Redistribution in Environmental Permit Markets: Transfers and Efficiency Costs with Trade Restrictions

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Abstract

Regulators often impose trade restrictions in environmental permit markets to redistribute value to groups that do not directly benefit from permit trade, such as labor in regulated firms, at the expense of lowering gains from trade. I evaluate the efficiency and distributional impacts of two common trade restrictions in Iceland's fisheries permit market: segmented trading by firm size and individual production requirements. Using detailed harvest and permit trading data linked to administrative records on worker employment and earnings, I conduct a difference-in-differences analysis showing that permit trade increases the harvest share of productive boats by 15 percentage points, shifts income from lower- to higher-income workers, and reduces aggregate labor intensity by 12%. I further demonstrate that the trade restrictions, designed to counteract these labor impacts, are binding and lower productivity. To quantify the distinct trade-offs from each restriction, I develop a model of fishery production and permit trading to simulate profits, labor demand, and worker earnings in equilibria without the restrictions. Per dollar of foregone profit, segmentation increases labor demand 20 times more than the production requirement, while the production requirement redistributes 14% more income to low-income workers than segmentation. Implementing both restrictions outperforms the production requirement alone and is preferable to segmentation alone if regulators aim to balance job creation with a compressed income distribution.

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1 Introduction

Environmental permit markets are widely used to manage commons like air, water, lands, and fisheries.[1] Their appeal lies in achieving abatement or production targets at minimum cost by setting an aggregate cap, allocating permits, and allowing producers to trade them (Crocker 1966; Dales 1968). However, policymakers often have goals beyond cost-effectiveness, such as job protection or reducing income and environmental disparities. Unrestricted trading can undermine these objectives. While the sale of initial permit allocations provides lump-sum transfers (Montgomery 1972), these benefits mainly accrue to firm owners, limiting their potential to address redistributive concerns involving workers or local communities. These concerns can even drive policymakers to avoid environmental markets altogether (Grainger and Parker 2013; Newell, Pizer, and Raimi 2014; Ryan and Sudarshan 2024).

When regulators do adopt market-based policies, they often restrict permit trading to prevent production changes and to meet redistributive goals. Two common designs are to segment permit markets by producer characteristics like size or to require producers to use rather than sell a fraction of their allocated permits. Such limits are common in permit markets in fisheries (Kroetz, Sanchirico and Lew 2015; Ho 2023), wetlands banking (Aronoff and Rafey 2024), water (Gillig et al. 2005; Hagerty 2023), and air pollutants (Fowlie and Perloff 2013; Burtraw and Roy 2023; Shapiro and Walker 2024). Trade restrictions in pollution markets may prevent undue pollution exposure in marginalized communities. In resource settings, trade restrictions can benefit labor by increasing jobs (labor demand) or the preventing the concentration of earnings in higher-paying firms. These benefits are important if workers cannot recover earnings elsewhere or shift to more productive firms and if there is a desire to preserve a "way of life" in the commons.[2]

What are the efficiency and distributional consequences of trading limits in permit markets? Answering this question requires understanding how segmentation and production requirements affect equilibrium permit prices and corresponding production choices. First, I present a stylized theoretical framework to demonstrate profit and production ef-

[1]Roughly a fifth of global greenhouse gas emissions are covered by emissions trading schemes (World Bank, 2024). Emissions trading has been central in policies like the U.S. Clean Air Act Amendments (Schmalensee and Stavins 2019; Shapiro and Walker 2023), and about a third of fisheries operate under tradable catch share regimes (Costello et al. 2016). Payments-for-ecosystem-services programs account for around $40 billion in annual transactions globally (Salzman et al. 2014).

[2]For example, Congress passed a six-year moratorium on permit trading in America's fisheries due to the "challenge...to maintain employment and a cherished way of life in fishing communities" (NAAS 1999).

fects of these regulations. Segmentation creates distinct permit prices across market segments, while the production requirement rotates the supply curve, lowering trade gains. Answering the question also requires mapping production choices to the redistributive outcomes of interest to the regulator, in my case labor demand and worker earnings. I therefore must know how firm owners and labor split the returns from harvesting different quantities. With equilibrium production changes, profit functions, and linkages to worker outcomes, I can evaluate the cost of redistribution: the foregone profits against increased labor demand and earnings to low-income workers, in markets with trade restrictions versus ones without them.

These efficiency-distributional trade-offs are central to environmental market design, where policies often impose trade restrictions to mitigate losses among adversely affected groups. I explore these trade-offs in the context of Iceland's fisheries permit market, one of the world's oldest and largest in harvest terms. Permits to harvest fish are freely allocated, but firms are restricted from selling more than half their allocation (*the production requirement*). In addition, the cap on total harvests is spit between small and big boats, with no trading allowed between them (*segmentation*). The intended gains are more jobs and shifts in earnings to groups that otherwise lose out from permit trade. The production requirement supports crews on boats that might otherwise sell most of their permits, while segmentation protects small-boat crews and by preventing permit sales to larger boats. These groups can be distinct depending on the permit allocations, average incomes of workers on the boats, and how profitability relates to size.

The setting provides detailed data to assess permit trading impacts through the market's staggered expansion. I combine data on daily harvests, boats, and prices; regulatory data on permit trades and allocations; and administrative records of workers' employment and earnings histories. Observing daily harvests and permit transactions reveals productivity heterogeneity while linking permit holdings to harvests and profits. Fixed crew sizes and observed revenue-sharing schemes enable mapping production choices to labor demand (person-days) and earnings.

I analyze the expansion of permit trading to small boats to assess its impact on productivity, labor demand, and income redistribution. Before 2001, small boats could not trade permits; afterward, they could trade in a segmented market with some medium-sized boats, while large boats were already in a permit market. A difference-in-differences analysis comparing small boats entering trading in 2001 to large boats already trading reveals gains from trade: boats with above-median harvests per person-day gained 15 percentage points in harvest share from less productive boats, relative to the initial permit allocation. However, as higher-productivity boats are less labor-intensive, aggregate labor demand fell by 12%. Among workers who remain in fishing, permit trading redistributed earnings from low- to high-income workers, increasing income dispersion. Low-productivity boats, which pay lower wages, lost harvests, widening the earnings gap between low- and high-income fishery workers by 25%. These effects are amplified in this setting because crew wages are tied to harvest revenue through bargaining agreements, and workers do not offset lost earnings with income outside the fishery.

Next, I examine the efficiency impacts of the two trading limits. The production requirement binds, with 16% of firm-years bunching just above 50% of their permit allocation. Bunching firms have 10% lower average daily harvests than nearby non-bunching firms, indicating increased production on labor-intensive, low-earning boats. For permit market segmentation, I find that permit prices are 30% lower on average in the small-boat market, leading to higher aggregate harvests among small boats, which are labor-intensive and have lower-income workers, than in a unified market.

The reduced-form analyses provide evidence of gains from trade, redistributive impacts, and effects of trade restrictions. Quantifying efficiency costs and isolating the impact of each restriction requires counterfactual market equilibria: how permit prices and corresponding permit choices, earnings, and labor demand change without the production requirement or market segmentation. To achieve this, I develop a joint model of permit trading and production decisions that links permit choices to prices and profits, aggregating them to construct permit supply and demand curves. Earnings are tied to permit choices through revenue-sharing regimes, and labor demand is determined by the days needed to harvest the permit amount and the fixed crew size.

In the model, boats vary in profitability based on observable traits. After trading permits, they face daily cost shocks and select the highest-profit days to meet their permit quantity. Each boat's permit quantity, meanwhile, is where marginal profits equal the permit's shadow cost (permit price plus transaction costs). However, they must also harvest at least half their permit allocation. Gains from trade arise from differences in marginal profits and in permit allocations. A portion of harvest revenue goes to labor earnings and the remainder to boat owners, who also take the gains or losses from permit trade.

There are two objectives in estimating the model. The first is to estimate the permit choice function and its relationship to profits. This requires the parameters of the daily cost shock distribution and the transaction cost function. Choices of days with varying revenue identifies the variation in daily cost shocks, while the optimality condition on permit choice identifies mean daily costs. I estimate transaction costs by relating permit allocations to permit choices, conditional on boat characteristics. Due to the lack of an analytical solution for the day choice likelihood, I use the method of simulated moments (Pakes 1986) to estimate these parameters and construct the permit choice and profit functions. The second objective is to link permit choices to labor demand and earnings. Fixed crew sizes, labor earnings tied to harvest revenue, and worker-firm connections enable estimation of labor demand (person-days) and earnings in relation to harvest revenue. These relationships are then held fixed in alternative market designs.

I can then isolate the effect of each trade restriction by simulating counterfactual market equilibria with the estimated profit and permit choice functions. Without the production requirement, boats make an unconstrained permit choice. Without segmented markets, all boats face the same permit price. I search for the new equilibrium permit price (or prices if the market is segmented) that clears the counterfactual market at the aggregate permit supply found in the data. Differences in total profits between the market equilibrium and production at each permit allocation gives the gains from trade. The gains from the market with restrictions are still considerable, increasing aggregate profits by 12% above a benchmark where boats are forced to harvest their permit allocation.

Comparing markets with each restriction to a simulated market without the trade restrictions, I find that segmentation reduces gains from trade by only 5% across all years despite 30% differences in permit price, as permit supply and demand are inelastic (the marginal profit curves of small boats are very flat). In equilibrium, the production requirement imposes a greater constraint on production, destroys more gainful trades, and lowers gains from trade by 15%.

The policies have distinct benefits. Market segmentation increases labor demand. It shifts production to smaller, more labor-intensive boats, increasing labor demand by about one person-day for every thousand dollars of foregone profit, compared to a market without trade restrictions. This effect is 20 times greater per dollar than that of the production requirement. Smaller boats are on average much more labor-intensive than the high net sellers whose harvest increase under the production requirement.

The production requirement is more effective at redistributing income, raising incomes for bottom-quintile workers by 14% more per dollar of foregone profit when compared to segmentation. The difference stems from segmentation benefiting small-boat workers, who are higher in the income distribution than those on boats selling much of their allocation. However, these restrictions are a costly form of redistribution: transferring a dollar from the top to the bottom half of the fishery income distribution via the production requirement costs $6.19, nearly four times the cost of redistribution through the US tax code (Hendren 2020) and also higher than other regulatory tools like electricity pricing (Borenstein 2011). In addition, the redistribution is to low-income fishery workers, who are still relatively high in Iceland's income distribution when working on fishing boats.

The rationale for these trade restrictions is less about efficient redistribution and more about ensuring fisheries provide equitable employment opportunities, preserving a threatened "way of life." Combining the two trade restrictions outperforms the production requirement alone, increasing labor demand more while achieving similar redistribution to low-income workers per dollar of foregone profit. This approach also shifts costs, transferring losses from low-profit small-boat owners to the highest-profit boat owners, who are net buyers in the permit market and face reduced profits as permit prices rise. If job creation were prioritized over equity, segmentation alone might suffice. However, combining the policies allows regulators to balance labor demand and income redistribution, supporting both job creation and higher incomes for low-income fishery workers.

Related literature. This paper's main contribution is to assess trade-offs in different permit market designs when regulators have redistributive aims for groups that do not benefit from permit trade. I focus on two common design choices: segmentation of permit markets and individual trade restrictions.

I motivate my modeling approach with reduced-form evidence of reallocation from the staggered introduction of permit trading, as assessed in air pollution (Greenstone et al. 2022; Colmer et al. 2024) and fisheries (Costello, Gaines, and Lynham 2008; Lee and Thunberg 2013, 2019; Reimer et al. 2014; Isaksen and Richter 2018; Ardini and Lee 2018).[3] I build on research estimating costs through structural models of firm choices (Carlson et al. 2000; Ellerman et al. 2000; Borenstein et al. 2002; Keohane 2006; Chan 2015) and

[3]For details on changes in fisheries production as the permit market was introduced, see Arnason (1996; 2005; 2012), Mathiasson and Agnarsson (2010), and Agnarsson, Matthiasson, and Giry (2016), and other cites therein.

compliance costs inferred from permit prices under firm conduct assumptions (Fowlie, Knittel, and Wolfram 2012; Deschenes, Greenstone, and Shapiro 2017; Shapiro and Walker 2021). Productivity gains from tradeable permit schemes have been studied in fisheries (Ho 2022; Reimer et al. 2022), though most work evaluates overall impacts of permit trading rather than trade-offs inherent in market design choices.

The project also complements work investigating sources of inefficiency in environmental markets (Hahn 1984; Fowlie 2010; Hahn and Stavins 2011; Regnacq, Dinar, and Hanak 2016; Hagerty, 2023; Aronoff and Rafey 2024), the impact and value of design choices like banking or permit allocation rules (Fowlie and Perloff 2014; Toyama 2024), and the functioning of environmental markets using aggregate variables (Joskow, Schmalensee, and Bailey 1998; Newell et al 2005; Arnason, 2005). A smaller set of research focuses on the production and price impacts of the segmentation and production restrictions at the center of my analysis (Kroetz, Sanchirico, and Lew 2015; Burtraw and Roy 2023).

In highlighting heterogeneous impacts across firms and workers, the project contributes to a large literature on the distributional impacts of environmental damages and regulation (e.g. Hernandez-Cortes and Meng 2023; Hsiang, Oliva, and Walker 2015; Grainger and Parker 2013; Grainger and Costello 2015). Of particular relevance are papers on the impact to jobs and earnings from air pollution regulation (Greenstone 2002; Walker 2013) and the energy transition (Colmer et al 2023). This work highlights the kinds of distributional concerns that often motivate less efficient policies (Ryan and Sudarshan 2023). In my case, the policies create alternative permit market equilibria, akin to a recent literature assessing market designs based on outcomes relevant to policymakers, not just notions of allocative efficiency (Agarwal, Hodgson, and Somaini 2020; Aspelund and Russo 2023).

This project contributes to the literature on the production and efficiency impacts of regulatory design. Researchers have studied firm responses to regulations based on region, age, size, or sector, estimating implicit taxes from these designs (Becker and Henderson 2000; Gao et al. 2009; Bushnell and Wolfram 2012; Fowlie, Knittel, and Wolfram 2012; Garicano et al. 2016; Fowlie and Reguant 2022; Ito and Sallee 2018; Costello and Grainger 2022). My paper extends these analyses by quantifying and comparing trade-offs in regulatory design, evaluating efficiency costs and gains to targeted groups, similar to the literature on the marginal value of public funds (Hendren 2016; Hendren and Sprung-Keyser 2020) and redistribution costs in block electricity pricing (Feldstein 1972; Borenstein 2012) or small business set-asides (Athey, Coey, and Levin 2012; Nakabayashi 2013).

2 Framework

I present a modeling framework to analyze how trading limits impact the gains from permit trading and other production outcomes of interest to the regulator. I first consider a simple, deterministic setting where firms choose permits directly given heterogeneous profit functions to consider the efficiency impacts of the permit market design.

2.1 Set-up

There exist a set of firms i with characteristics $\mathbf{z}_i$ and choose a quantity q_i to extract from a commons and receive profits $\Pi(q_i, \mathbf{z}_i)$. Profits are smooth and concave in production q_i.

I first show graphically the efficiency consequences of trading limits in a permit market. A regulator has determined that aggregate production should not exceed $\bar{Q}$. Let $\bar{q}_i$ be the allocation of permits to firm i, such that $\sum_i \bar{q}_i = \bar{Q}$. Permits can be traded in a market with permit price r.

Assuming firms take prices as given and will harvest all post-trade permits, firms solve the following maximization problem:

$$\max_{q_i} \Pi(q_i, \mathbf{z}_i) + r(\bar{q}_i - q_i) \tag{1}$$

The solution to which defines firm i's **permit choice function**:

$$\frac{\partial}{\partial q_i}\Pi(q_i, \mathbf{z}_i) = r \implies q(r, \mathbf{z}_i) \tag{2}$$

which is decreasing in r when marginal profits are decreasing in q_i. I will later extend this to allow for dependence on allocation $\bar{q}_i$ due to transaction frictions.

Next, define firm i's **net permit position** x to be its individual permit choice relative to its permit allocation:

$$x(r, \mathbf{z}_i, \bar{q}_i) = \bar{q}_i - q(r, \mathbf{z}_i) \tag{3}$$

where $q(r, \mathbf{z}_i)$ is defined as in (2). It is increasing in r. A firm is a permit seller if $x(r, \mathbf{z}_i, \bar{q}_i) > 0$ and a permit buyer if $x(r, \mathbf{z}_i, \bar{q}_i) < 0$.

Let **aggregate permit supply** be the total excess permits among sellers:

$$\mathcal{S}(r) = E[x(r, \mathbf{z}_i, \bar{q}_i)|x(r, \mathbf{z}_i, \bar{q}_i) > 0] \cdot \Pr(x(r, \mathbf{z}_i, \bar{q}_i) > 0) \tag{4}$$

which is increasing in r.

Let **aggregate permit demand** be the over-production among buyers:

$$\mathcal{D}(r) = -E[x(r, \mathbf{z}_i, \bar{q}_i)|x(r, \mathbf{z}_i, \bar{q}_i) < 0] \cdot \Pr(x(r, \mathbf{z}_i, \bar{q}_i) < 0) \tag{5}$$

which is decreasing in r.

