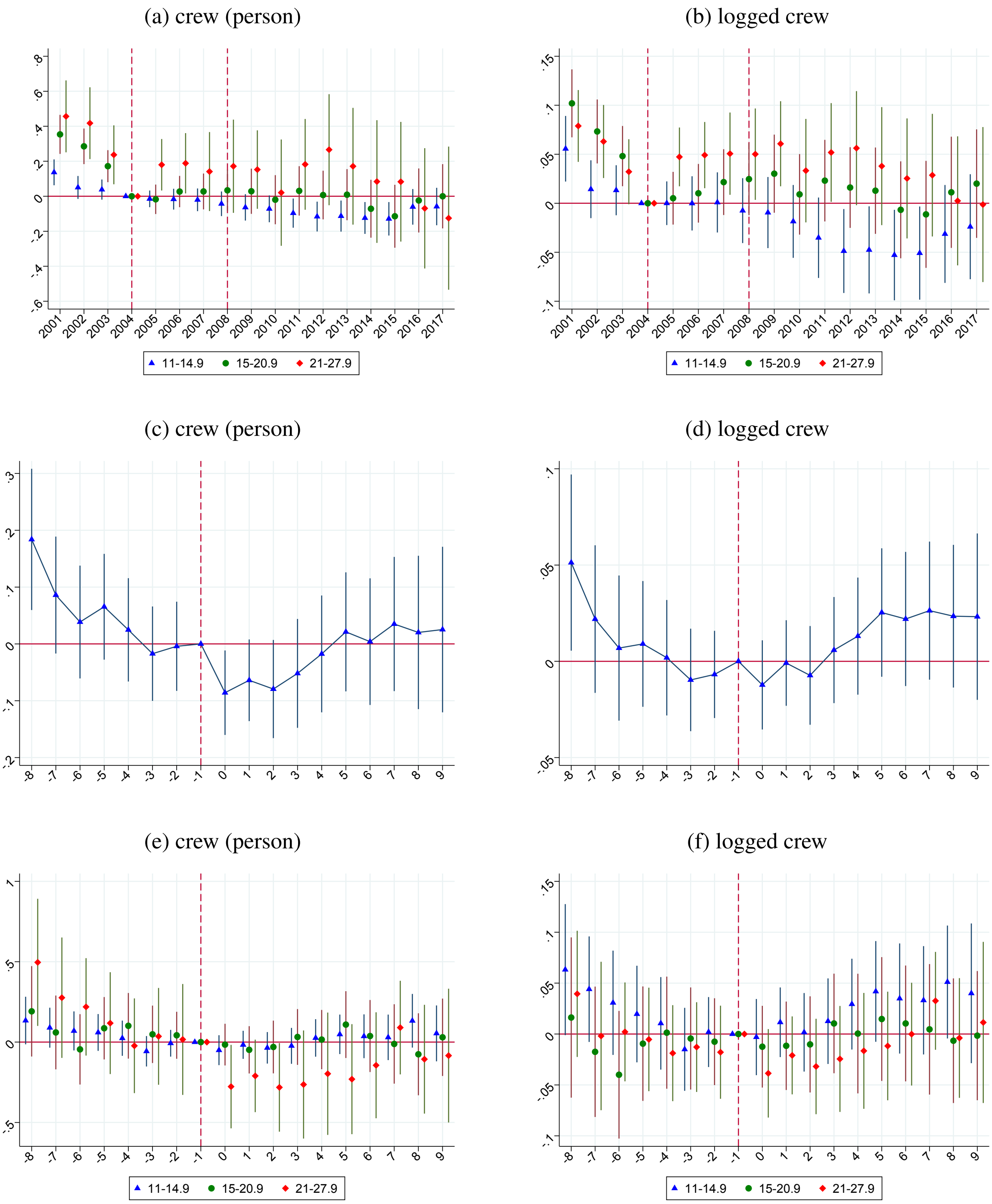


Figure E11: Impacts of the trading policy and quota acquisition on crew size

Note: Panels A and B plot the event study coefficients of ITT of the trading policy. Year 2004 and the non-tradable group (0–10.9m) are normalized. From 2004, the groups 15–20.9m and 21–27.9m may trade. From 2007, the group 11–14.9m may trade. Panels C–F plot the event study coefficients of ATT of quota acquisition, for years before and after the acquisition. Vessels in the non-tradable group and that are in the tradable group and do not trade are the base group.