2.2 Graphical analysis of gains from permit trade and trading restrictions

I analyze the gains from trade graphically, aggregating firm decisions to characterize the competitive equilibrium in the permit market. The permit price in competitive equilibrium is defined by market-clearing:

$$\sum_i q(r, \mathbf{z}_i) = \bar{Q} \iff \mathcal{S}(r) = \mathcal{D}(r) \tag{6}$$

Figure 1(a) graphs a permit market equilibrium. On the x-axis is permit quantity, which is limited by the aggregate permits $\bar{Q}$.[4] The equilibrium permit price is r^*, which equalizes aggregate permit demand and aggregate permit supply: $D(r^*) = \mathcal{S}(r^*)$. The equilibrium quantity Q^* is the total number of permits traded in equilibrium. The remaining permits $\bar{Q} - Q^*$ are harvested from the firm's allocations.

The gains from permit trade are the familiar area between the aggregate demand and supply curves (area OAB). These two curves depend not only on heterogeneity in the marginal value of production among firms—i.e. heterogeneity by characteristics $\mathbf{z}_i$ in firm's production choices $q(r, \mathbf{z}_i)$ at a given permit price—but also on heterogeneity in the initial permit allocations $\bar{q}_i$. While the friction-less, competitive market equilibrium will implement the profit-maximizing allocation independently of the initial allocation (Coase 1960; Montgomery 1972), the *gains from trade* in the permit market are the difference be-

[4] Aggregate supply $\mathcal{S}(r)$ and aggregate demand $\mathcal{D}(r)$ do not necessarily cross the x-axis at the origin and $\bar{Q}$, respectively, because firms can be allocated more permits than would maximize $\Pi(q, \mathbf{z}_i)$; it depends on the permit allocation across firms i.

tween the aggregate profits at the market equilibrium and if each firm harvested only their initial allocation. Therefore the gains from trade depend on the heterogeneity in the profitability of firms by characteristics $\mathbf{z}_i$ and on how much the initial permit allocation differs from the profit-maximizing one.[5]

A regulator's goal might not be to maximize aggregate profits in the commons. I consider two interventions in real-world permit markets: requiring a level of production and segmenting permit markets.[6]

Production requirements. A regulator might be concerned with the presence of producers who create few production profits $\Pi(q, \mathbf{z}_i)$ and trade away most of their freely allocated permits. This could be because of an animosity to purely financial players or because regulators value a particular distribution of production inputs like labor across firms. Shifting permit allocations might not be politically feasible and would only change returns from permit trading without affecting the allocation of production. Instead the regulator enforce a possibly firm-specific trade limit: firm i must produce at least $\underline{q}_i$, usually a fraction of the permit allocation. There is a ceiling on each firm's net permit position, i.e.

$$\tilde{x}(r, \mathbf{z}_i, \bar{q}_i) = \min\{x(r, \mathbf{z}_i, \bar{q}_i), \bar{q}_i - \underline{q}_i\} \tag{7}$$

A harvest requirement constrains aggregate permit supply.[7] Firms that would otherwise sell permits into the market are forced to produce and sell nothing. The restriction binds on more firms as permit prices increase and the incentive to sell grows. Therefore the restriction rotates the aggregate supply function $\mathcal{S}(r)$ up and counter-clockwise. Figure 1(b) visualizes this rotation, which prevents some gainful trades (the efficiency loss is area ACD) but raises the share of harvests out of permit allocations (i.e. reducing aggregate trade Q^*). It also reduces seller surplus (area CDE) by reducing total profits to the net sellers who are forced to harvest more—and increase their harvest profits, the aim of the

[5]The extreme case is when the regulator replicates the profit-maximizing allocation in the initial allocation of permits. Then there are no gains from trade.

[6]Trade limits need not lower efficiency; many times, segmentation is an attempt to better match the shadow marginal cost, as reflected in the permit price, to the social marginal damages, without considering differing welfare weights. Hot spots in local air pollution is a canonical example (Montgomery 1972; Mendelsohn and Muller 2009; Fowlie, Walker, and Wooley 2020). Heterogeneous benefits of land, like in wetlands, is another example (Aronoff and Rafey 2023).

[7]The harvest requirement could affect aggregate permit demand if delineated in absolute quantities, rather than relative to a permit allocation. In practice, these rules are usually relative to some fraction of the allocation.

regulation—and trade less.

The size of the efficiency loss depends on how much aggregate permit supply is constrained by the policy (e.g. how many firms would choose to sell most permits) but also on the slopes of the aggregate permit supply and demand curves. These depend on the profit functions of the firms as well as the distribution of permit allocations.

Segmentation. A regulator might want to ensure that firms of some characteristic such as size or region produce some share of the aggregate production $\bar{Q}$. Therefore the aggregate cap is split into two markets, such that $\bar{Q}_1 + \bar{Q}_2 = \bar{Q}$. Each firm is assigned to market 1 or 2 by their characteristics $\mathbf{z}_i$, with no trade allowed between them. This ensures a specific type of production can exist, e.g. production by small firms or an even distribution across regions. While each firm's optimization problem (1) and therefore the permit choice function $q(r, \mathbf{z}_i)$ has not changed, the permit markets now clear according to the separate caps $\bar{Q}_1$ and $\bar{Q}_2$. The equilibrium permit prices r_1 and r_2 in the segmented markets will in general differ from the market-clearing price r^* in the unified market.[8]

Figure 2 shows the aggregate demand and supply curves in each permit market and the new equilibria in the two markets; it is isomorphic to a simple model of international trade across two countries. Here, market 1 consists of firms that would sell permits in aggregate in a unified market, i.e. $\sum_i x(r^*, \mathbf{z}_i | i \text{ in market } 1) > 0$. Instead, those permits are harvested among the firms in market 1, with permit transactions clearing at a lower value (point C). Ensuring higher harvests increases the harvest profits in market 1 (the aim of the restriction) but does not leave the firms in market 1 better off in aggregate; they have lost the gains from trading to the firms in market 2 whose profits are higher on the margin. Those losses are area ABC in Figure 1(c). Likewise, firms in market 2 lose out on gainful harvest (area DEF). Again, the size of these losses depend on the differences in aggregate permit supply and demand in each market, which depends not only on differences in harvest profit functions but also differences in individual permit allocations.

[8] If the regulator sets caps at exactly the production shares between the two groups of firms reflected in the profit-maximizing allocation, then the permit prices in the two markets will be equal to each other and equal to the price in the unified market (the shadow marginal cost of production under the aggregate cap).

2.3 Empirical goal

The graphical analysis clarifies how to evaluate the costs of limits in a permit market, relative to the outcomes that regulators were trying to impact with the limits.

Estimating efficiency losses. Estimating the cost (the foregone profits) of permit trading limits requires the aggregate permit supply and demand curves under each limit and with the limits removed. The determinants of these curves, in turn, are the permit choice functions $q(r, \mathbf{z}_i)$ and the initial permit allocations $\bar{q}_i$ for each firm i. The individual choices and allocations are necessary to aggregate excess demand and supply under different permit prices and find market equilibria under alternative designs.

Estimating outcomes of interest. The costs should be evaluated against improvements in the outcome of interest for the regulator. That is, the permit market and production behaviors must be assessed jointly: one must understand how outcomes change as permit choices change in each firm. These outcomes are highly specific to each setting. In my setting, they are the following:

1. The **production requirement** increased demand for labor at each firm. To assess this, I require each firm's **labor demand function** $\ell(q(r, \mathbf{z}_i), \mathbf{z}_i)$. This is a component of the profit function $\Pi(q_i, \mathbf{z}_i)$. Regulators might also be interested in the **wage bill**, i.e. total labor earnings. Let $w(q_i, \mathbf{z}_i)$ be the total earnings to workers in firm i with characteristics $\mathbf{z}_i$ and quantities q_i.

2. **Segmentation** increased *production* profits among a particular class of firms, like small-scale producers or particular regions. Note that it did not aim to increase total profits, since segmentation destroys gains from trade. Therefore I require the **production profits** of the protected class, i.e. $\sum_i \Pi(q(r, \mathbf{z}_i), \mathbf{z}_i)$ for i in the protected market.

In summary, the empirical model must relate production profits and labor demand to permit choices and recover the permit choice function for each firm. The former requires information on output prices and a model of production decisions in the commons to estimate functions of production profit and labor demand. The latter requires a model of trading behavior in the permit market. Each component must take account of important features of production and permit trading in the setting, such as input choices under uncertain production and additional trading frictions. In describing the setting and data, I will highlight these features and their implications for the empirical model.

3 Data and Setting

I now describe the setting and data, which inform my assessment of the distributional consequences of permit trading and how I will implement the framework empirically.

3.1 Fisheries

Fisheries production. My setting is Iceland's groundfish fishery, the major fishery in Iceland.[9] Many details of the fishing harvesting technology are observed directly, a key advantage for researchers. Boats are the large piece of fixed capital, outfitted with different mixes of fishing gear designed to catch different species. Usually boats are observed with only one or two types of gear in a year. Throughout the year, boat captains make decisions of when to go out fishing, searching for areas where large harvests are likely. On all boats except trawlers, trips usually range only one day or maybe two. During this period, almost all harvests for most boats occurred from Icelandic waters and were landed in Icelandic ports. About 30% of boats are in fleets owned by single firms, a fraction that does not change throughout the consolidation over the decades I consider. Almost all processed fish is exported. I assume that boats are price-takers from a global market for fish products.

Labor in fishing production. In fisheries, labor supply decisions are straightforward: each boat has a few key roles, from the captain or first mate to deckhands. Crew numbers range from 2-3 on the smallest boats to a few dozen on the largest bottom trawlers. In Iceland, all crews are paid out of shares of harvest revenue with a minimum monthly salary that rarely binds. The shares are determined in negotiations between the unions for crew-members of different ranks and the associations of boat-owners.[10] The shares vary depending on boat size and gear mix. During my period of analysis, only one major collective bargaining agreement was struck, in 1998, which did not change until after 2008.

In general, these agreements create a tight link between harvest revenue and labor earn-

[9]Groundfish or demersal fisheries are those that target bottom-dwellers like cod and haddock. The other major fishery targets migrating schools neither near the shore nor the ocean floor like herring, capelin, and mackerel (pelagic fisheries).The groundfish or demersal fishery is responsible for about 75% of total revenue.

[10]A fraction of harvest revenue goes right to boat owners as a function of oil prices and then the remainder is split according to a formula between the boat owner and the crew. The crew share is then split into "pieces" where higher-ranked positions get multiples.

ings, a link I can observe directly in data. Throughout the analysis of alternative permit market designs, I take the wage bill-revenue relationship as given.[11]

3.2 Iceland's permit market

The permit market in Iceland's fisheries is one of the largest and oldest permit markets in the fisheries, covering virtually all commercial species.

History. Key dates on the introduction and expansion of the permit market for groundfish, and the years on which I focus in this paper, are included in Figure 3.[12] In 1991, large vessels were allowed to trade their permits, beginning Iceland's now 30-year experience with market-based fisheries management. Small boats faced non-tradeable cod permits before being added into a permit market in 2001.

Details of the permit market. Boat owners are allocated harvesting rights as shares of aggregate harvest in each species (*total allowable catch*). These shares were initially determined by catch history. Each year around May, the government approves of the level of these caps for the new regulatory year beginning in September, based on recommendations from the country's Marine Resource Institute, converting shares into actual quantities in tons of fish.[13] Permits are freely allocated to boats, and permits can only be owned by boat-owners. Both these permanent shares and the permits each year can be sold to other boats, though in practice the permanent shares are mostly sold upon the exit of a firm. The rental market for permits, however, is large: in any year, about 10-20% of harvests are made using permits purchased from another boat. Permit trades are cleared via brokers, often retired fishermen. The permit market allows for some permits to be exchanged across species and some shifting across years. Arnason (2005) and Gretarsson (2008) review the history of the Icelandic permit market.

Harvest requirement. The permit market includes a strict limit on trading: boats are allowed to trade only half their annual permit allocation each year. The harvest requirement responded to concerns from government ministers and labor union representatives that

[11] Given this remuneration structure, I assume that captains, who often are responsible for daily fishing decisions, are aligned with the objective of boat-owners in maximizing harvest revenue for every day of fishing.

[12] Regulation of pelagic fisheries—species like herring, capelin, and mackerel that move in schools in the middle of the ocean–follows a different timeline and regulatory structure.

[13] Caps are usually set at the estimated "maximum sustainable yield" with carve-outs for unregulated boats in years before small boats were in their own market.

boat owners might stay in the fishery but sell most or all of their freely allocated permits.[14] With little actual harvest, labor demand and earnings would fall on those boats. Firms with fleets, however, are permitted to allocate permits freely across their own boats.[15]

The creation of a segmented market. Small vessels (below 6 GRT) were given non-tradeable cod production permits but were otherwise allowed to harvest. In 2001, regulators placed the small boats in their own, segmented permit market.[16] Medium-sized boats (up to 15 GRT) were moved from the large- to the small-boat market a year later. The separate market was directly in response to organizing by small-boat owner associations and concerns that a culturally important and "accessible" form of fishing would be wiped out by permit trading. The small- and large-boat permit market operated according to the same rules about trading limits and allocations, with the aggregate cap split between each market. The small-boat permit market receives about 10-15% of the total allowable catch in the years I study. While in practice large boat permits can be traded to small boats (not vice versa), inter-market trades are limited and mostly within the few firms that have both small and large boats.[17]

3.3 Data

A major advantage of the Icelandic setting is the ability to link detailed production data to information about the earnings and employments of workers in the commons. I have collected detailed fisheries data from a variety of sources and combined it with tax and pay-slip data on Icelandic workers. Appendix Section B summarizes the sources in more detail.

[14]The "zombie boat" concern is not unfounded. Numerous US fisheries have documented empty boats owned by investors solely to participate in permit trading (NOAA Fisheries, 2018).

[15]There are other regulatory limits to trading. For example, firms are required to seek approval for trades across regions of the country from local labor unions. In practice, these trades are usually approved. There are also limits to permit ownership; in particular, a firm can only own 15% of a given species. The largest firms hold about 5-10% of permits in cod-equivalents. Giry et al (2015) describe evidence of common ownership across large fishing firms beyond these ownership limits, but I do not observe those linkages.

[16]Boat size is measured in gross tons (GT) or, later, gross register tons (GRT). Both are closely related and standard measures of volume. When they conflict, regulators took the minimum of both measures before focusing only on GRT after 2001 in accordance with international agreements.

[17]Small boats undertaking seasonal fishing in the summer continued to operate under day restrictions throughout this period until most were placed in the permit market in 2004; they mostly discontinued fishing until a coastal fishing program was introduced in 2008. They represent less than 2% of total annual revenue at their peak and so I do not consider them here. I focus on commercial fishing boats that fish year-round.

Data on boat harvests. Icelandic regulatory agencies collect extensive data on fishing boats and fishing behavior. I obtain data on every landing of fish, i.e. every instance that a boat brings fish to shore, for all registered Icelandic vessels. For trawlers that take multi-day trips, I use a log-book dataset that registers harvests for each day at sea (whether landed or not). The log-book dataset also includes information on crew sizes. Lastly, I obtain fish price data as averages of species-region-gear-month bins.[18]

Data on boats and crews. I obtain data on detailed characteristics of boats like engine power, measures of size, and the year of production. I also obtain the ownership history of each vessel while in Iceland. Vessel IDs are assigned at first registration and remains the same even if ownership changes. Lastly, I obtain the crew registry that logs every individual who works on a fishing vessel by day, personal ID, and position, though only covering a subset of boats.

Data on permit market trades and prices. I obtain data on all permit transfers between fishing boats and permit allocations across all species. I also obtain information on permit rental prices for all regulated species, available as monthly averages starting in 1992 and daily from mid-2000.[19] Lastly, the harvest requirement binds at the level of "cod-equivalent" units, where regulators create exchange rates between species to aggregate permit allocations and to allow for species exchanges. I collect these yearly species exchange rates.

Linking to administrative data on workers. The most unique element of the Icelandic setting is the ability to link the production data to information about workers, whether in fisheries or not. Iceland has maintained detailed demographic, earnings, and employment information from pay-slips, tax returns, and census records. I have received the entire employment and earnings history of all workers ever flagged as working on a fishing boat from 1981 to 2021. Because earnings on fishing boats had their own tax deductions, anyone who worked on a fishing boat can be flagged in the administrative datasets, allowing me to fill in for years where the crew registry is not comprehensive. I also received a random cross-section each year of 10% of workers who were never flagged as working in the fisheries. The tax and pay-slip data has IDs for all firms at which the worker filed earnings in the year, which I matched to the boat ownership files in order to flag the kind

[18]The price data reports bins from competitive fish auctions as well as those from direct purchases by fish processors. In my time period I do not see a statistically meaningful difference in the prices within bins.

[19]I thank Asgeir Danielsson and Olgeir Kristinsson for sharing older permit price information, collected from interviews with permit brokers by the Central Bank.

of boat the worker was likely to work on.[20] Much of this data was digitized by Sigurdsson (2024). More details on how I linked the production and administrative data are available in Appendix Section B.

3.4 Summary Statistics

Table 1 presents summary statistics on Iceland's fisheries and workers, across three years:the first year of my analysis (1997), the first year small boats could trade permits with medium boats (2002), and the last year I consider (2012).[21]

Generally, the time period was characterized by substantial consolidation. The number of firms and workers fell.[22] The nature of fishing production is also changing: the share of the fleet on small boats is falling, and their share of harvests is falling even more precipitously. Meanwhile, the harvest share of trawlers is about the same and falling slightly; other medium- and large-sized boats are taking on more fishery harvests. Total revenue is rising, with a large spike in 2012 due to a wave of mackerel and capelin that migrated to Iceland in this time.

Workers on fishing boats, meanwhile, are overwhelmingly male and less educated and younger than the average working Icelander. The share of foreign-born workers in Iceland and particularly on fishing boats is rising quickly in this period, from being almost negligible in the 1990s. They are also much likelier to be outside Iceland's capital region—Reykjavík is the country's only major urban center—though the region and nearby towns are major fishing ports in their own right. Importantly, fishery workers are high-earning; the average fishery worker makes almost twice the national average in a given year. Small-boat workers, meanwhile, are at the mean income distribution among non-fishery workers. There is a large pool of workers only loosely attached to the fisheries. A considerable share of fishing workers have sources of income outside the fishery; in particular, about 43% of small-boat workers have less than 90% of their earnings in fishing in each year. In addition, many workers spend only a small share of their working life in the fisheries, though this is concentrated on young men who work on trawlers for a short time before moving to other education or work.

[20] For firms with fleets, I assign firms to be small- or large-boat according to the smallest boat in the fleet. In practice, few firms have both large and small boats.

[21] While my data extends to 2020, I end the analysis at 2012 as the size threshold for segmenting the two markets shifted upward starting 2013.

[22] There was also a large vessel buy-back program in place in the mid-1990s targeted at small boats though not only eligible to them (Agnarsson 2001).

4 Evidence on Permit Market's Impact and Designs

In this section, I will give evidence of gains from trade from the introduction of permit trading to small boats. I then will investigate the efficiency consequences of the two designs: the segmented market and the harvest limitation.

4.1 Impact of introduction of permit trading

Production impacts: shift to more productive boats. The introduction of permit trade among small boats provides an empirical opportunity to isolate the impact of permit trade itself. For a few years before 2001, small-boat firms operated under non-tradable cod quotas, the major species they caught. When in the permit market, these cod permit allocations remained the same but could be traded, alongside the additional species that became regulated.

I therefore begin by dividing the boats in the small-boat permit market at the median catch per man-day each year, find the share of permits allocated to above- and below-median boats in 2000 (the final year before trading), and calculate the difference between the permit allocation share and the share of final harvest These trends are plotted in Figure 4(a). Before 2001, the differences are not exactly zero because non-cod species are not regulated and medium-sized boats (6-15 GT) were in the large-boat permit market at this time.

After 2001, however, the share grows substantially: the more productive boats have almost 20 percentage points more of the harvest than they did of the permits in 2000. production exactly in the direction economic theory would expect: toward boats that harvest more for every unit labor.

How much did permit trading affect the overall labor intensity of fisheries production among these boats? Figure 4(b) plots the average man-days per ton of harvest (the inverse of the productivity measure used in sub-figure a) across years in red. It then also plots the implied average labor intensity if boats are re-weighted using their 2000 allocation share. This isolates the change in aggregate labor intensity due to changes in the harvest shares to boats of varying productivity, versus changes in productivity itself. The difference between the two measures grows over time, in line with the growing change in harvests relative to the pre-market allocation shares. Figure 4(c) shows the relative difference over time. By 2006, the shift in production due to permit trade caused average labor intensity to fall by about 12%. Permit trading made fisheries less labor intensive and reduced aggregate labor demand for every unit of harvest.

Labor impacts: winners and losers. Production became less labor intensive over time after the introduction of permit trade. Labor demand therefore fell. However, regulators are also concerned with the distribution of fishery income, and the changes in harvests documented in Figure 4 would directly impact the earnings of fishery workers. I therefore next compare outcomes of workers on small boats in 2001 to their large-boat counterparts, and correlate subsequent outcomes to the labor intensity of their boat in 2000. Namely, if y_{it} is earnings or employment of worker i in year t, I run the following regression:

$$\begin{aligned}\ln y_{it} = &\alpha + \phi_t + \gamma \cdot \mathbf{1}(\text{in small boat in 2000}) + \\ &+ \sum_{t \neq 2000} \delta_t \cdot \mathbf{1}(\text{in small boat in 2000}) + X_{it}'\beta + \epsilon_{it}\end{aligned}$$

where the coefficient of interest is δ_t: how outcomes change differentially among less labor-intensive boats within each permit market. Controls X_{it} are birth cohort fixed effects. I then run a "triple-differences" specification, comparing average outcomes for boats beneath and above the median harvest per person-day in 2000 to average outcomes overall among large boats.

Figure 5(a) plots δ_t for the preferred specification with birth-cohort fixed effects. Notably, among workers in fisheries in 2000, there is not a discernible effect on average on total earnings. In fact, there is not a statistically meaningful difference in the earnings outcomes among workers on less- and more-intensive boats in any given year. The average earnings difference is falling in the period before permit trading, and average earnings rise in the period after. This impact accounts for the large fraction of workers who exit the fishery every year.

However, permit trading could still make incomes less equal among those who remain or enter the fishery after 2000. I therefore investigate the sample of fishery workers each year. Figure 5(b) shows the difference in average earnings between workers on high- and low-productivity boats each year, relative to earnings of large-boat workers that were always in permit trading. Here, one can see the divergence in earnings that follows due to the shift in harvest revenue from low- to high-productivity boats. Earnings differences grow about 30% between the two groups, with low-productivity workers falling relative to 2000 while workers on high-productivity boats maintain similar earnings differences to their large-boat counterparts. The exception is the first year after permit trading is introduced; in this year, medium sized boats (who make up most of the above-median productivity boats) had yet to be put into the large-boat permit market.

Panels A and B of Table 2 summarizes a series of additional outcomes around the permit market expansion in 2001, among workers who were on small boats in 2000. Small boat workers are likelier to exit the fishery, but they were also likelier to do so in the 1990s; likewise, a smaller share of earnings comes from fishing boats. On average across years, there is a clear gradient in the earnings consequences by the labor intensity of small boats. Those with higher harvests per person-day saw higher earnings and were likelier to remain in the fisheries after 2000 than those on boats with lower catch per person-day. Workers seem able to recuperate earnings in other jobs outside the fishery, though a full accounting should compare cumulative non-fishery income to cumulative fishery income.

It is clear that those who do remain on small boats, however, along with those that later join small vessels, do lose out relative to counterparts who were on small boats in the 1990s. Panels C and D of Table 2 focuses on the cross-section of fishery workers each year. It shows that the average earnings difference widened considerably in the years after 2001, widening by 1.0 million ISK from 2.8 million ISK in 2000 (panel C). The change was concentrated in boats with lower catch per man-day (panel D). In the 1990s, the average earnings difference was about 0.5 million ISK smaller than in 2000.

What do these changing earnings trends imply for the distribution of income from the commons? Table 3 shows some statistics on income and demographic characteristics for the three groups tracked in this reduced-form analysis. Before permit trading, workers on the low-productivity boats are relatively low-income compared to their counterparts, on average falling at the 37th percentile of fishery income. Therefore their falling earnings relative to workers on high-productivity boats implies redistribution from low- to higher-income workers due to permit trading. However, fishing is a high-earning job: even workers on low-productivity boats are on average in the upper half of the country's income distribution in 2000.[23]

Considerable churn in the fishery labor market, plus the notable changes in earnings differences across different fishing boats, suggests that different types of workers are ending

[23]This compares fishery workers each year to the country's income distribution; it could be that fishery workers have relatively low lifetime incomes, with much income earned in the years they are fishing.

up on low-productivity boats after permit trade. Table 3 shows that there are considerable changes in the demographics of fishery workers in the 2000s. Workers on low-productivity boats become older on average, while the average age of high-productivity boat workers falls. The foreign share grows considerably across both productivity groups, with growth of foreign workers in fisheries outpacing the overall growth in foreign-born workers in the Icelandic labor market during this period. However, the foreign share was already higher among low-productivity boats in 2000, and the relative increase is higher among high-productivity boats. Low-productivity boats are also likelier to be in the capital city region, Iceland's only urban area, so permit trading acts to shift fishery income out to rural workers. There are not meaningful differences in the share of income that comes from fishing across different groups.

4.2 Consequence of designs

Despite evidence of a shift to production on more productive boats, the permit market is designed to limit gains from trade, by requiring half the permit allocation to be harvested and segmenting the market between large and small boats. I next show evidence of the efficiency impacts of these designs.

Harvest requirement. Boats in the permit market were not permitted to trade more than half their permit allocation. Figure 6(a) shows a histogram of permit holdings post-trade relative to the permit allocations across all firm-years. There is clear evidence of bunching right above the regulatory threshold of 50%.[24] For this to have an efficiency consequence, boats right above the threshold would need to take more days at sea to reach the regulatory threshold, relative to other boats right around the thresholds. Sub-figure (b) then narrows in around the 50% threshold and produces average catch per day for boats at these thresholds, with the histogram from sub-figure (a) for reference. Boats at the bunching mass have lower catch per day than those right above or those right below, clear evidence that the harvest requirement binds to force some boats to harvest more than they otherwise would. Because earnings are directly tied to harvest revenue, this regulation has the effect of increasing earnings for the workers on the boats.

Segmented markets. The debates around the small boats centered around an interest in protecting small-scale fishing. Figure 7(a) confirms that small boats catch less per day:

[24]The 8% of firm-years below 50% almost all exit in the next year, indicating either the punishment is that severe, or they planned to exit anyway.

the average harvest per man-day in the small-boat market is about two-thirds that in the large-boat market. This alone is not evidence of inefficiency, which is about differences in the marginal shadow cost of each permit market. The prevailing marginal shadow cost can be read from the permit rental prices in each market: if caps for species are overly generous to the small-boat market, permits in that market will trade at a discount relative to large-boat permits.

Therefore I compare permit prices from all transactions within the same species for the 10 years after the introduction of the permit market:

$$\ln(\text{Permit price of transaction } i \text{ in year } t) = \alpha + \beta \cdot \mathbf{1}(\text{small-boat market}) \tag{8}$$
$$+ \text{Species-year fixed effect} + \epsilon_{it} \tag{9}$$

where the coefficient of interest is β: the average relative difference between the permit price across all transactions, within each species-year permit market.[25] Figure 7(b) shows the results of the exercise each year. In most years, small-boat permits trade at a considerable discount of 20% to 30% relative to the big-boat permits, though I cannot reject that the permit prices are equivalent in 2006 and 2007. This indicates that in most years, the regulator allocates more aggregate harvests to the small permit market than would prevail in a unified market. Combined with the fact in Figure 6(a), the design therefore induces more labor use at the expense of some profits.

4.3 Discussion

This section has provided evidence of gains from trade in the permit market, consequences to workers, and the efficiency consequences of designs to limit permit trading. Permit trading induces harvests to shift to producers who can harvest more using fewer inputs. It lowers overall labor demand in the commons while also shifting earnings from the commons from lower- to higher-income workers. Regulators attempted to ameliorate these impacts by limiting permit trading for each boat and segmenting markets. There is evidence that the limits bind on boats, forcing more harvests on more labor-intensive boats.

To quantify the exact degree to which the limits shift production and increase earnings to targeted workers requires simulating alternative market equilibria under designs where

[25] I ignore the species exchange provisions, where boats can shift a fraction of (mostly cod) permits into other species according to fixed exchange rates.

the harvest requirement did not bind and the permit market was unified. As the framework in Section 2 makes clear, the efficiency consequences—comparing gains from trade in the current market to the less restricted one—require the actual and counterfactual permit choice functions, with which I can construct the excesss permit supply and demand curves. One must then be able to link the permit choices to the production outcomes of interest to the regulator: the harvest profits on small boats and earnings on the boats constrained by the harvest requirement.

I therefore extend the stylized framework in Section 1 to capture some of the salient features of fisheries production and the Icelandic permit market.

5 Model

I develop a joint model of fisheries production and permit trading. The model elaborates on the firm's problem in Section 2 to capture additional transaction frictions beyond the regulatory limits and capture important elements of production in the fisheries. Together, they show how I evaluate efficiency and production consequences at the time of permit allocation before harvests, costs, and trading friction shocks are realized.

5.1 A model of permit trade

The model focuses on each year separately, with an aggregate cap of permits $\bar{Q}$, split between two markets where relevant.

Boats. Each fishing boat is indexed by i. They are differentiated in their profit function $\Pi(q_i, \mathbf{z}_i)$, which maps permit quantity q_i to profits according to observable characteristics $\mathbf{z}_i$ and in their permit allocations $\bar{q}_i$. Characteristics include the gear mix available on each boat, boat size and region. While fisheries harvests consist of many species under separate permits, I consider permit quantity along one dimension, in line with the units by which the production requirement binds. In some years, boats receive non-tradeable permits; in that case, $q_i = \bar{q}_i$ and their profits are $\Pi(\bar{q}_i, \mathbf{z}_i)$. Boats in permit markets make a choice of how many permits to hold. I consider each boat i's optimization problem separately, i.e. I do not account for joint optimization of permit or fishing decisions in fleets. This is an important simplification as fleet owners can trade permits costlessly across their boats.

Regulations and other trading frictions. Before any production decisions are made, boats in the permit market choose permits to hold for the year. As described in the framework, I extend the simple maximization problem in (1) in Section 2 to account for the two regulated limits to trading:

1. The production requirement: boats are required to hold half their permit allocation. That is, they must hold at least $\underline{q}_i = \bar{q}_i/2$.

2. Segmentation: the permit price for each boat is a function of its size $z_i \in \mathbf{z}_i$. In particular, there is a threshold $\bar{z}$ determining the relevant permit market.

$$r_i = \begin{cases} r_1 & \text{if } z_i \leq \bar{z} \\ r_2 & \text{if } z_i > \bar{z} \end{cases} \tag{10}$$

I make two remaining adjustments in response to empirical facts about permit trade in my setting, such that boats with similar characteristics $\mathbf{z}_i$ might differ in permit choices. The Icelandic permit market lacks a centralized exchange and clearly defined trading periods within the year; boats use brokers to find willing sellers and buyers as the year progresses. Figure 3 shows clear evidence of bunching around the permit allocation, which indicates that the marginal cost of permits grows as boats choose permits farther from their allocation.

I therefore introduce transaction costs that allow permit choice to depend on permit allocations $\bar{q}_i$: I denote the transaction cost function as $TC(\bar{q}_i - q_i)$, a smooth, convex, and increasing in transaction volume $|\bar{q}_i - q_i|$. The costs need not be symmetric around $\bar{q}_i$: transaction costs can differ for buyers and sellers.

I assume that remaining variation in permit choice q_i for boats of similar characteristics $\mathbf{z}_i$ and permit allocations $\bar{q}_i$ comes from an idiosyncratic shock to the marginal cost of a permit Δ_i, drawn from a distribution F_Δ. This boat-level shock does not impact harvest profits. It summarizes differences in permit choices that affect the value of permits beyond the profitability of boats. The Δ_i shock can allow the effective marginal cost of a permit to fall below the equilibrium price.[26]

[26]Because I assume boats are price-takers in the permit market, I do not allow for market power which would introduce additional mark-ups. While permit holdings have consolidated over time in Iceland as in other fishery permit markets (Giry et al 2015), the largest firms own less than 10% of the permits in any year, and there are many market participants. I therefore do not consider permit market power a first-order concern in the setting.

Permit choices. With the addition of trading frictions, the interpretation of the equilibrium changes slightly relative to the deterministic set-up in Section 2. I want to consider a regulator assessing the value of the commons at the time of permit allocation, which I assume occurs before trading. I therefore want to think about the efficiency impacts before the trading friction shock is realized. Each boat receives its permit allocation $\bar{q}_i$, observes the market-clearing price r_i and receives the permit cost shock Δ_i. The boat the maximizes total profits under the production restriction:

$$\max_{q_i} \Pi(q_i, \mathbf{z}_i) + r_i \cdot \Delta_i \cdot (\bar{q}_i - q_i) - TC(\bar{q}_i - q_i) \text{ subject to } q_i \geq \bar{q}_i/2 \tag{11}$$

First, consider the unconstrained solution via the first-order condition, which implicitly defines the unconstrained permit choice function:

$$\frac{\partial}{\partial q_i}\Pi(q_i, \mathbf{z}_i) - \frac{\partial}{\partial q_i}TC(\bar{q}_i - q_i) = r_i \cdot \Delta_i \implies q(r_i, \mathbf{z}_i, \bar{q}_i, \Delta_i) \tag{12}$$

I then consider the permit choice function averaged over the Δ_i shock, meaning that permit choice functions are the same for boats with the same observable characteristics and permit allocation:

$$q(r_i, \mathbf{z}_i, \bar{q}_i) = E_\Delta[q(r_i, \mathbf{z}_i, \bar{q}_i, \Delta_i)] \tag{13}$$

The production requirement leads to an additional constraint, which also depends on the initial allocation. This characterizes the actual permit choice function, i.e. the solution to (11):

$$\tilde{q}(r_i, \mathbf{z}_i, \bar{q}_i) = \begin{cases} \bar{q}_i/2 & \text{if } q(r_i, \mathbf{z}_i, \bar{q}_i) \leq \bar{q}_i/2 \\ q(r_i, \mathbf{z}_i, \bar{q}_i) & \text{if } q(r_i, \mathbf{z}_i, \bar{q}_i) > \bar{q}_i/2 \end{cases} \tag{14}$$

Let the net permit position under a harvest requirement be

$$\tilde{x}(r_i, \mathbf{z}_i, \bar{q}_i) = \bar{q}_i - \tilde{q}(r_i, \mathbf{z}_i, \bar{q}_i, \Delta_i) \tag{15}$$

Market equilibrium. The aggregate demand and supply curves are market-specific. They are the excess permits among net sellers and excess production among net buyers, among participants in each market. For the small-boat market,

$$S_1(r) = E[\tilde{x}(r_i, \mathbf{z}_i, \bar{q}_i) | \tilde{x}(r_i, \mathbf{z}_i, \bar{q}_i) > 0, z_i \leq \bar{z}] \cdot \Pr(\tilde{x}(r_i, \mathbf{z}_i, \bar{q}_i) > 0, z_i \leq \bar{z}) \tag{16}$$

$$D_1(r) = -E[\tilde{x}(r_i, \mathbf{z}_i, \bar{q}_i) | \tilde{x}(r_i, \mathbf{z}_i, \bar{q}_i) < 0, z_i \leq \bar{z}] \cdot \Pr(\tilde{x}(r_i, \mathbf{z}_i, \bar{q}_i) < 0, z_i \leq \bar{z}) \tag{17}$$

and analogously for the large-boat market but conditioning on $z_i > \bar{z}$.