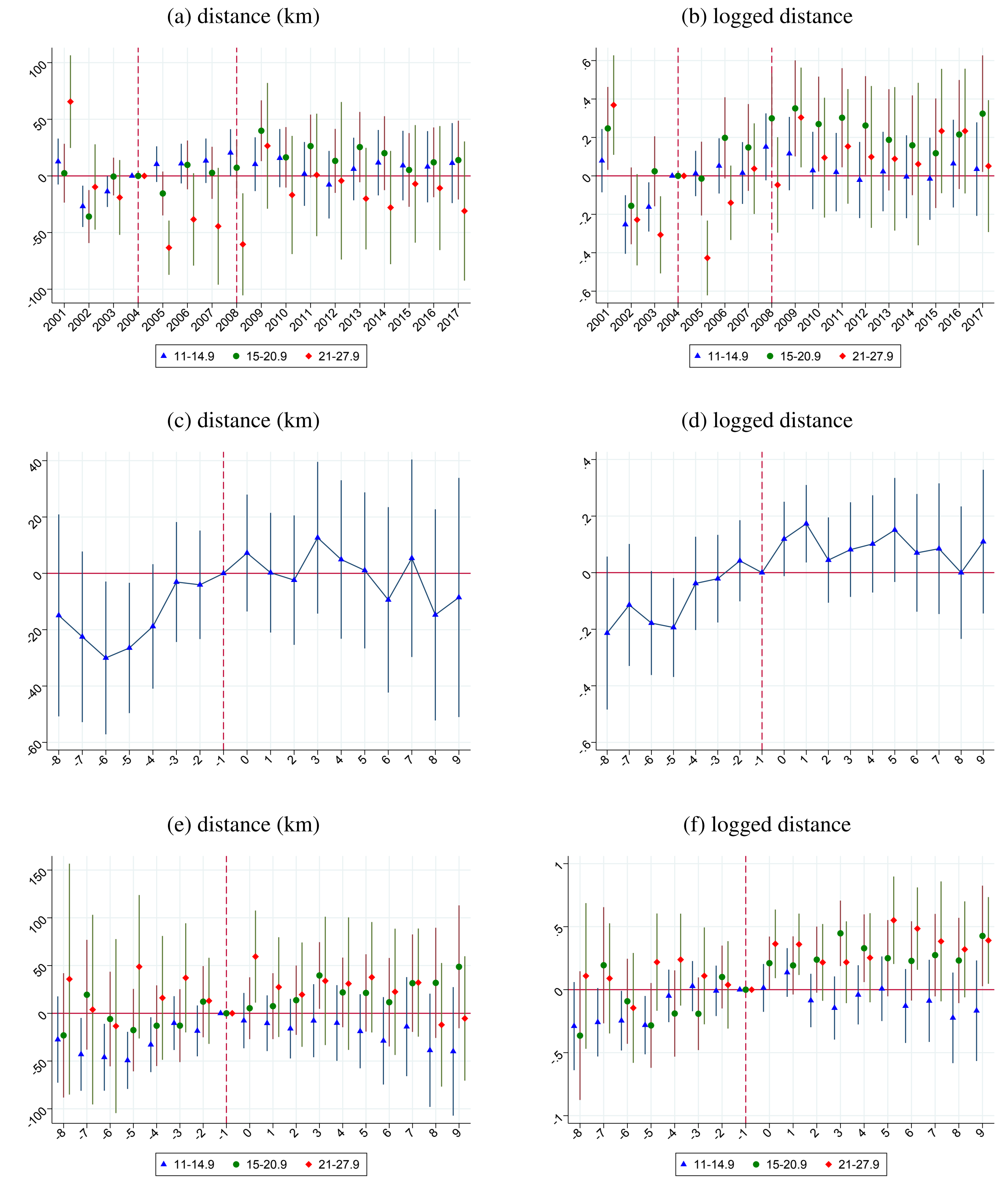


Figure E12: Impacts of the trading policy and quota acquisition on distance from fishers' municipality to major catch location

Note: Panels A and B plot the event study coefficients of ITT of the trading policy. Year 2004 and the non-tradable group (0–10.9m) are normalized. From 2004, the groups 15–20.9m and 21–27.9m may trade. From 2007, the group 11–14.9m may trade. Panels C–F plot the event study coefficients of ATT of quota acquisition, for years before and after the acquisition. Vessels in the non-tradable group and that are in the tradable group and do not trade are the base group.