For each boat i in permit market n, the equilibrium condition then is the permit price r_n^* that equates ex-ante supply with ex-ante demand:

$$\sum_{i \in n} q(r_i, \mathbf{z}_i, \bar{q}_i) = \bar{Q}_n \iff S_n(r_n^*) = D_n(r_n^*) \tag{18}$$

The market equilibrium is then the set of permit decisions at the equilibrium price in the market:

$$\tilde{q}(r_n^*, \mathbf{z}_i, \bar{q}_i), \forall i \in n \tag{19}$$

The efficiency metric is the aggregate profits from the expected permit allocation:

$$\sum_i \Pi(\tilde{q}(r_i^*, \mathbf{z}_i, \bar{q}_i)], \mathbf{z}_i) \tag{20}$$

which is the profits for each boat under the expected permit allocation at the equilibrium price. In years in which some boats are given non-tradeable permits, the profits are measured at the allocated permits.

Alternative designs and equilibria. The framework in Section 2 shows that one can characterize the efficiency impacts of the permit trading rules by using the permit choice functions of firms and constructing new supply and demand functions. In particular,

1. The production requirement: solve for each boat's expected net permit position using the unconstrained permit choice function:

$$x(r_i, \mathbf{z}_i, \bar{q}_i) = \bar{q}_i - q(r_i, \mathbf{z}_i, \bar{q}_i) \tag{21}$$

   and construct the ex-ante supply and demand curves in (16) and (17) but using $x(r_i, \mathbf{z}_i, \bar{q}_i)$. Find the new equilibrium in each market where ex-ante supply and ex-ante demand meet.

2. Segmentation: find the sum of the supply and demand curves of each market n, weighted by the population in the market, i.e.

$$\mathcal{S}(r) = \sum_n S_n(r) \text{ and } D(r) = \sum_n D_n(r) \tag{22}$$

and the new equilibrium r^* is characterized by the intersection of total excess supply and demand: $\mathcal{S}(r^*) = D(r^*)$.

The two can be combined, where one constructs the total supply and demand curves using the unconstrained permit choice function.

5.2 A model of fishery production

I now turn to the construction of the profit function $\Pi(q_i, \mathbf{z}_i)$ which maps post-trade permit holdings to value. Fisheries production is characterized by choices of days at sea over uncertain harvest quantities. I outline a model of day choice where, after permit trading, boats receive shocks to the daily cost of production throughout the year and choose a harvest schedule that will allow them to harvest permits in expectation.[27]

Input choices: labor. Fisheries production is characterized by two important inputs: days at sea and the crew. The evidence suggests that, within narrowly defined categories of gear mixes throughout the year and boat size, production is Leontief in days and labor: a given production quantity requires a set number of days at sea and a number of people to serve the crew of the boat. Therefore, demand for labor (person-days) is determined in a straightforward way in this setting.

Boats of characteristics $\mathbf{z}_i$ have a defined crew size $L(\mathbf{z}_i)$. Consider a day choice function $D(q_i, \mathbf{z}_i)$ that maps permit holdings to total days at sea. **Labor demand** is the number of person-days of production, i.e. the chosen number of days at sea multiplied by the

[27] Fisheries economists have pointed to many other details of fisheries production that can determine value conditional on observable boat characteristics, including the access and use of information (Englander, 2024), congestion and the decision of where to search (Huang and Smith, 2014), and differential targeting of valuable species (Smith, 2012). There is a long literature in fisheries economics on models of location and species choice (e.g. Smith and Wilen 2003; Huang and Smith 2014; Birkenbach et al 2020). These margins carry over to the Icelandic setting; however, permit market cover boats the vary greatly in observable characteristics and behaviors and along these other margins. Because I aim to focus on the broad goals regulators bring to the design of permit markets and the link to labor supply in the fisheries, I will necessarily abstract from many particular production margins.

crew size of the boat. Therefore for given permit holdings, labor demand is

$$\ell(q_i, \mathbf{z}_i) = L(\mathbf{z}_i) \cdot D(q_i, \mathbf{z}_i) \tag{23}$$

Labor demand is therefore pinned down by the day choice $D(q_i, \mathbf{z}_i)$ to which I turn next.

Input choice: days at sea The days of the year are indexed by t with T possible days. Given permit holdings q_i, boats make a choice of days: the vector of choices is $\mathbf{d}_i$ where $d_{it} = 1$ if day t is chosen. The total number of days of production is $D(q_i) = \sum_t d_{it}$. The boat forms expectations over daily revenue and daily harvests with information set $\mathcal{I}_i$. Therefore expectations are formed for

1. The number of permits that would be harvested on a given day q_{it}. I define expected quantity for boat i on day t as $E[q_{it}|\mathcal{I}_i]$.

2. The revenue from fishing on a given day R_{it}. I define expected revenue for boat i on day t as $E[R_{it}|\mathcal{I}_i]$.

Daily revenue is not just price times permit quantity because there are unregulated species. It is the aggregate across all possible species, multiplied by the market price for each species at that time. These are the gains to fishing on day t.

The cost for i of fishing on day d is $c_{it} > 0$, which are revealed after permit trading. I assume that daily costs c_{it} are drawn independently from a distribution conditional on characteristics $\mathbf{z}_i$. Call this distribution $F_{c|\mathbf{z}}$, and the vector of cost draws $\mathbf{c}_i$.

With post-trade permit holdings q_i, boats choose the days that maximize expected profits. That is, they will choose the highest-profit days until they harvest their permit holdings in expectation. Appendix Section A outlines the day selection process formally. I denote $\mathcal{S}(q_i, \mathbf{c}_i)$ to be the set of days of highest profit until harvests equal permit holdings for a given draw of costs $\mathbf{c}_i$.

Building the profit function. In the model, permit trade occurs before costs c_{it} are realized to make day choices. The **ex-post profit function** is the profits from the chosen days, after cost shocks are revealed:

$$\tilde{\Pi}(q_i, \mathcal{I}_i, \mathbf{c}_i) = \sum_{t \in \mathcal{S}(q_i, \mathbf{c}_i)} E[R_{it}|\mathcal{I}_i] - c_{it} \tag{24}$$

and the **ex-ante profit function** takes the average across daily cost draws:

$$\Pi(q_i, \mathbf{z}_i) = \int \tilde{\Pi}(q_i, \mathcal{I}_i, \mathbf{c}_i) \cdot dF_{c|\mathbf{z}} \tag{25}$$

where I supress dependence on the information set. This is the producer surplus at the time of permit trade, before within-year shocks are realized.

5.3 Identification

I observe day choices $\mathbf{d}_i$, *realized* revenues R_{it} and quantities q_{it} on days boats did go out to fish, permit choices q_i allocations $\bar{q}_i$, boat characteristics $\mathbf{z}_i$, and day characteristics $\mathbf{z}_t$.

Revenue and quantity expectations. I specify each boat i's information set $\mathcal{I}_i$ to be the characteristics I observe $\mathbf{z}_i$ and some seasonal indicators $\mathbf{z}_t$. If forecast errors are independent of production costs, then I can identify expected revenues and quantities from regressing realized revenues and quantities on $\mathbf{z}_i$ and $\mathbf{z}_t$. Appendix A has more details.

Identifying costs with quantity constraints. The object of interest is the cost distribution $F_{c|\mathbf{z}}$, from which I can generate the ex-ante profit function. Define $F_{c|\mathbf{z}}(\mu^c(\mathbf{z}_i), \sigma^c(\mathbf{z}_i))$ as the location $\mu^c(\mathbf{z}_i)$ and scale parameters $\sigma^c(\mathbf{z}_i)$ of the cost distribution for some boat. I emphasize that these are functions of boat characteristics $\mathbf{z}_i$.

I assume that daily costs c_{it} are drawn independently from the cost distribution $F_{c|\mathbf{z}}$. If boats were not constrained to match their permit holdings q_i, $F_{c|\mathbf{z}}$ would be identified directly from the probability of fishing at different expected daily revenues; variation in expected daily revenues traces out values of the CDF of daily costs for each boat each year.

If boats will always meet a fixed quantity q_i, then optimality of day choices alone identifies only the scale parameter $\sigma^c(\mathbf{z}_i)$ of the cost distribution, not the location. The intuition is the same as in the basic static discrete choice model (Train 2009). Boats will always choose the most profitable days until they hit their quantity constraint, and only relative returns matter for the choice of particular days. To see this, consider a boat observed to choose day 1 with revenue R_1 but not day 2 with revenue R_2, where either day alone can meet the permit holdings. There is the mean daily cost $\bar{c}$ and a cost shock ϵ_t. The choice reveals that

$$R_1 - \mu^c(\mathbf{z}_i) - \epsilon_1 \geq R_2 - \mu^c(\mathbf{z}_i) - \epsilon_2 \iff \epsilon_2 - \epsilon_1 \geq R_2 - R_1$$

which gives information about $\sigma^c(\mathbf{z}_i)$ but not $\mu^c(\mathbf{z}_i)$.

Instead, the optimality of permit choices q_i for boats in the permit market reveal information about mean costs. To show this, first note that the same days will be chosen to meet a quantity goal, regardless of the mean $\mu^c(\mathbf{z}_i)$. That is, the set of chosen days $S(q_i, \mathbf{z}_i, \mathbf{c}_i)$ is the same for any $\mu^c(\mathbf{z}_i)$ and therefore can be rewritten as $S(q_i, \mathbf{z}_i, \varepsilon_i)$. The ex-ante revenue for a given quantity q_i therefore depends only on the scale parameter $\sigma^c(\mathbf{z}_i)$, as well as a portion of the production costs that varies across days. Let the vector of cost shocks $\epsilon_{it} = c_{it} - \mu^c(\mathbf{z}_i)$ (with the vector denoted as ε_i). Then I can rewrite the ex-post profits into three functions:

$$\begin{aligned}
\Pi(q_i, \mathbf{z}_i, \mathbf{c}_i) &= \sum_{t \in S(q_i, \mathbf{z}_i, \varepsilon_i)} E[R_{it}|\mathcal{I}_i] - \mu_c - \epsilon_{it} && (26)\\
&= \sum_{t \in S(q_i, \mathbf{z}_i, \varepsilon_i)} E[R_{it}|\mathcal{I}_i] - \sum_{t \in S(q_i, \mathbf{z}_i, \varepsilon_i)} \epsilon_{it} - \mu^c(\mathbf{z}_i) \cdot D(q_i, \mathbf{z}_i, \varepsilon_i) && (27)\\
&= R(q_i, \mathbf{z}_i, \epsilon_i) - c(q_i, \mathbf{z}_i, \varepsilon_i) - \mu^c(\mathbf{z}_i) \cdot D(q_i, \mathbf{z}_i, \varepsilon_i) && (28)
\end{aligned}$$

Then, ex-ante profits integrates over the possible cost shocks:

$$\Pi(q_i, \mathbf{z}_i) = R(q_i, \mathbf{z}_i) - c(q_i, \mathbf{z}_i) - \mu^c(\mathbf{z}_i) \cdot D(q_i, \mathbf{z}_i) \tag{29}$$

The three functions are invariant to changes in $\mu^c(\mathbf{z}_i)$, using similar intuition to how consumer surplus can be calculated up to a constant with logit demand functions (Train 2009).

Then, consider the unconstrained optimality condition (14), i.e. permit choice with no production restriction:

$$\begin{aligned}
\frac{\partial}{\partial q_i}\Pi(q_i, \mathbf{z}_i) &= \frac{\partial}{\partial q_i} TC(\bar{q}_i - q_i) + \Delta_i \cdot r_i && (30)\\
\iff \frac{\partial}{\partial q_i} R(q_i, \mathbf{z}_i) - \frac{\partial}{\partial q_i} c(q_i, \mathbf{z}_i) - \mu^c(\mathbf{z}_i) \cdot \frac{\partial}{\partial q_i} D(q_i, \mathbf{z}_i) &= \frac{\partial}{\partial q_i} TC(\bar{q}_i - q_i) + \Delta_i \cdot r_i && (31)
\end{aligned}$$

The transaction cost function $TC(\bar{q}_i - q_i)$ is common to all boats, and permit price r_i is observed. Therefore the mean cost is identified among boats of the same characteristics $\mathbf{z}_i$. Note that one cannot identify mean costs from the boats outside the permit market, who are given non-tradeable quotas. Instead, I will extrapolate from the permit market boats.

Identifying market parameters. The (marginal) transaction costs is a non-linear function of permit transaction volume, i.e. the magnitude between final permit holdings and the permit allocation. The permit cost shock Δ_i represents any other unobserved determinants of permit choice, e.g. search frictions. It is therefore crucial to include detailed heterogeneity in the profit functions $\Pi(q_i, \mathbf{z}_i)$ in order to rule out permit choice differences due to differences in harvest profitability.

I assume that Δ_i is independent of the permit allocation $\bar{q}_i$. The assumption rules out boat-specific heterogeneity in how permit allocations impact permit choice. For boats not at the constraint of permit holdings, the transaction cost function is identified from the variation between marginal profits and permit allocations, and any residual variation conditional on $\bar{q}_i$ identifies Δ_i.

Boats at the production constraint, meanwhile, bunch at constrains permit decisions such that a group of boats that bunch at 50% of their permit allocation. Because q_i is decreasing in Δ_i, each boat has a threshold $\bar{\Delta}_i$ that places them at 50% of their allocation:

$$\bar{\Delta}_i = \frac{1}{r_i} \cdot \left(\frac{\partial}{\partial q_i} \Pi(\bar{q}_i/2, \mathbf{z}_i) - \frac{\partial}{\partial q_i} TC(\bar{q}_i/2) \right) \tag{32}$$

$$\text{such that } \Delta_i > \bar{\Delta}_i \implies q_i = \bar{q}_i/2 \tag{33}$$

The transaction cost function and mean cost are identified from unconstrained boats, and therefore the threshold $\bar{\Delta}_i$ can be identified. The propensity to bunch at 50% of the allocation reveals the cumulative distribution function at $\bar{\Delta}_i$:

$$\Pr(q_i = \bar{q}_i/2) = 1 - F_{\Delta}(\bar{\Delta}_i) \tag{34}$$

Identifying the labor demand and labor earnings function. I lastly require two functions of interest to regulators: the relationship between labor demand and harvests and that between total labor earnings and harvest revenue. I observe crew sizes on each day L_{it}. The main determinants of crew size are size and gear choice. The latter can vary throughout the year for boats using a mix of gears (e.g. handline and gillnets). In addition, there is more heterogeneity in crew size on larger boats, conditional on flexible functions of size and gear mix. Therefore I assume that any remaining variation in crew size is independent of day choice. I can then estimate $L(\mathbf{z}_i)$ via regression of crew sizes on $\mathbf{z}_i$ and construct labor demand (person-days).

I can identify labor earnings under a similar assumption. I observe the joint distribution of annual labor earnings y_{ij} for each worker j in a *firm* and the firm's harvest revenue. Thus, the worker's boat is not observed for firms with fleets, and it is not possible to report worker's days at sea or boat because not all workers appear in the crew registry.[28] I know that earnings are paid out in shares of harvest revenue that depend on complex formula of workers' experience, the gear mix, the size of the boat, and the type of species. I therefore assume that unobserved determinants of the wage bill are independent of harvest revenue and regress the firm's wage bill on harvest revenue.

5.4 Remarks

Table 4 summarizes the parameters of interest from the model. The model allows me to estimate profitability under substantial heterogeneity of harvest technologies, different regulatory regimes that restrict quantities at the boat level. In encompassing this heterogeneity and focusing on permit market designs, I abstract from many aspects of both the production process and Iceland's permit market. For example, I ignore any optimization within fleet; about 30% of boats are in fleets where firms might shift permits costlessly across them.

Importantly, I rule out boat-specific profitability differences: permit demand is based only on ex-ante differences in profitability by observable characteristics $\mathbf{z}_i$. I then assume that any boat-level differences in marginal profits, conditional on permit price and permit allocation, are idiosyncratic in Δ_i and do not affect profits. In reality, Δ_i could reflect boat-specific differences in profitability rather than idiosyncratic shocks to the marginal value of permits.

Second, I assume a single period of trading before production shocks are revealed. In reality, trading occurs throughout the year by a search process run by brokers, followed by an opportunity to bank permits into the next year, pull them up, or exchange different species up to a limit.[29] I assume that these balancing schemes are only used to meet the realized harvest shocks. In addition, there is some evidence of price dispersion throughout the year, though 92% of the permit price variation across transactions is across years

[28] It is vanishingly rare for workers to work in multiple boats within the same firm, in years when all boats register all crews in the crew registry after 2011. Workers do sometimes report earnings from multiple fishing firms, but this is observable.

[29] Up to 15% of permits can be banked into the next year. Up to 5% of permits can be pulled from the next year. Permits for cod can be exchanged for permits of other species, but not vice versa, up to a certain fraction of initial allocation.

rather than within them.[30]

I place permit trading first and only once in order to capture the consequence of the harvest requirement in a straightforward static framework. Placing permit trading throughout the year or at the end would requirement before production would require taking account of a boat's evolving expectations of its permit status and/or explicitly modeling the banking decision in order to generate an equilibrium, end-of-year permit price. I avoid the computational complexity of this dynamic decision in my static framework but do not allow for gains from trade from stochastic production within the year. That said, I capture a lion's share of the heterogeneity in production: regressing annual harvests on the characteristics $\mathbf{z}_i$ I use to determine profits (year-gear mix-size) gives an R^2 of 96%.

I also assume a static day choice decision and therefore do not consider price uncertainty within the year or updates as harvest shocks are revealed. Day choices, too, might depend on past harvests or species targeting; any decision that deviates from choosing the highest expected revenue days would be rationalized by high cost draws.

Lastly, I do not consider exit decisions by firms or changes to boats in response to different counterfactual designs. These are important production decisions during my study period: there is a significant drop in firms throughout the period and particularly after their boats are placed in the permit market. Boats sell their permanent rights to permits upon exit. In addition, there is evidence of bunching beneath the size threshold defining small boats (i.e. at 6 GT and then at 15 GT once all boats are in the permit market). I hold the boat size distribution fixed everywhere, but changes to boat size could be an important margin of efficiency gains in a unified permit market, for example.

5.5 Estimation

Estimation proceeds in steps following from the identification argument. I first estimate expected daily revenue and quantities as an input into the estimation of a parametric daily cost distribution. These allow me to form the ex-ante profit functions and estimate the determinants of permit demand.

First step: estimate expected daily revenue and quantities. I assume that the information sets $\mathcal{I}_i$ with which boats form expectations include characteristics $\mathbf{z}_i$ (size, age,

[30] See Appendix Section A.4 for a discussion of price dispersion

region) and monthly indicators $m(d)$. I can then estimate daily expected quantities and revenues by linear regression:

$$\ln q_{id} = \alpha_q + \mathbf{z}_i' \cdot \beta_q + \phi_R^{m(d)} + \xi_i^q \tag{35}$$

$$\ln R_{id} = \alpha_R + \mathbf{z}_i' \cdot \beta_R + \phi_R^{m(d)} + \xi_i^q \tag{36}$$

where $\mathbf{z}_i$ includes the logarithm of boat size and the region of the boat's home port, and $\phi^{m(d)}$ represent month fixed effects. I then exponentiate predicted values from these regressions to give estimated expected harvests and revenues.

Daily harvests q_{id} are measured in cod-equivalent units, where I aggregate expected landings each day according to the species exchange rates determined by regulation. The values then reflect how many permits need to be harvested by i in each day t. Daily revenue measures are formed by aggregating revenues for all species, whether regulated or not. In the model, permit holdings should match expected aggregate harvests, since boats choose days to match their post-trade permit holdings. The model-derived expected harvests scales with observed permit holdings on average, but the model-derived values are on average 9% higher. This reflects the fact that actual permit trading in the data occurs dynamically throughout the year as harvests are realized and that boats are able to bank permits. It might also

Second step: estimate daily cost distribution from day choices. With expected daily revenues and quantities, I can turn to the day choices to estimate the daily cost distribution $F_{c|\mathbf{z}}$. In this step, I estimate both the mean and variance of the cost draws. Conditioning on the permit choice q_i, I allow boats only to pick among positive-profit days. The condition that all chosen days have positive profits is an implication of the optimality of permit choice q_i and identifies mean costs.

I parameterize the daily cost distribution $F_{c|\mathbf{z}}$ as log-normal with location parameter $\mu(\mathbf{z}_i)$ and scale parameter $\sigma(\mathbf{z}_i)$. In particular, they are gear-mix-specific functions of boat size. If g is the gear mix of the boat, then

$$\mu(\mathbf{z}_i) = \alpha_1^g + \alpha_2^g \cdot \log(\text{boat size}) \tag{37}$$

$$\sigma(\mathbf{z}_i) = \alpha_3^g + \alpha_4^g \cdot \log(\text{boat size}) \tag{38}$$

There are six gear mixes g, so each year has 24 parameters. The probability of choosing a day at sea is the probability that the day is among the most profitable days up until the boat reaches its permit holdings q_i and that those days are all of positive profits. This does not have an analytical solution, and simulating choice probabilities for each day is computationally burdensome. I therefore estimate the cost parameters by the method of simulated moments (Pakes 1986; McFadden 1989). I use the observed ranked order of daily revenues and the aggregate number of days as moments. The steps are available in Appendix Section C.

Third step: calculate the profit function. With estimates of the cost parameters, I can integrate over the estimated cost distribution $\hat{F}_{c|\mathbf{z}}$, for any quantity goal q_i and boat characteristics $\mathbf{z}_i$. I also create the ex-ante day choice function $D(q_i, \mathbf{z}_i)$, i.e. the expected number of days before cost shocks are realized, to estimate labor demand. I calculate the profit function across a grid of possible permit holdings q_i and boat sizes by simulating from the estimated cost distributions for a boat of characteristics $\mathbf{z}_i$. The steps are available in Appendix Section C.

Fourth step: estimate market parameters. With the profit function $\Pi(q_i, \mathbf{z}_i)$, I can estimate the transaction cost function $TC(\bar{q}_i - q_i)$ and the distribution of permit cost shocks F_Δ. Following Toyama (2024), I assume the following functional form for the transaction cost function:

$$TC(\bar{q}_i - q_i) = \frac{1}{1+\eta} \exp(\alpha + \beta \cdot \mathbf{1}(q_i < \bar{q}_i)) \cdot \mathbf{1}(q_i < \bar{q}_i) \cdot |\bar{q}_i - q_i|^{1+\eta} \tag{39}$$

which is smooth at $q = \bar{q}$. I allow for level differences in the transaction costs for buyers and sellers β. The marginal transaction cost is therefore

$$\frac{\partial}{\partial q_i} TC(\bar{q}_i - q_i) = \text{sgn}(\bar{q}_i - q_i) \cdot \exp(\alpha + \beta \cdot \mathbf{1}(q_i < \bar{q}_i)) \cdot |\bar{q}_i - q_i|^{\eta} \tag{40}$$

where $\text{sgn}(\bar{q}_i - q_i)$ is the sign function for the net permit position, such that it is positive for sellers and negative for buyers. The three parameters (α, β, η) define the transaction cost function. I parameterize F_Δ as a log-normal distribution with location parameter μ_Δ and σ_Δ and estimate the parameters via maximum likelihood. Away from the bunching threshold, Δ_i is point-identified. The likelihood contribution of the firms bunching at 50% of their permit allocation is the probability of being above the threshold $\bar{\Delta}$. Appendix Section C outlines the steps in detail.

Labor demand. Given the independence assumption on the unobserved determinants of crew size, I regress crew sizes on gear mix g-specific functions of log size, for each year:

$$L_{it} = \alpha + \phi^g + \beta^g \cdot \ln(\text{Boat size}) + \epsilon_{it}^L \tag{41}$$

The predicted values of this regression is $L(\mathbf{z}_i)$. I then scale the day choice function to find the ex-ante labor demand for each boat i:

$$\ell(q_i, \mathbf{z}_i) = L(\mathbf{z}_i) \cdot D(q_i, \mathbf{z}_i) \tag{42}$$

I also estimate the ex-ante wage bill function via a regression of wage bill w_i on single-boat firms, where I can condition flexibly on $\mathbf{z}_i$:

$$w_i = \alpha + \phi^g + \beta^g \cdot \ln(\text{Boat size}_i) + (\gamma + \phi^g + \delta^g \cdot \ln(\text{Boat size}_i)) \cdot R_i + \epsilon_i^R \tag{43}$$

which relies on variation in total harvest revenue R_i conditional on boat size and gear mix. The predicted values then give the ex-ante wage bill $w(q_i, \mathbf{z}_i)$.

5.6 Results

I estimate parameters for each year from 1999 to 2003.

Cost parameters. Panel A of Table 5 shows estimates of average cost (total estimated cost per kg output) aside the average revenue for different boat characteristics. Generally, larger boats have higher costs, though the average cost per unit output is lower, reflecting well-known scale economies in fisheries production (Ho 2023). It also shows that the mean annual cost of boats across the 7 gear types for three years, compared to mean annual revenue; costs are much lower, an indication of the low variable costs in fishing. However, the average profit per kg (revenue minus costs) varies considerably by gear mix. That is, shifting production can be valuable for lower daily costs to harvest but also because the quality (ISK per kg) of the output might be higher. Generally, costs are much higher for trawlers, though this might in part reflect a bias from taking multi-day trips.

Market parameters. Panel B of Table 5 shows estimates for the market parameters for three of the years. First the distribution of Δ is very wide and not centered at 1, indicating wide dispersion in marginal profits unexplained by distance from the permit allocation or permit rental price. Further refinements of the profit function estimation could ameliorate some of this residual. Appendix Section C.5 has details on model fit. The model is able to fit observed permit holdings very closely, despite vastly simplifying the actual permit trading behavior that occurs throughout the year, except for boats with the lowest permit holdings and allocations. I also systematically under-predict permit holdings among small boats, indicating that it might be important to allow for variation in transaction costs or the Δ_i distribution by boat characteristic.

Labor. Table 5 shows the results of regressing the total wage bill on harvest revenue at the firm level. The time period is from 1996 through 2007, covering my period of focus and the period of the major collective bargaining agreement determining crew shares. Year fixed effects control for fuel price changes, which do impact the share given to labor. I include specifications with and without firm fixed effects; meaningful differences with firm fixed effects could indicate important unobserved variation in the revenue-sharing function. Specification (2) with firm fixed effects relies on across-year variation in revenues within the same firm. The predicted values from both regressions give estimates of the labor share of revenue between 21% and 39% (the 10-90 range). A back-of-the-envelope calculation from the shares in the collective bargaining agreements indicates that about a third of harvest revenues go to crews, roughly in line with these values. Harvest revenues absorb considerable variation in the wage bill across firms, though about 10% remains unexplained. This might be due to provisions for higher shares for workers with more experience on some types of boats, variation within the year in fuel prices causing changes in shares, payouts of minimum earnings if a certain harvest revenue is not reached, or variation in the number of ranked positions (engineer, first mate) that receive extra shares.

6 The Value of Permit Trading and Counterfactual Designs

With estimates of profit functions and the market parameters in hand, I can simulate permit choice functions and estimate the gains from trade in the permit market. I can also consider market equilibria under alternative designs that remove the trading limits. This will generate new permit choices and therefore change the production outcomes of interest to the regulator.

6.1 Computing counterfactual permit prices and supply and demand curves

The estimated parameters allow me to construct individual permit choice functions for all boats i in every permit market with and without the harvest requirement and under any permit price. I assess the following counterfactuals:

1. No harvest requirement: Remove the bunching at 50%, in both big- and small-boat markets.

2. Unified market: place all boats in one market starting in 2001.

3. Both a unified market and no harvest requirement

From these permit choices, I can construct the aggregate permit supply and demand curves underpinning the welfare analysis in the framework I outline. Specifically, I calculate permit choices for all boats in each market under a grid of permit prices. I then take the difference with the permit allocation to find whether the boat has excess demand (more permits demanded than allocated) or excess supply (fewer permits demanded than allocated) at that permit price. I then sum the excess demand and excess supply among all boats in the permit market.

I use a simple algorithm to search for the precise equilibrium permit price in the alternative markets. For each candidate price, I calculate each boat's expected permit choice, sum them to find the aggregate permit holdings, and shift to a new candidate in the direction that will allow the market to clear, i.e. for the aggregate permit holdings (i.e. the total allowable catch) to match the aggregate amount in the data each year. The steps are described in Appendix Section D. The alternative permit choices can be directly mapped to labor demand and the wage bill using the estimated relationships. Harvest profits, too, can be calculated.

6.2 Designs' impact on gains from trade

Figure 8 shows empirical analogues of the stylized graphical framework for a particular year. Other years can be found in Appendix Section D. In 8(a), I show the equilibrium under the actual permit market design: segmented markets under a harvest requirement. The small-boat permit market (in red) has a much smaller cap than the large-boat permit market (in blue) and therefore is shifted much closer to the origin. The graphs confirm the presence of gains from trade, the sum of the areas under each supply curve and above each demand curve. Comparing aggregate profits at the market equilibrium (34.6 billion ISK) to the profits if each boat harvested only their permit allocation (30.9 billion), I find that permit trade increased total profits by 3.69 billion ISK in 2003 (see column 1 in Table 6), or about 12%.

Figure 8(a) also shows the efficiency impacts of segmentation, namely the areas ABC and DEF. These are the foregone profits that the boats would have gotten under the equilibrium price in the simulated unified market. In 2003, I estimated those losses to be about 270 million ISK, or 7% of the total gains from trade. The consequences of segmentation vary by year. In 2002, segmentation lowered the gains from trade by only about 1% despite a similar difference in permit price to other years (20.9 ISK). Both permit supply and demand in that year were particularly inelastic in the small-boat market.

Figure 8(b) shows the simulated unified market in order to isolate the impact of the harvest requirement. The change in permit supply is clear, with the area ABC in 8(b) representing the foregone profits from requiring harvest. In 2003, the harvest requirement lowered the gains from permit trade by 760 million ISK or 16%. In 1999 and 2000, the harvest requirement was binding on more firms and had an even greater impact, lowering gains from trade by as much as 32%.[31]

Figure 9 then emphasizes the gains in each market separately as one removes each trading limit to the market with the highest gains from trade: a unified market with no harvest requirement. Removing the requirement in the segmented market increases the gains from trade by 720 million ISK; then unifying the market adds another 310 million ISK in gains. The trade limits together therefore destroyed about a quarter of the gains from trade in 2003.

The first column of Table 6 shows gains from trade from pooling all years, for four market designs: the efficient benchmark with no trade limits, including each limit individually, and then the actual design implementing both. Segmentation destroys about 5% of the gains from trade, while the harvest requirement is three times more costly, destroying about 15% of gains from trade. The fact that the efficiency loss from segmentation is small, relative to the large difference in permit price, is due to the relative (in-)elasticities

[31] This could be because over time, firms adjust their permanent permit rights (and therefore their annual permit allocation) in order to be sure they are not at risk of being near 50% of their permit allocation. In practice, though, boats mostly sell those permanent rights at exit. Other permit right sales do happen, though.

of the permit demand and supply curves.[32] This emphasizes the importance of the model to elucided the permit supply and demand curves to understand efficiency consequences.

A simple decomposition shows how each limit affects the gains from trade. Note that

$$\text{Gains from trade} = \text{Total transaction volume} \times \text{Average gain}$$

The value of a permit trade is the difference in harvest profits from shifting production from the seller to the buyer. Market segmentation lowers the possible difference in production profits by restricting who can sell to whom; it therefore impacts the average gain from trade. In fact, trade volume slightly rises slightly (comparing the third and fourth row of Table 6). The efficiency loss comes from a 5% drop in the average gain from trade. Many valuable permit trades remain despite segmentation.

The harvest requirement, meanwhile, acts by restricting some valuable trades entirely. A set of permits that can be sold in the limit-less market are restricted to be harvested. The volume of trades that are removed depends on how many producers are constrained by the requirement in the new equilibrium. The harvest requirement has a negligible impact on the average value of trades (comparing the second and fourth row of Table 6), such that buyers are able to find other sellers in most instances with similar profit differences. However, the average trade falls by 15%, constraining more production than segmentation and reducing the value of the permit market more.

6.3 Cost of Redistribution via Trade Limits

The graphical analysis has emphasized how to assess the foregone profits from limiting trading in the permit market. Table 7 highlights who benefits from the limits by translating the increased production on targeted boats to changes in worker earnings. It decomposes earnings into the aggregate wage bill (a function of harvest revenue) and the remaining harvest profits plus returns in the permit market, which run to boat owners. I split this into two groups: the group of workers who gain from the limit and the group of workers who lose, along with their respective boat owners. I will take each trade limit in turn.

[32] In fact, one could also find the opposite result: larger relative differences in profits than in permit prices, if permit demand and supply are very elastic. This would create wide but shallow triangles in the graphical analysis.

Segmentation was designed to increase harvests on the small and medium-sized boats (<15 gross tons) that were placed in their own permit market. I find that segmentation increased the harvest share for these boats by about 2 percentage points. Small-boat workers therefore saw an aggregate increase of $2.4 million, with losses to boat owners in aggregate as many net sellers lose seller surplus from selling to large boats in the unified market. Beyond small-boat owners, the incidence of segmentation falls on large-boat labor given the fall in harvests among small boats. There is in fact a slight increase in earnings to large-boat owners, as equilibrium prices rise and shift surplus from big-boat permit buyers to big-boat permit sellers.