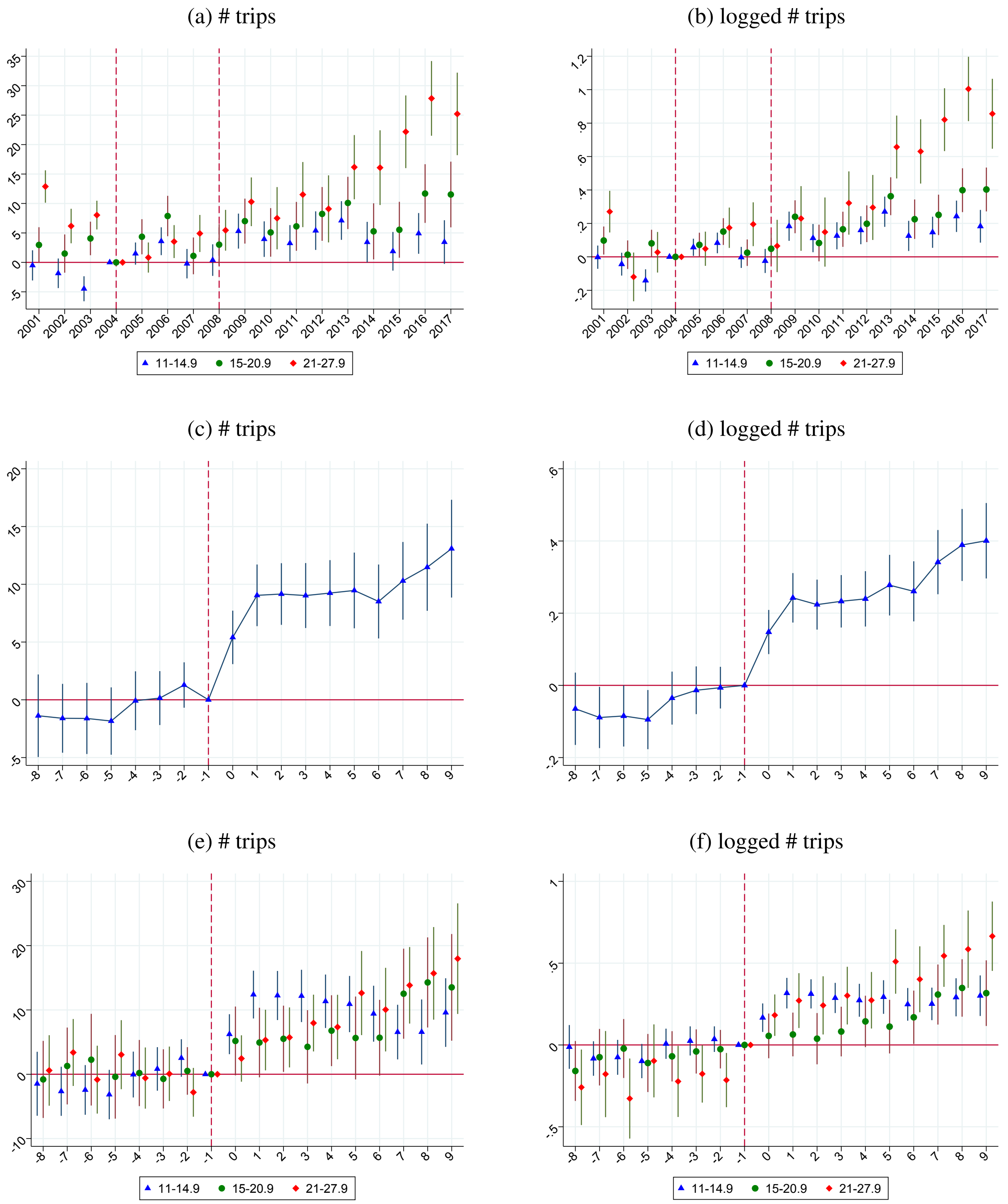
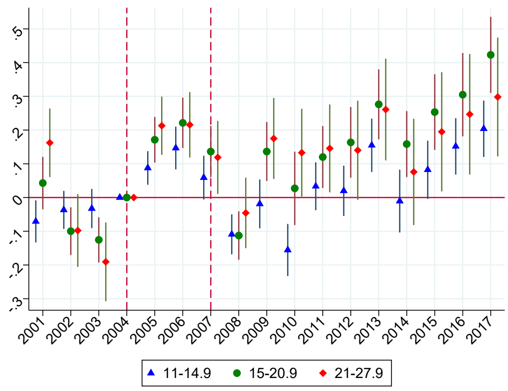


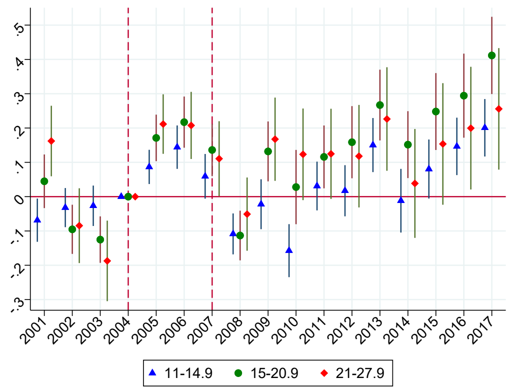
Figure E13: Impacts of the trading policy and quota acquisition on the number of trips in a year

Note: Panels A and B plot the event study coefficients of ITT of the trading policy. Year 2004 and the non-tradable group (0–10.9m) are normalized. From 2004, the groups 15–20.9m and 21–27.9m may trade. From 2007, the group 11–14.9m may trade. Panels C–F plot the event study coefficients of ATT of quota acquisition, for years before and after the acquisition. Vessels in the non-tradable group and that are in the tradable group and do not trade are the base group.

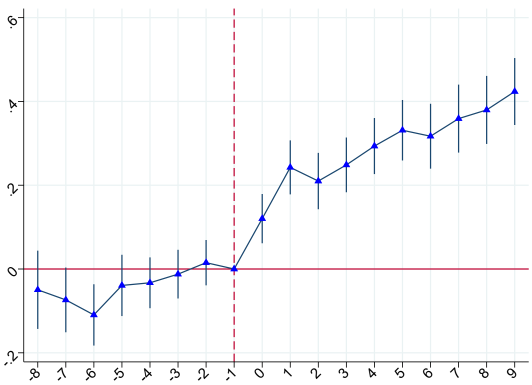
(a) productivity using OLS-with-FE estimator



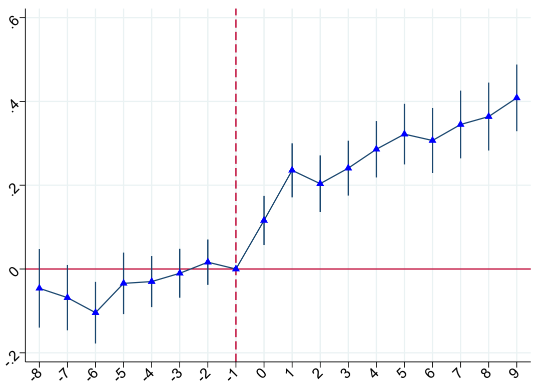
(b) productivity using the proxy variable approach