The harvest requirement was designed to increase harvests on boats that would otherwise harvest only a small fraction of their permits. This was in order to raise earnings for their crews. Table 7 shows that earnings gains were about $12 million in aggregate to those workers, with considerable losses to the boat owners who lose profits from selling permits. Just as before, workers on all other boats lose on average from the shift in harvests. Owners of those other boats gain on average due to higher permit prices that increase seller surplus at the expense of buyer surplus.

I can now compare the cost from foregone profits to the gains to workers under each trading limit. One can think of the gains in two ways: protecting jobs (labor demand) writ large and protecting low-income workers from permit trade. Table 8 shows that market segmentation is a much more effective policy at increasing total labor demand; small boats are much more labor intensive on average than the net sellers that increase harvests under the harvest requirement. However, the harvest requirement is the superior redistributive policy. Figure 10 shows changes in average earnings across ventiles of the fishery income distribution. There are many small-boat workers who are relatively high in the fishery income distribution, and therefore shifting harvests (and therefore earnings) to them is not well targeted toward low-income workers. The harvest requirement, meanwhile, increases earnings at the bottom half of the income distribution by about 20%, compressing the income distribution more. This targeting ability means that, despite the larger efficiency gains, it is actually about 10% less costly per dollar of foregone profit to redistribute to the lower half of the income distribution via the harvest requirement than via market segmentation. This is a relatively costly way to redistribute income, however. Shifting a dollar from the highest to the lowest income person in the tax code costs about $2 (Hendren 2020). However, one can make other comparisons: for example, redistribution via tiered electricity pricing in the US increases earnings at the bottom of the income distribution by only about 12%, with considerable deadweight loss (Borenstein 2011). On the other hand, even low-fishery income workers are rather high in the Icelandic income distribution, with small-boat workers roughly falling around the 40th percentile.

The interaction of the two policies not only preserves but enhances the benefits of each trade limit individually, as seen in the third column in Table 8. The actual design that segments the market and imposes the harvest requirement increases labor demand by a third relative to segmentation alone and increases redistribution to the low-income fishery workers by about third relative to the harvest requirement alone (and at about the same per-dollar cost). This is because both being a net seller and a small boat targets labor-intensive production while also shifting harvests up even more among the lowest-income, most labor-intensive boats: the net sellers in the small-boat market.

7 Conclusion

Economists have for decades expounded the promise of environmental markets, which maximize the value of an environmental commons by shifting production to those that value it most. In practice, however, the ability to increase aggregate value can conflict with other goals in managing environmental commons.

Trading limits can strike a balance between productive efficiency and distributional objectives and help overcome the concerns that lead regulators to avoid market schemes entirely.

This paper focuses on regulatory attempts to meet those other goals. I study trading limits in Iceland's fisheries permit market, one of the oldest and largest in the world. It features two common designs that limit trade in permit markets. Firms are required to harvest half their permit allocations in order to ensure jobs and earnings to all workers, and the market is segmented between large and small boats to protect small-scale production.

I assemble unique data that links administrative data on worker employment and earnings histories to detailed information on firm behavior in the permit market and in fishery production and combine it with extensive institutional knowledge of how firm revenue maps to earnings. This allows me to consider jointly changes in fisheries production and downstream impacts on earnings. I find that many workers are able to exit the fishery and find jobs that ameliorate most of the earnings consequences. Nevertheless, investigating those who remain in fisheries, permit trading shifts earnings from lower- to higher-income fishery workers. I then document evidence of the efficiency consequences of the trading limits.

I then develop and estimate a joint model of fishery production and permit trading to assess the value of permit trading and consider the consequences of designs that protect workers and firms. I find that each type of trading limit has distinctive efficiency and distributional consequences. Segmentation greatly increases labor demand, but with notably small efficiency consequences given the considerable permit price differences across markets. The harvest requirement is costlier but much more targeted at low-income fishery workers. Implementing both together enhances their effects, with a similar per-dollar redistributive cost as under the harvest requirement alone.

The paper presents an analytical framework to thinking through distributional goals in permit market design more generally. I highlight the key analyses needed to assess trade-offs in permit market design: first, a compelling model of firm production to understand alternative production decisions, and second, how those production decisions link to the outcomes that the government cares about. Researchers can undertake such an exercise in many settings. A prominent one might be permit market design that responds to environmental justice concerns, i.e. the concentration of pollution in minority and/or low-income communities. While there is evidence that pollution disparities *fell* after a permit market is introduced (Hernandez-Cortes and Meng, 2023), researchers might undertake a similar analysis as this one to understand how and when to intervene in permit trading.

Having looked at a setting where regulators committed themselves to market schemes and asked how to intervene to meet those goals, the paper speaks to the tendency of regulators to avoid market-based schemes in many environmental settings. Presenting more flexible market designs that take seriously the multiple goals of regulators might allow for a larger set of tools for governments to respond to rampant environmental degradation across the world, while also explaining why some policies are undertaken more than others in the push toward environmental sustainability.

Citations

Agarwal, Nikhil, Charles Hodgson, and Paolo Somaini. 2020. "Choices and Outcomes in Assignment Mechanisms: The Allocation of Deceased Donor Kidneys." NBER Working Paper No. 28064.

Agnarsson, Sveinn (2007), "Krókabátar: Olnbogabörn flotans." *Vísbending*, 2, 2.

Arnason, Ragnar (2005), "Property rights in fisheries: Iceland's experience with ITQs." *Reviews in Fish Biology and Fisheries*, 15, 243–264.

Aronoff, Daniel, and Will Rafey. 2024. "Conservation priorities and environmental offsets: Markets for Florida wetlands." NBER Working Paper, No. 31495.

Aspelund, Karl, and Anna Russo. 2024. "Additionality and Asymmetric Information in Environmental Markets: Evidence from Conservation Auctions." Working Paper.

Burtraw, Dallas, and Nicholas Roy. (2023). "How Would Facility-Specific Emissions Caps Affect the California Carbon Market?" Resources for the Future, report no. 23-09.

Bushnell, James B., and Catherine Wolfram. 2012. "Enforcement of vintage differentiated regulations: The case of new source review." *Journal of Environmental Economics and Management* 64.

Borenstein, Severin. 2012. "The Redistributional Impact of Nonlinear Electricity Pricing." *American Economic Journal: Economic Policy*, 4 (3): 56–90.

Carlson, Curtis et al. (2000). "Sulfur dioxide control by electric utilities: What are the gains from trade?" *Journal of political Economy* 108.6, pp. 1292–1326.

Colmer, Jonathan, et al. 2022. "Does Pricing Carbon Mitigate Climate Change? Firm-Level Evidence from the European Union Emissions Trading Scheme." Working Paper.

Costello, Christopher, Steven D. Gaines, and John Lynham (2008), "Can catch shares prevent fisheries collapse?" *Science*, 321, 1678–81.

De Loecker, Jan, and Chad Syverson. (2021). "An Industrial Organization Perspective on Productivity." *Handbook on Industrial Organization* (vol 4).

Dickstein, Michael J, and Eduardo Morales. (2018). "What do Exporters Know?" *Quarterly Journal of Economics*, 133(4), 1753-1801.

Ellerman, A. Denny, et al. 2000. *Markets for Clean Air: The U.S. Acid Rain Program.* Cambridge University Press.

Englander, Gabriel (2023), "Information and spillovers from targeting policy in peru's anchoveta fishery." *American Economic Journal: Economic Policy*, 15(4), 390-427.

Fowlie, Meredith. 2010. "Emissions Trading, Electricity Restructuring, and Investment in Pollution Abatement." *American Economic Review*, 100 (3): 837–69.

Fowlie, Meredith, Christopher Knittel, and Catherine Wolfram. 2012. "Sacred Cars? Cost-Effective Regulation of Stationary and Nonstationary Pollution Sources." *American Economic Journal: Economic Policy*, 4 (1): 98–126.

Fowlie, Meredith, and Mar Reguant. 2022. "Mitigating Emissions Leakage in Incomplete Carbon Markets." *Journal of the Association of Environmental and Resource Economists*, 9 (2).

Garicano, Luis, Claire Lelarge, and John Van Reenen. 2016. "Firm Size Distortions and the Productivity Distribution: Evidence from France." *American Economic Review* 11 (6).

Greenstone, Michael. 2002. "The Impacts of Environmental Regulations on Industrial Activity: Evidence from the 1970 and 1977 Clean Air Act Amendments and the Census of Manufactures." *Journal of Political Economy* 110 (6).

Greenstone, Michael, et al. 2022. "Can Pollution Markets Work in Developing Countries? Experimental Evidence from India." Working Paper.

Grainger, Corbett A. and Christopher Costello (2015), "Distributional effects of the transition to property rights for a common-pool resource." *Marine Resource Economics*, 31, 1–26.

Grainger, Corbett A. and Dominic P. Parker (2013), "The political economy of fishery reform." *Annual Review of Resource Economics*, 5, 369–86.

Greenstone, Michael, Nicholas Ryan, and Anant Sudarshan. (2022) "Can Pollution Markets Work in Developing Countries? Experimental Evidence from India." Working Paper.

Grétarsson, Helgi Á. (2008), *Réttarsaga fiskveiða frá landnámi til 1990*. Ritröð Lagastofnunar Háskóla Íslands.

Grétarsson, Helgi Á. (2009), "Af handfæra- og strandveiðibátum: Lagaþroun 1996–2009." *Rannsóknir í félagsvísindum*, 10, 115–53.

Hagerty, Nick. (2023). "What Holds Back Water Markets? Transaction Costs and the Gains from Trade." Working Paper.

Hahn, Robert. 1984. "Market Power and Transferable Property Rights." *The Quarterly Journal of Economics*, Vol. 99, No. 4.

Hahn, Robert, and Robert Stavins. 2011. "The Effect of Allowance Allocations on Cap-and-Trade System Performance." *Journal of Law and Economics*, Vol. 54, No. 4.

Hernandez-Cortes, Danae, and Kyle C. Meng. (2023). "Do environmental markets cause environmental injustice? Evidence from California's carbon market." *Journal of Public Economics*, vol. 207.

Ho, Phuong. 2023. "Why Is Trading So Important in Cap and Trade? The Roles of Economies of Scale and Productivity." Working Paper.

Hsiang, Solomon, Paulina Oliva, and Reed Walker. "The Distribution of Environmental Damages." *Review of Environmental Economics and Policy*, volume 13, issue 1.

Huang, Ling and Martin D. Smith (2014), "The dynamic efficiency costs of common-pool resource exploitation." *American Economic Review*, 104, 4071–410.

Isaksen, Elizabeth Thuestad, and Andries Richter. 2019. "Tragedy, Property Rights, and the Commons: Investigating the Causal Relationship from Institutions to Ecosystem Collapse." *Journal of the Association of Environmental and Resource Economists*, 6 (4).

Ito, Koichiro, and James Sallee. 2018. "The Economics of Attribute-Based Regulation: Theory and Evidence from Fuel Economy Standards." *Review of Economics and Statistics* 100 (2).

Jin, Di, Min-Yang Lee, and Eric Thunberg. 2019. "An Empirical Analysis of Individual Fishing Quota Market Trading." *Marine Resource Economics* 39 (4).

Keohane, Nathaniel O. 2006. "Cost savings from allowance trading in the 1990 Clean Air Act: Estimates from a choice-based model." *Moving to markets in environmental regulation: Lessons from twenty years of experience*, 19: 23.

Kroetz, Kailin, Kailin Kroetz, James Sanchirico, and Daniel K. Lew. (2015). "Efficiency Costs of Social Objectives in Tradable Permit Programs." *Journal of the Association of Environmental and Resource Economists* 2 (3), 339 - 366.

Lee, Min-Yang, and Eric Thunberg. 2013. "An inverse demand system for New England groundfish: welfare analysis of the transition to catch share management." *American Journal of Agricultural Economics* 95 (5).

Lee, Min-Yang, and Greg Ardini. 2018. "Do IFQs in the US Atlantic Sea Scallop Fishery Impact Price and Size?" *Marine Resource Economics* 33 (3).

Newell, Richard, James N. Sanchirico, and Suzi Kerr (2005), "Fishing quota markets." *Journal of Environmental Economics and Management*, 49, 437–462.

Pakes, Ariel. 1986. "Patents as Options: Some Estimates of the Value of Holding European Patent Stocks." *Econometrica* 54 (4).

Rafey, Will. (2023). Droughts, deluges, and (river) diversions: Valuing market-based water reallocation." *American Economic Review*, Vol. 113, No. 2, pp. 430–471.

Reimer, Matthew, Josh Abbott, and A. Haynie. 2022. "Structural behavioral models for rights-based fisheries." *Resource and Energy Economics* 68.

Regnacq, Charles, Ariel Dinar, and Ellen Hanak. 2016. "The Gravity of Water: Water Trade Frictions in California." *American Journal of Agricultural Economics*, vol. 98, issue 5.

Ryan, Nicholas, and Anant Sudarshan. "Rationing the Commons." *Journal of Political Economy* 130 (1): 210-257.

Shapiro, Joseph, and Reed Walker. 2021. "Is Air Pollution Regulation Too Lenient? Evidence from US Offset Markets." NBER Working Paper No. 28199.

Sigurdsson, Josef. (2024). "Labor Supply Responses and Adjustment Frictions: A Tax-Free Year in Iceland." Working Paper.

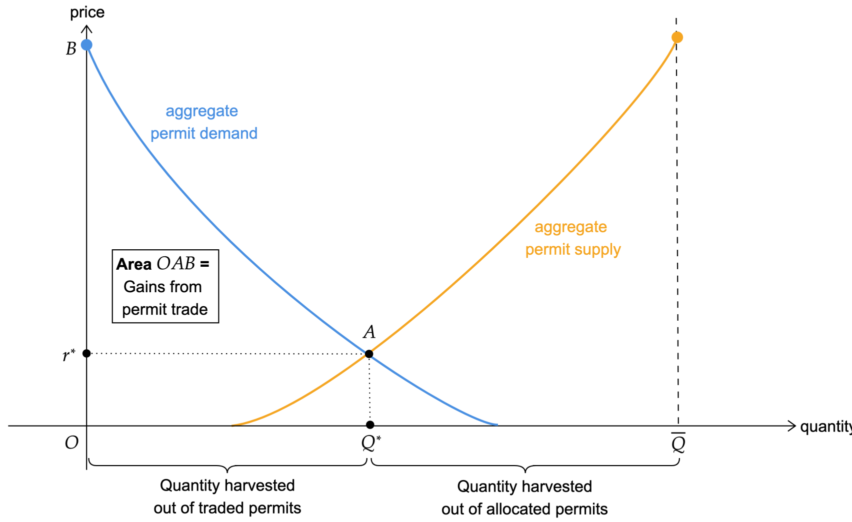
Smith, Martin D. (2012), "The new fisheries economics: Incentives across many margins." *Annual Review of Resource Economics*, 4, 379–429.

Toyoma, Yuta. (2024). "Dynamic Incentives and Permit Market Equilibrium in Cap-and-Trade Regulation." *American Economic Journal: Microeconomics*, Volume 16, no. 3, 374–423.

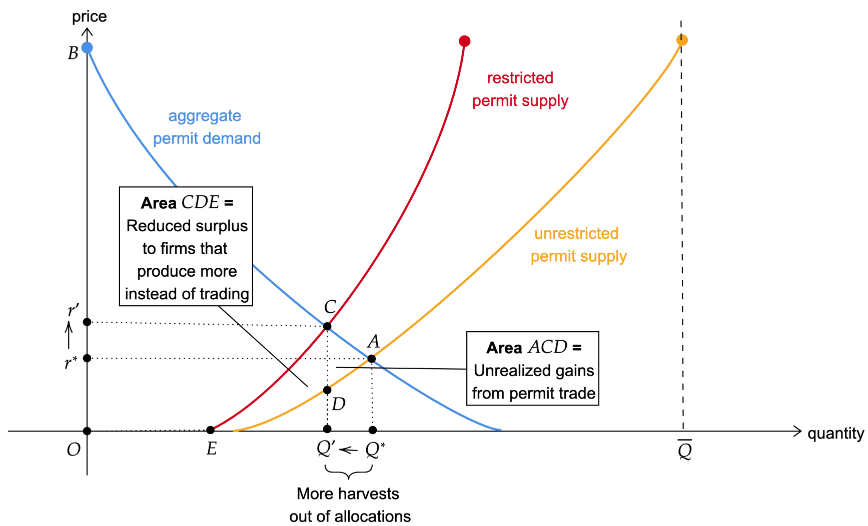
Walker, Reed. (2013). "The Transitional Costs of Sectoral Reallocation: Evidence From the Clean Air Act and the Workforce." *Quarterly Journal of Economics*, 128 (4): 1787-1835.