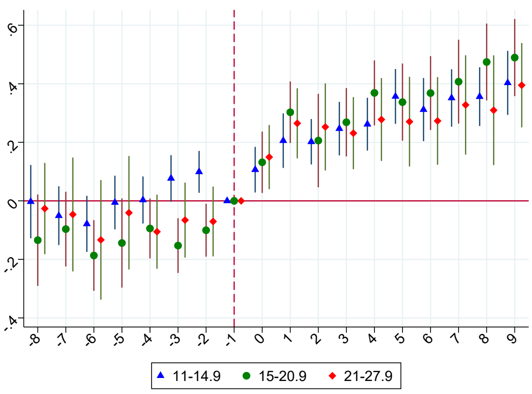
(c) productivity using OLS with FEs



(d) productivity using the proxy variable approach



(e) productivity using OLS with FEs



(f) productivity using the proxy variable approach

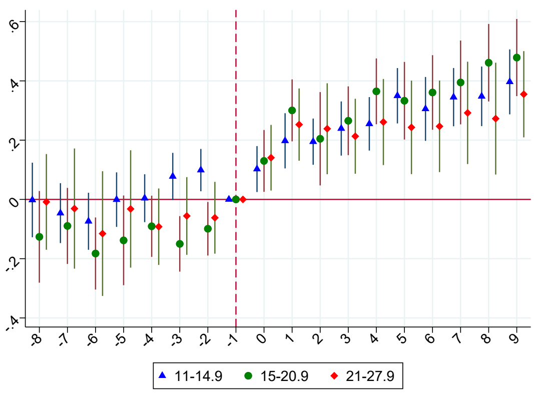


Figure E14: Impacts of the trading policy and quota acquisition on productivity

Note: Panels A and B plot the event study coefficients of ITT of the trading policy. Year 2004 and the non-tradable group (0–10.9m) are normalized. From 2004, the groups 15–20.9m and 21–27.9m may trade. From 2007, the group 11–14.9m may trade. Panels C–F plot the event study coefficients of ATT of quota acquisition, for years before and after the acquisition. Vessels in the non-tradable group and that are in the tradable group and do not trade are the base group.

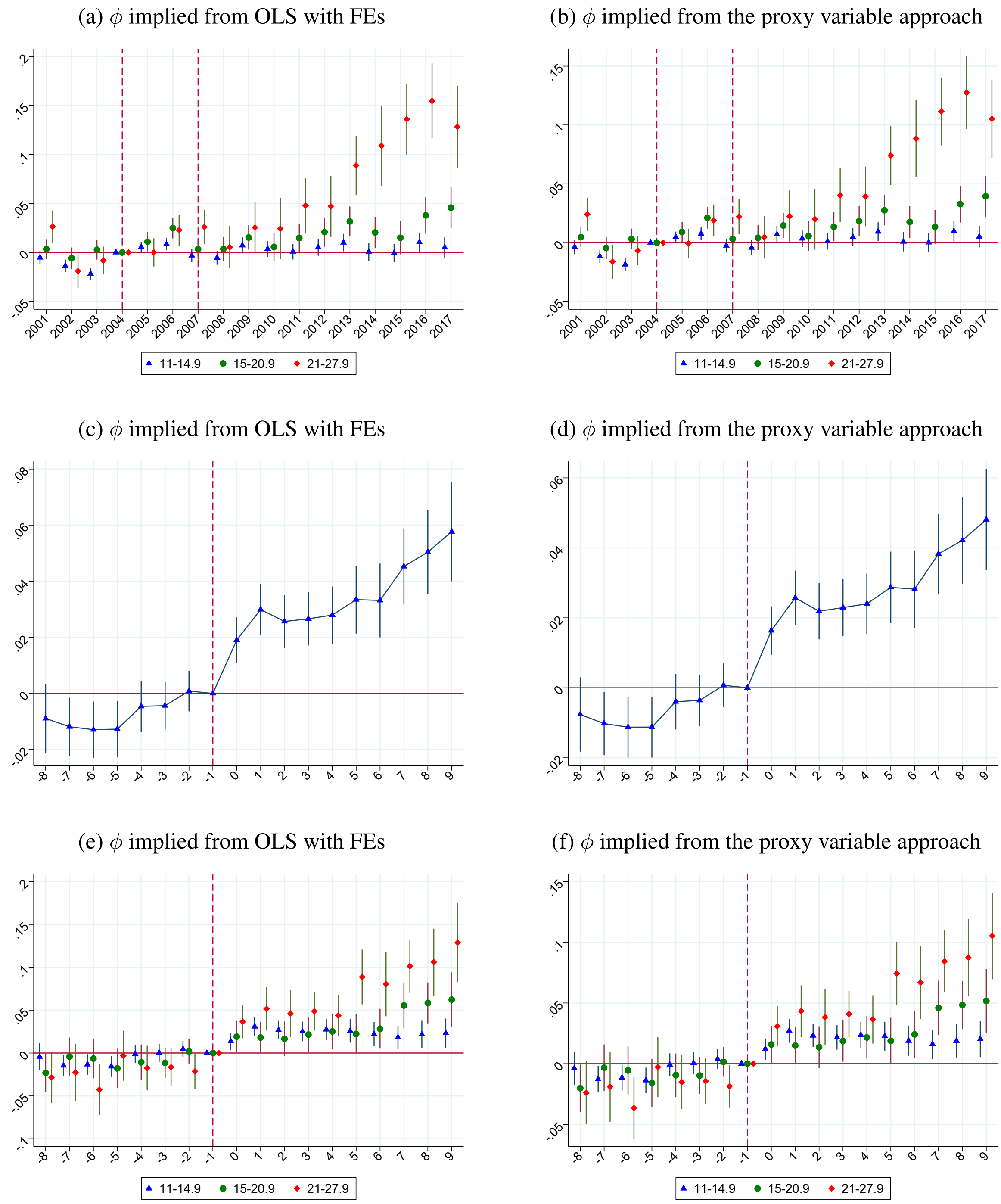


Figure E15: Impacts of the trading policy and quota acquisition on output elasticity of total cost

Note: Panels A and B plot the event study coefficients of ITT of the trading policy. Year 2004 and the non-tradable group (0–10.9m) are normalized. From 2004, the groups 15–20.9m and 21–27.9m may trade. From 2007, the group 11–14.9m may trade. Panels C–F plot the event study coefficients of ATT of quota acquisition, for years before and after the acquisition. Vessels in the non-tradable group and that are in the tradable group and do not trade are the base group.

Table E2: Effects of trading policy on catch quantity and fish sales price

	(1) weight (tonne)	(2) logged weight	(3) price (NOK/kg) (trip-level)	(4) logged price (trip-level)	(5) average value (NOK/kg) (yearly)	(6) logged avg value (yearly)
Panel A: ITT (pooling all trade qualified groups)						
Trade qualified	9.579***	0.085***	0.077	0.005	-0.194	-0.005
	(1.611)	(0.027)	(0.060)	(0.004)	(0.132)	(0.006)
Panel B: ITT by trade qualified group (license group)						
21-27.9m × From 2004	39.611***	0.226***	0.316**	0.019**	0.271	0.020*
	(6.908)	(0.047)	(0.150)	(0.008)	(0.242)	(0.012)
15-20.9m × From 2004	19.357***	0.127***	0.427**	0.026**	-0.170	0.001
	(3.470)	(0.033)	(0.164)	(0.010)	(0.314)	(0.013)
11-14.9m × From 2008	0.580	0.044	-0.061	-0.003	-0.285	-0.012
	(2.606)	(0.035)	(0.065)	(0.004)	(0.201)	(0.009)
Panel C: pooled ATT						
Quota acquisition	72.483***	0.464***	-0.092	-0.006	-0.228*	-0.014**
	(4.594)	(0.023)	(0.074)	(0.005)	(0.122)	(0.006)
Panel D: ATT by license group						
Quota acquisition × 21-27.9m	157.203***	0.623***	-0.198	-0.009	-0.192	-0.011
	(19.930)	(0.056)	(0.140)	(0.010)	(0.225)	(0.013)
Quota acquisition × 15-20.9m	100.464***	0.493***	0.077	0.006	-0.082	-0.005
	(8.898)	(0.058)	(0.136)	(0.009)	(0.211)	(0.013)
Quota acquisition × 11-14.9m	37.155***	0.408***	-0.156*	-0.011*	-0.304**	-0.019**
	(2.992)	(0.028)	(0.088)	(0.006)	(0.137)	(0.008)
Panel E: pooled LATE using IV DID FE						
Quota acquisition	44.552***	0.396***	0.320	0.021	-0.904	-0.024
	(5.803)	(0.120)	(0.259)	(0.017)	(0.625)	(0.026)
Kleibergen-Paap rk Wald F	131.991	131.991	118.702	118.702	131.991	131.991
Panel F: LATE by license group, using IV DID FE						
Quota acquisition × 21-27.9m	159.263***	0.916***	1.300*	0.079**	1.022	0.079
	(19.650)	(0.183)	(0.717)	(0.040)	(1.018)	(0.051)
Quota acquisition × 15-20.9m	122.392***	0.803***	2.382***	0.146***	-1.051	0.006
	(15.604)	(0.211)	(0.628)	(0.036)	(2.043)	(0.082)
Quota acquisition × 11-14.9m	24.509***	0.298**	0.142	0.010	-1.068	-0.037
	(6.440)	(0.125)	(0.240)	(0.016)	(0.689)	(0.030)
Kleibergen-Paap rk Wald F	13.406	13.406	10.232	10.232	13.406	13.406
Observations	30,776	30,776	1,158,487	1,158,487	30,067	30,067

Note: Panels represent specifications. Columns represent dependent variables. All specifications use yearly observations and include year fixed effects, vessel fixed effects, and owner fixed effects. Panels A and B estimate ITT of the trading policy: $Y_{it} = \beta_{ITT}\textit{Trade Qualified}_{it} + \eta_i + \tau_t + \epsilon_{it}$. Panels C and D estimate ATT of quota acquisition: $Y_{it} = \beta_{ATT}\textit{Quota Acquisition}_{it} + \eta_i + \tau_t + \epsilon_{it}$. Panels E and F estimate ATT of quota acquisition using IV DID with fixed effects specification: the treatment *Quota acquisition*$_{it}$ is instrumented by the policy assignment *Trade qualified*$_{it}$. Standard errors in parentheses are clustered by vessel's municipality. Significance level: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table E3: Effects of trading policy on production factors (log levels)