Tables and Figures

Figure 1. Graphical analysis of a permit market and a production requirement



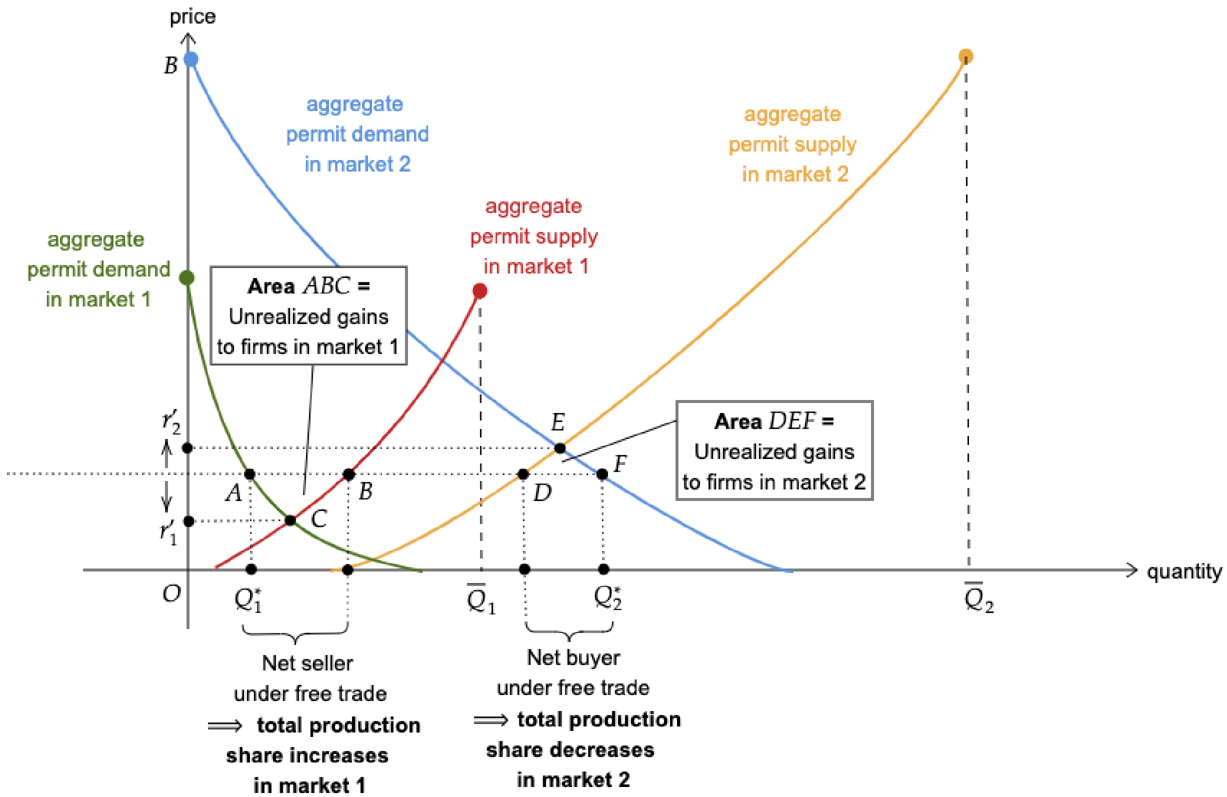
(a) Gains from permit trade



(b) Production requirement

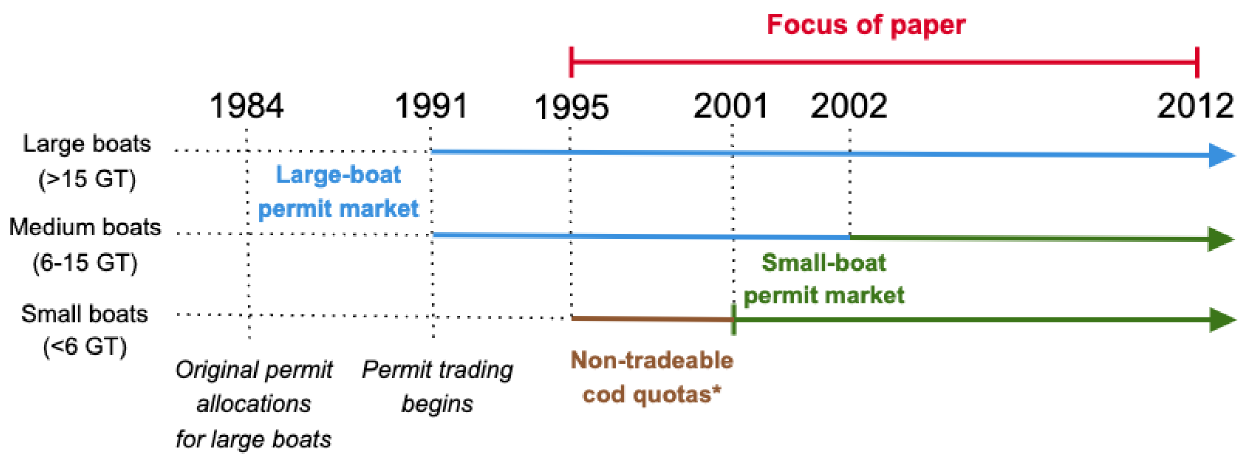
Note: The figure describes the lost gains from trade from two common types of trading limits in a permit market: requirements to produce a minimum amount from permit allocations and segmenting a market. It does so under a competitive market equilibrium in a permit market for a generic initial permit allocation. It outlines aggregate permit demand and aggregate permit supply curves, which depend both on market participants' permit choices—which are themselves functions of production profits—and the initial allocations to each participant. Sub-figure (a) shows the basic equilibrium and the gains from trade. Sub-figure (b) shows the supply shift that occurs when there is a production requirement that binds firms with low production.

Figure 2. Graphical analysis of segmentation



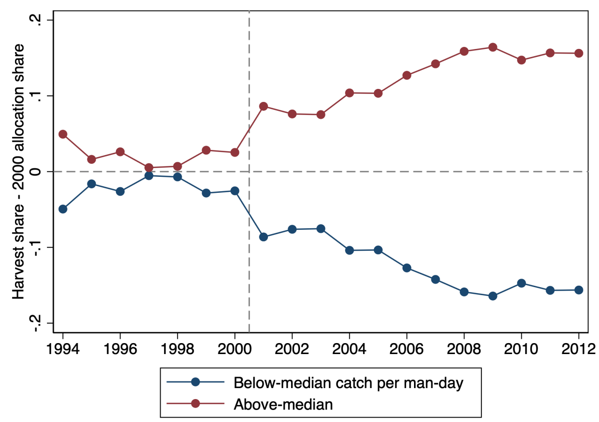
Note: The figure describes the lost gains from trade from segmenting a permit market. It does so under a competitive market equilibrium in a permit market for a generic initial permit allocation. It outlines aggregate permit demand and aggregate permit supply curves, which I define in the text as the relationship between excess permits or excess production and permit prices. The foregone profits are the two triangles. Segmentation is designed to increase production in the market with the more generous cap, i.e. the one with a lower equilibrium permit price. This increases production profits but at the expense of returns in the permit market.

Figure 3. Timeline of Fishery Regulation in Iceland

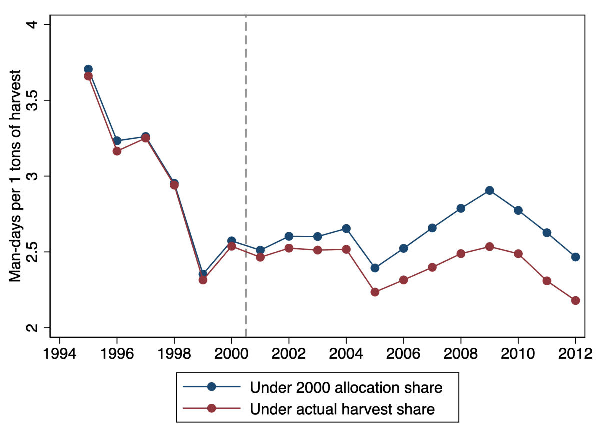


Note: The figure shows some key years in Icelandic fisheries management that are relevant to this paper. There is an asterisk on the non-tradeable cod quotas because about 250 small boats were also under day restrictions after 1995; many of these day boats operated mostly seasonally and represent less than 2% of aggregate revenue, so they are not a focus of this paper. They were also placed into the permit market in 2004, though many later transitioned to a summer coastal fishing program in 2008.

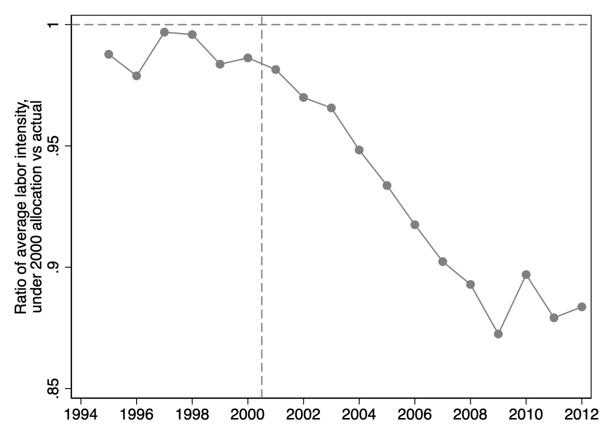
Figure 4. Impact of permit market trade on harvests and labor intensity



(a) Reallocation of harvest among small boats



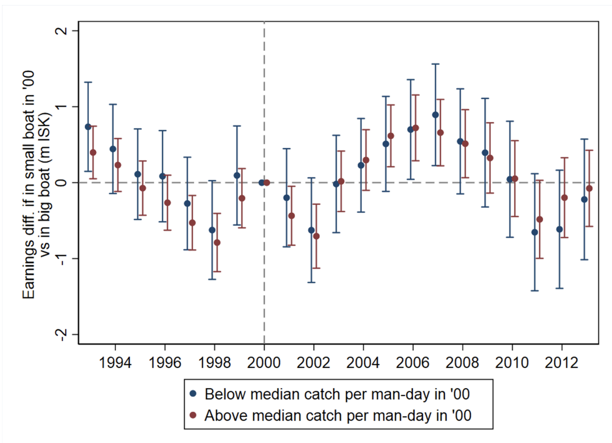
(b) Labor intensity (harvests per person-day), actual vs. if allocation harvested



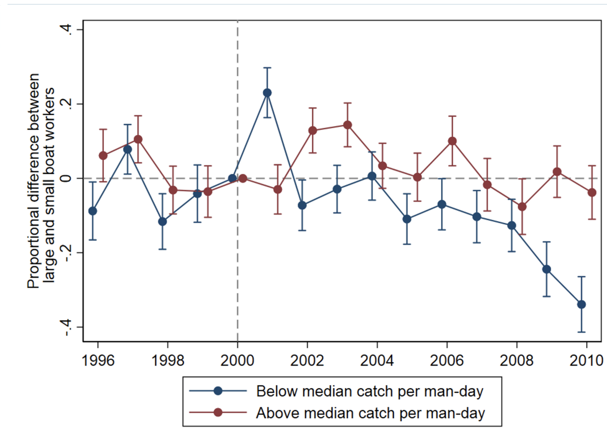
(c) Relative difference of labor intensity, actual vs. if allocation harvested

Note: The figure shows key changes in production after permit trading is introduced for small boats. Sub-figure (a) shows the differences in harvest share, relative to the allocation share, among small and medium boats after permit trading is introduced, split at the median catch per man-day (a measure of productivity). Sub-figure (b) shows how this impacted the average labor intensity of production. It compares the average labor intensity (man-days per ton of harvest, i.e. the inverse of the productivity measure used in sub-figure a) in red to the implied average when the boats are weighted by their 2000 allocation share. It shows how how much of the change in labor intensity can be attributed to the shift in harvest due to permit trade. Sub-figure (c) takes the ratio of the two measures in sub-figure b to show that the observed labor intensity is about 88% lower than what would be observed if the same boats had kept their harvest shares at their 2000 allocation share. Permit trading has made fisheries production less labor-intensive.

Figure 5. Impact of permit market trade on worker income



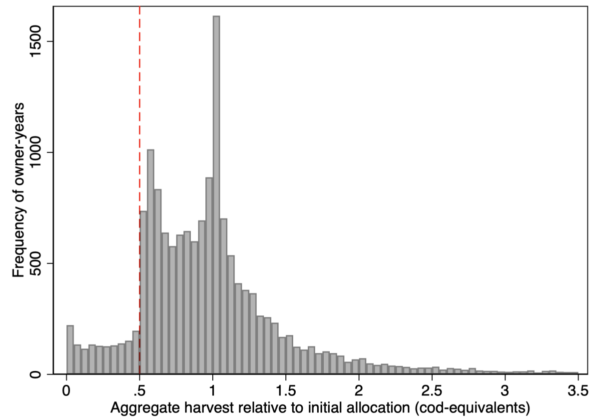
(a) Average earnings difference in panel of workers in small boats vs big boats in 2000



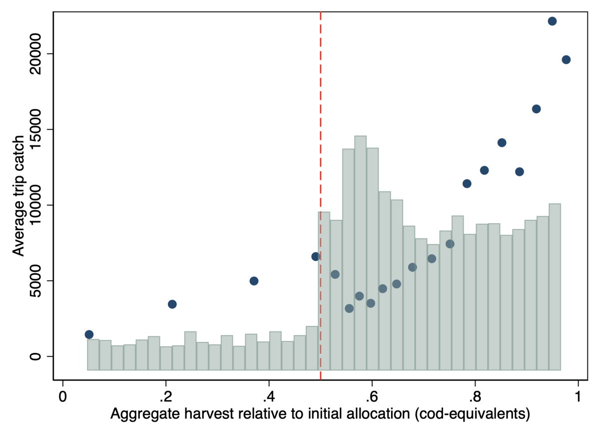
(b) Average earnings difference between workers in small boats vs big boats every year

Note: The figure shows key changes worker outcomes on the introduction of permit trading in Icelandic fisheries. Sub-figure (a) shows the average earnings difference among workers in small boats in 2000 only, split along median harvest per person-day, relative to large-boat workers in 2000. This traces their earnings whether they are in the fishery or not. Sub-figure (b) shows the average earnings difference among workers each year relative to large-boat workers, i.e. it conditions on being in the fishery every year. It shows that across most years, average earnings fall on less-productive boats. These workers tend to be low-income already. Permit trading transfers income from lower- to higher-income workers.

Figure 6. Harvest requirement's impact



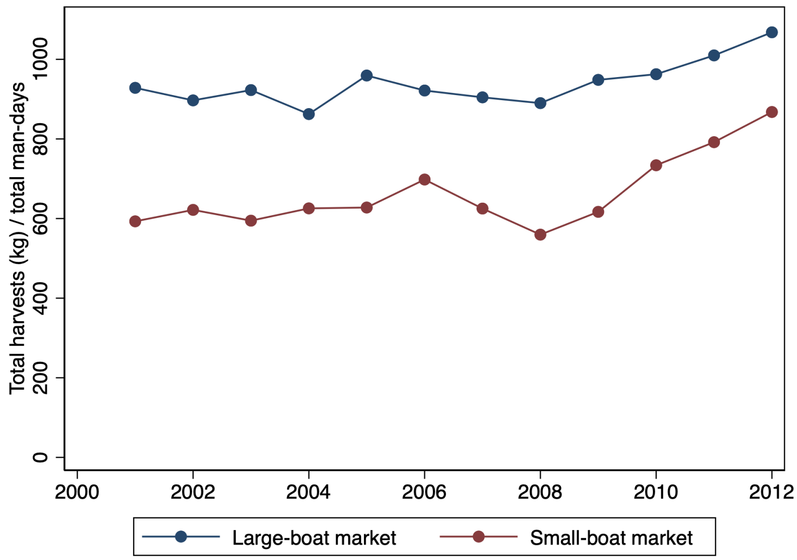
(a) Permit holdings relative to allocation: bunching at 50%



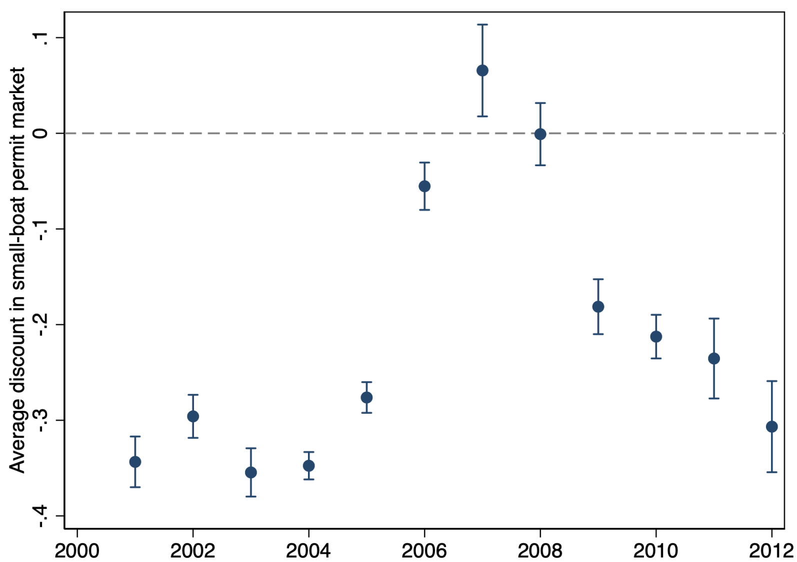
(b) Binned scatter-plot: average trip less productive above cutoff

Note: The figure shows that the harvest requirement binds: there is considerable bunching at 50% of the permit allocations. About 8% of firm-years are below 50%, most of whom exit in the following year. Subfigure (b) zooms in to show that bunching firms have lower average daily harvests, going out on more days to get to the 50% mark.