	(1) logged length (m)	(2) logged crew (person)	(3) logged distance (km)	(4) logged # trips
Panel A: ITT (pooling all trade qualified groups)				
Trade qualified	-0.001	-0.040***	0.039	0.072***
	(0.001)	(0.009)	(0.061)	(0.021)
Panel B: ITT by trade qualified group (license group)				
21-27.9m × From 2004	0.022***	-0.015	-0.029	0.060
	(0.007)	(0.014)	(0.084)	(0.064)
15-20.9m × From 2004	-0.001	-0.055***	0.059	0.009
	(0.001)	(0.015)	(0.100)	(0.038)
11-14.9m × From 2008	-0.005***	-0.038***	0.043	0.099***
	(0.002)	(0.011)	(0.071)	(0.024)
Panel C: pooled ATT using DID FE				
Quota acquisition	0.005*	0.008	0.169***	0.311***
	(0.003)	(0.009)	(0.065)	(0.027)
Panel D: ATT by license group, using DID FE				
Quota acquisition × 21-27.9m	0.042**	0.002	0.283**	0.463***
	(0.017)	(0.018)	(0.113)	(0.062)
Quota acquisition × 15-20.9m	0.001	0.004	0.287**	0.236***
	(0.002)	(0.019)	(0.124)	(0.044)
Quota acquisition × 11-14.9m	-0.003	0.011	0.086	0.304***
	(0.002)	(0.015)	(0.079)	(0.037)
Panel E: pooled LATE using IV DID FE				
Quota acquisition	-0.005	-0.184***	0.182	0.335***
	(0.005)	(0.046)	(0.284)	(0.094)
Kleibergen-Paap rk Wald F	131.991	131.991	131.991	131.991
Panel F: LATE by license group, using IV DID FE				
Quota acquisition × 21-27.9m	0.086***	-0.072	-0.102	0.242
	(0.027)	(0.053)	(0.339)	(0.244)
Quota acquisition × 15-20.9m	-0.005	-0.344***	0.367	0.070
	(0.006)	(0.116)	(0.589)	(0.234)
Quota acquisition × 11-14.9m	-0.014***	-0.175***	0.186	0.376***
	(0.005)	(0.050)	(0.289)	(0.090)
Kleibergen-Paap rk Wald F	13.406	13.406	13.406	13.406
Observations	30,776	30,776	30,776	30,776

Note: Panels represent specifications. Columns represent dependent variables. All specifications use yearly observations and include year fixed effects, vessel fixed effects, and owner fixed effects. Panels A and B estimate ITT of the trading policy: $Y_{it} = \beta_{ITT} \textit{Trade Qualified}_{it} + \eta_i + \tau_t + \epsilon_{it}$. Panels C and D estimate ATT of quota acquisition: $Y_{it} = \beta_{ATT} \textit{Quota Acquisition}_{it} + \eta_i + \tau_t + \epsilon_{it}$. Panels E and F estimate ATT of quota acquisition using IV DID with fixed effects specification: the treatment $\textit{Quota acquisition}_{it}$ is instrumented by the policy assignment $\textit{Trade qualified}_{it}$. Standard errors in parentheses are clustered by vessel's municipality. Significance level: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table E4: Effects of trading policy on productivity

	(1)	(2)	(3)
	OLS with FE	proxy variable	dynamic panel
	logged TFPQ ω	logged TFPQ ω	logged TFPQ ω
Panel A: ITT (pooling all trade qualified groups)			
Trade qualified	0.029	0.025	0.025
	(0.020)	(0.020)	(0.021)
Panel B: ITT by trade qualified group (license group)			
21-27.9m $\times$ From 2004	0.140***	0.129***	0.083*
	(0.041)	(0.041)	(0.044)
15-20.9m $\times$ From 2004	0.147***	0.145***	0.150***
	(0.032)	(0.033)	(0.034)
11-14.9m $\times$ From 2008	-0.037	-0.039	-0.033
	(0.024)	(0.024)	(0.024)
Panel C: pooled ATT using DID FE			
Quota acquisition	0.287***	0.276***	0.257***
	(0.022)	(0.022)	(0.022)
Panel D: ATT by license group, using DID FE			
Quota acquisition $\times$ 21-27.9m	0.317***	0.292***	0.243***
	(0.047)	(0.048)	(0.052)
Quota acquisition $\times$ 15-20.9m	0.390***	0.381***	0.358***
	(0.039)	(0.039)	(0.037)
Quota acquisition $\times$ 11-14.9m	0.233***	0.225***	0.216***
	(0.028)	(0.028)	(0.027)
Panel E: pooled LATE using IV DID FE			
Quota acquisition	0.133	0.118	0.117
	(0.094)	(0.094)	(0.097)
Kleibergen-Paap rk Wald F	131.991	131.991	131.991
Panel F: LATE by license group, using IV DID FE			
Quota acquisition $\times$ 21-27.9m	0.573***	0.528***	0.351**
	(0.168)	(0.171)	(0.174)
Quota acquisition $\times$ 15-20.9m	0.915***	0.898***	0.929***
	(0.202)	(0.203)	(0.218)
Quota acquisition $\times$ 11-14.9m	-0.002	-0.013	-0.002
	(0.094)	(0.094)	(0.098)
Kleibergen-Paap rk Wald F	13.406	13.406	13.406
Observations	30,776	30,776	30,776

Note: Panels represent specifications. Columns represent dependent variables. All specifications use yearly observations and include year fixed effects, vessel fixed effects, and owner fixed effects. Panels A and B estimate ITT of the trading policy using DID specifications in regression (1). Panels C and D estimate ATT of quota acquisition using DID with fixed effects specifications in regression (2). Panels E and F estimate ATT of quota acquisition using IV DID with fixed effects specification; the main regression is equation (2) but the treatment *Quota acquisition*$_{it}$ is instrumented by the policy assignment *Trade qualified*$_{it}$. Standard errors in parentheses are clustered by vessel's municipality. Significance level: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table E5: Effects of trading policy on economies of scale

	(1)	(2)	(3)
	OLS-with-FE estimator	proxy-variable estimator	dynamic panel estimator
	cost elasticity ϕ	cost elasticity ϕ	cost elasticity ϕ
Panel A: ITT (pooling all trade qualified groups)			
Trade qualified	0.005**	0.004**	0.004**
	(0.002)	(0.002)	(0.002)
Panel B: ITT by trade qualified group (license group)			
21-27.9m × From 2004	0.015**	0.012*	0.013**
	(0.007)	(0.006)	(0.006)
15-20.9m × From 2004	0.006	0.004	0.004
	(0.005)	(0.004)	(0.004)
11-14.9m × From 2008	0.003	0.003	0.002
	(0.002)	(0.002)	(0.002)
Panel C: pooled ATT using DID FE			
Quota acquisition	0.039***	0.033***	0.032***
	(0.003)	(0.003)	(0.003)
Panel D: ATT by license group, using DID FE			
Quota acquisition × 21-27.9m	0.075***	0.062***	0.061***
	(0.008)	(0.007)	(0.007)
Quota acquisition × 15-20.9m	0.040***	0.034***	0.032***
	(0.007)	(0.006)	(0.005)
Quota acquisition × 11-14.9m	0.029***	0.025***	0.023***
	(0.004)	(0.003)	(0.003)
Panel E: pooled LATE using IV DID FE			
Quota acquisition	0.023**	0.019**	0.018**
	(0.010)	(0.008)	(0.008)
Kleibergen-Paap rk Wald F	131.991	131.991	131.991
Panel F: LATE by license group, using IV DID FE			
Quota acquisition × 21-27.9m	0.062**	0.048**	0.051**
	(0.027)	(0.023)	(0.023)
Quota acquisition × 15-20.9m	0.038	0.028	0.026
	(0.031)	(0.027)	(0.025)
Quota acquisition × 11-14.9m	0.018**	0.015*	0.014*
	(0.009)	(0.008)	(0.007)
Kleibergen-Paap rk Wald F	13.406	13.406	13.406
Observations	30,776	30,776	30,776

Note: Panels represent specifications. Columns represent dependent variables. All specifications use yearly observations and include year fixed effects, vessel fixed effects, and owner fixed effects. Panels A and B estimate ITT of the trading policy: $Y_{it} = \beta_{ITT} \textit{Trade Qualified}_{it} + \eta_i + \tau_t + \epsilon_{it}$. Panels C and D estimate ATT of quota acquisition: $Y_{it} = \beta_{ATT} \textit{Quota Acquisition}_{it} + \eta_i + \tau_t + \epsilon_{it}$. Panels E and F estimate ATT of quota acquisition using IV DID with fixed effects specification: the treatment $\textit{Quota acquisition}_{it}$ is instrumented by the policy assignment $\textit{Trade qualified}_{it}$. Standard errors in parentheses are clustered by vessel's municipality. Significance level: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

F Economies of scale vs. cost shifting

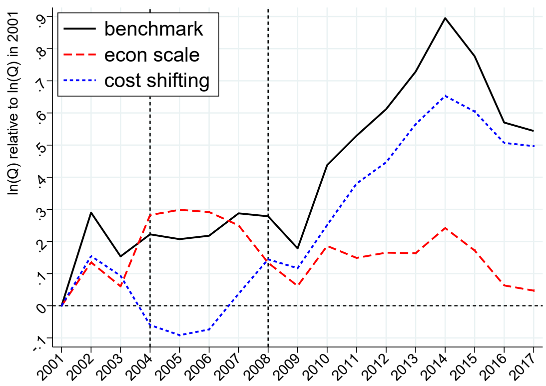
Table F6: Decomposition of change in output (thousand tonnes)

	(1) 2001–2014	(2) 2001–2004	(3) 2004–2007	(4) 2008–2011	(5) 2011–2014
Panel A: Licensed 0–10.9m					
Total	36.1	3.5	2.8	8.4	22.9
econ scale	8.0	4.3	-0.5	1.0	6.8
cost shifting	28.0	-0.8	3.3	7.3	16.1
Panel B: Licensed 11–14.9m					
Total	89.2	7.3	4.9	26.1	49.1
econ scale	15.3	8.4	0.2	3.6	7.9
cost shifting	73.9	-1.1	4.7	22.5	41.2
Panel C: Licensed 15–20.9m					
Total	280.0	8.6	17.6	73.4	158.9
econ scale	91.1	14.0	8.1	16.7	55.0
cost shifting	188.9	-5.4	9.5	56.7	103.9
Panel D: Licensed 21–27.9m					
Total	403.5	13.4	37.1	94.6	238.4
econ scale	221.8	12.1	26.2	52.7	143.9
cost shifting	181.7	1.3	10.9	41.8	94.6

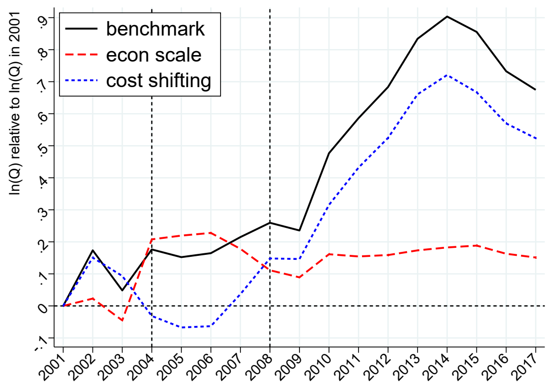
Table F7: Decomposition of change in $\ln(Q)$

	(1) 2001–2014	(2) 2001–2004	(3) 2004–2007	(4) 2008–2011	(5) 2011–2014
Panel A: Licensed 0–10.9m					
Total	0.90	0.22	0.07	0.25	0.37
econ scale	0.24	0.28	-0.03	0.01	0.10
cost shifting	0.66	-0.05	0.09	0.24	0.27
Panel B: Licensed 11–14.9m					
Total	0.90	0.18	0.04	0.33	0.32
econ scale	0.21	0.22	-0.03	0.05	0.04
cost shifting	0.69	-0.05	0.07	0.27	0.28
Panel C: Licensed 15–20.9m					
Total	1.26	0.11	0.14	0.43	0.42
econ scale	0.51	0.18	0.05	0.13	0.17
cost shifting	0.75	-0.07	0.10	0.29	0.24
Panel D: Licensed 21–27.9m					
Total	1.21	0.15	0.23	0.38	0.40
econ scale	0.64	0.15	0.20	0.20	0.22
cost shifting	0.57	0.00	0.03	0.18	0.17

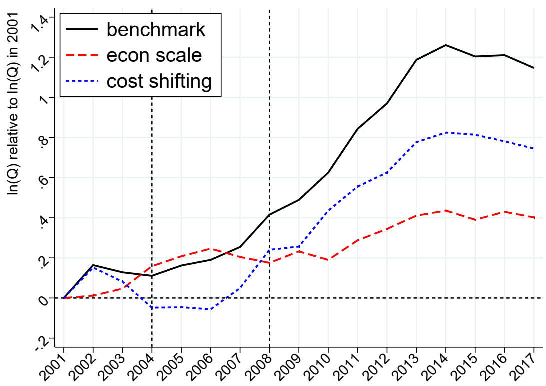
(a) licensed length 0–10.9m



(b) licensed length 11–14.9m



(c) licensed length 15–20.9m



(d) licensed length 21–27.9m

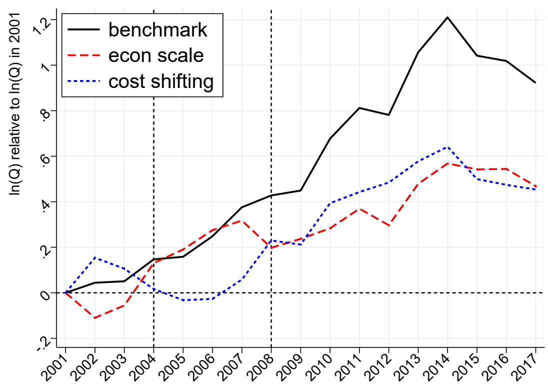
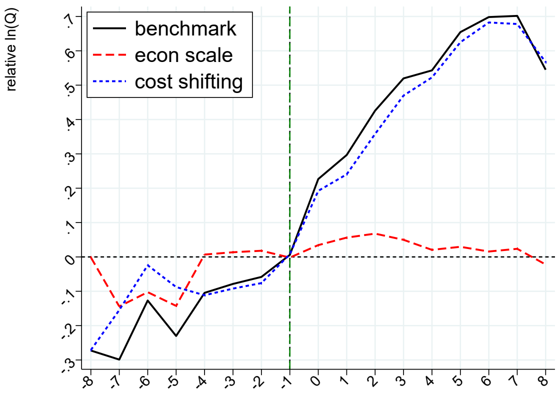


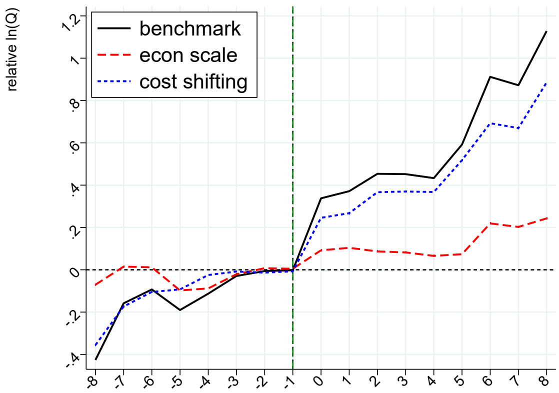
Figure F16: Decomposition of change in $\ln Q_{it}$ (logged thousand tonnes) by year

Note: The figure plots the change in output within a vessel from 2001 to each year. The average change number for each year is weighted by the vessel share of group catch.

(a) licensed length 11–14.9m



(b) licensed length 15–20.9m



(c) licensed length 21–27.9m

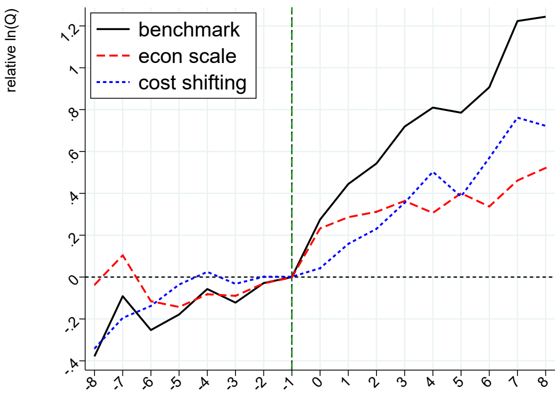


Figure F17: Decomposition of change in $\ln Q_{it}$ (thousand tonnes) by years from the first time a vessel acquires traded quotas

Note: The figure plots the change in output within a vessel over years. All changes are relative to the year when a vessel acquires traded quotas in its first time.