Figure 7. Segmented market's impact



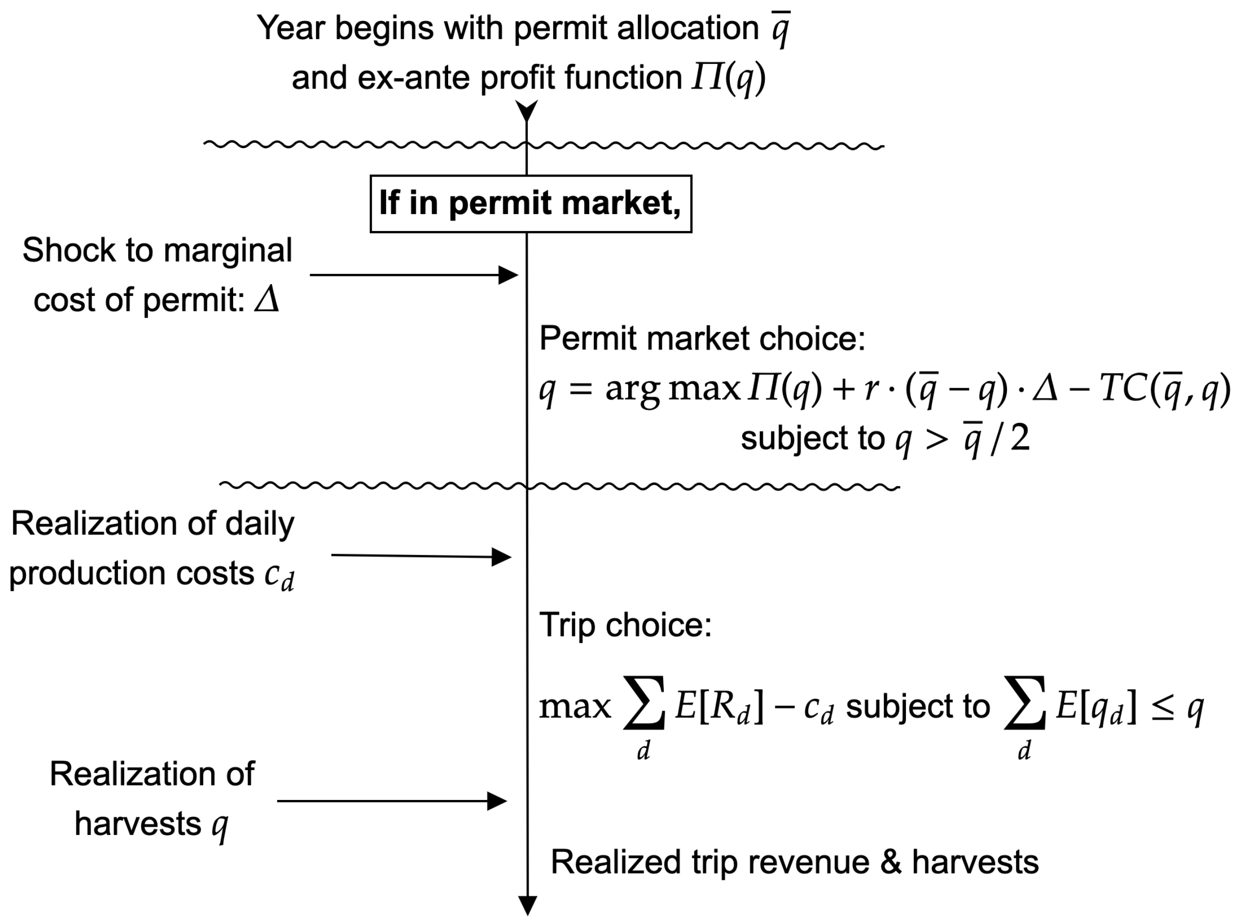
(a) Small-boat production is more labor-intensive



(b) Permits are on average cheaper in most years

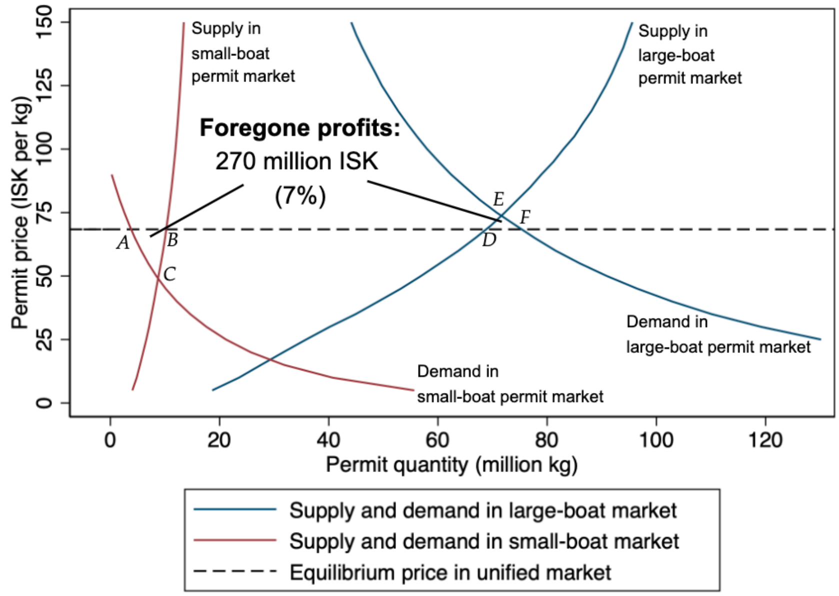
Note: The figure shows the impact of the small-boat market. First, sub-figure (a) highlights that small-boat production is more labor-intensive, i.e. lower harvests per person-day, than large-boat production. Sub-figure (b), meanwhile, highlights a sufficient statistic for efficiency differences due to segmentation: differences in the permit price, the effective shadow marginal cost of production. Regressing permit prices from all trades with species-year fixed effects, the coefficient reports the average percentage difference in permit transaction price in the small and large boat market. In most years, it is considerably lower, reflecting more generous caps to the small-boat market.

Figure 8. Timing of decisions, shocks in model

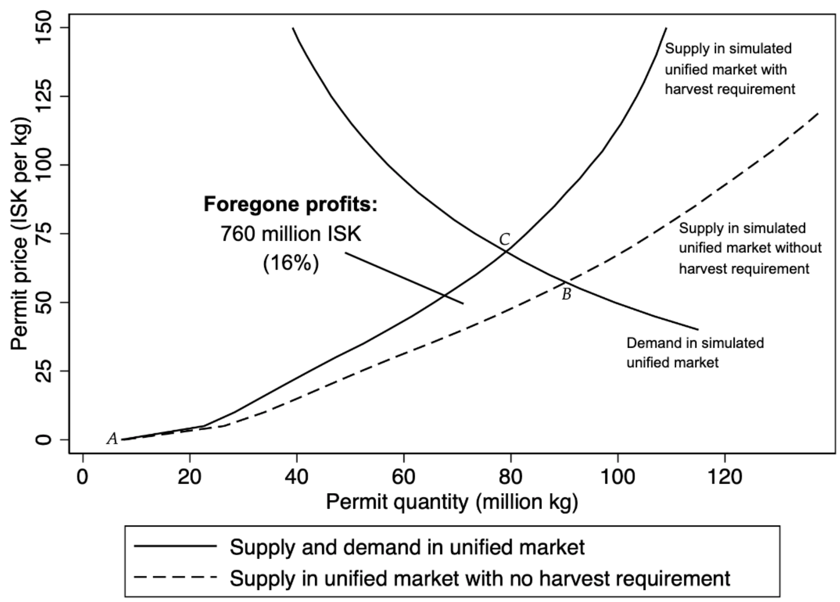


Note: The figure the timing of shocks and decisions in the model. For boats in the non-tradeable cod system, days are chosen based on permit allocation only; there is no permit choice. Boats are assumed to trade permits once, before cost shocks are realized, and therefore based on the ex-ante profit function. All quantities are in cod-equivalent units, the units at which the trade limit binds.

Figure 9. Graphical analysis: permit demand and supply in 2003



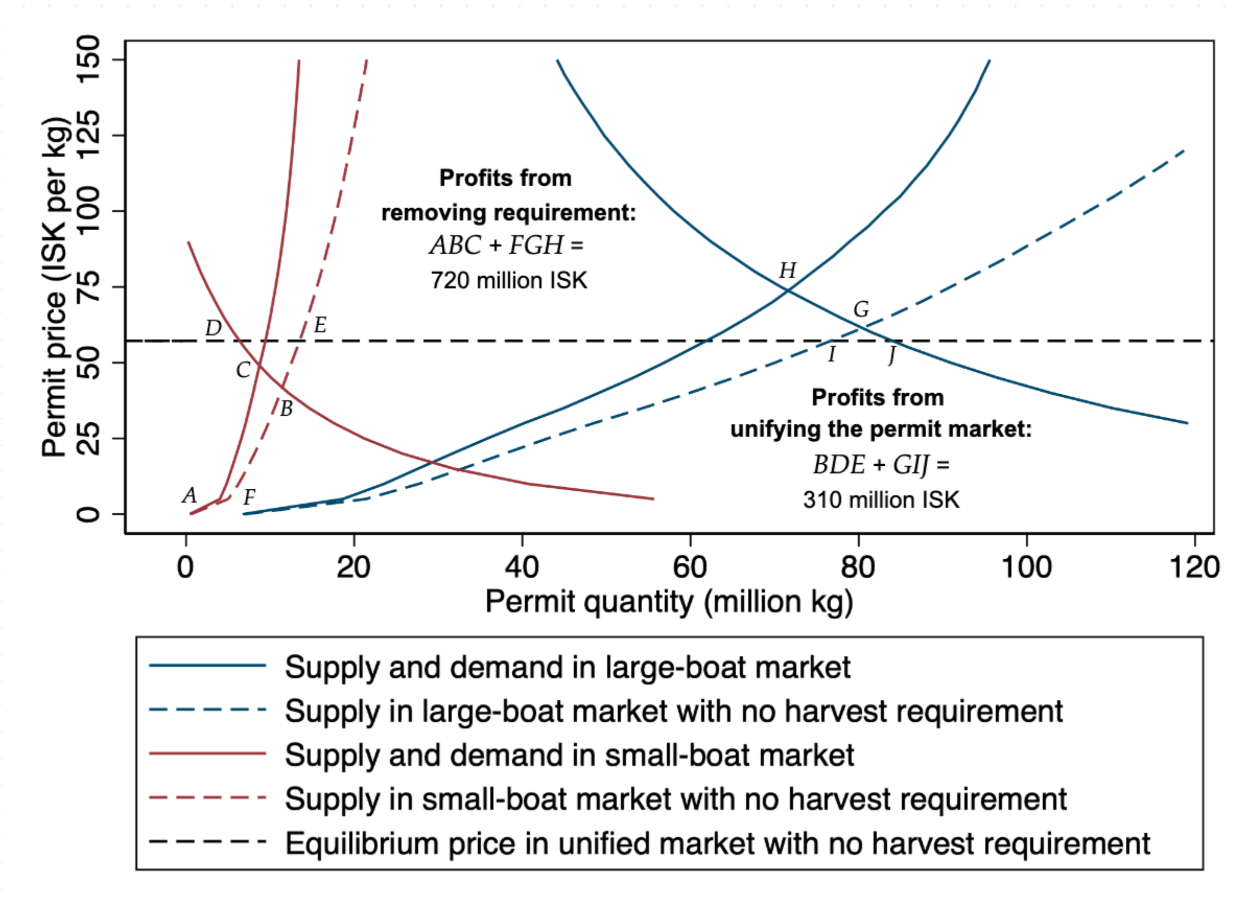
(a) Impact of segmentation



(b) Removing harvest restriction in a unified market

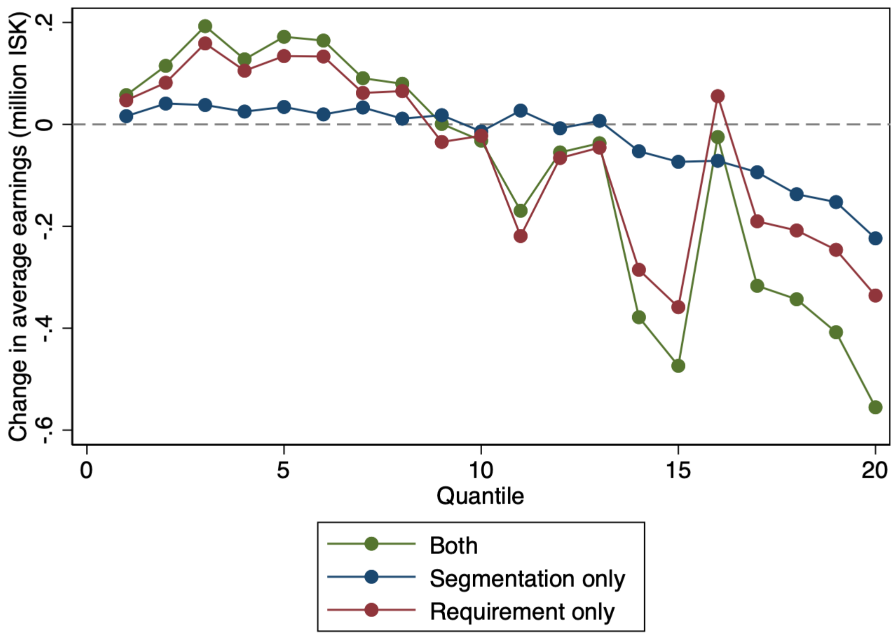
Note: These figures show the aggregate permit supply and demand curves for the actual permit market in 2003 in sub-figure (a) and a simulated unified market in sub-figure (b) with and without the harvest requirement. The unified equilibrium permit price reported in (a) is the intersection of the solid lines in (b). It then highlights the foregone profits in each.

Figure 10. Profits from removing both trading limits



Note: This figure shows the impact of removing the two trading limits from the permit market in 2003. It begins with the supply and demand in the segmented markets and then removes the harvest requirement to generate more permit supply. Then it highlights the remaining profit gains from unifying the market without the harvest requirement.

Figure 11. Trade-off of Trade Limits: Foregone profits vs. outcomes for targeted group



Note: The figure shows changes in earnings across the fishery worker income distribution. It plots changes in average earnings by ventile of the fishery worker income distribution, pooling across all years, for three market designs relative to the market with no trading limits: segmenting the market by boat size only (blue), introducing the harvest requirement only (red), and the actual design that implemented both (green).

Table 1. Summary Statistics

	1997	2002	2010
Panel A: Fishing Boats			
No. boats	906	884	636
No. firms	958	947	648
Total harvests (thousand cod-equivalent tons)	293	304	278
Total revenue (all species, billion ISK)	24.5	37.9	70.8
Total trips (million)	4.60	4.09	2.88
Fraction trawlers	0.135	0.103	0.106
Fraction small (< 6 gross tons)	0.432	0.376	0.356
Fraction medium ($6 - 15$ gross tons)	0.282	0.342	0.389
Fraction large (> 15 gross tons)	0.286	0.282	0.253
Harvest share to trawlers	0.576	0.589	0.553
Harvest share to small boats	0.087	0.060	0.018
Harvest share to medium boats	0.081	0.109	0.161
Panel B: Fisheries Labor			
No. workers	8771	7505	6051
No. workers, small boats	1100	1270	722
In capital city region	0.273	0.249	0.243
Average earnings (million '20 ISK)	7.39	8.99	10.2
Fraction male	0.962	0.960	0.950
Average age	35.1	37.3	39.5
Fraction UI	0.100	0.117	0.162
Fraction foreign-born	0.017	0.031	0.065
Fraction university degree	0.024	0.025	0.051
Average fraction earnings in fishing	0.796	0.814	0.814
Fraction with $> 90\%$ fish earnings, small boats	0.568	0.580	0.570
Fraction with $> 90\%$ fish earnings, large boats	0.642	0.659	0.705
Fraction moving next year	0.221	0.108	0.080
Fraction in fishery next year	0.766	0.791	0.822
Panel C: Comparison Sample of Non-Fisheries Workers (16-70)			
In capital city region	0.645	0.661	0.672
Fraction male	0.422	0.427	0.418
Average age	39.2	41.0	46.6
Average earnings (million ISK)	3.53	4.69	5.00
Fraction foreign-born	0.036	0.027	0.026
Fraction university degree	0.187	0.232	0.357

Note: Harvests are measured in cod-equivalents; see Appendix Section A. All monetary values are inflated using the consumer price index for Iceland in January 1, 2020. At that time, the market exchange rate was 122.4 ISK to 1 USD, i.e. 1 million ISK $\approx$ 8,170 USD. Panel C is information from a random sample of 10% of individuals who were never flagged as working in the fisheries through all the tax and pay-slip data. Boats with day restrictions are not included.

Table 2. Event-Study Estimates from Permit Market Expansion

	Overall income (1)	Fish income (2)	Not working (3)	In fisheries (4)	Frac. fishing income (5)	Moved (6)
Panel A: panel of workers in fisheries in 2000						
Pre-2000 $\times \mathbf{1}$(Small boat in '00)	-0.107	-0.139	0.093	-0.166	-0.084	0.061
	(0.127)	(0.137)	(0.005)	(0.006)	(0.012)	(0.006)
Post-2000 $\times \mathbf{1}$(Small boat in '00)	0.094	0.314	0.041	-0.057	-0.001	0.033
	(0.127)	(0.138)	(0.004)	(0.006)	(0.012)	(0.005)
Panel B: panel of workers in fisheries in 2000, split by '00 median daily catch						
Post-2000 $\times \mathbf{1}$(Below '00 median)	0.030	0.243	0.0422	-0.077	-0.012	0.013
	(0.174)	(0.184)	(0.006)	(0.008)	(0.016)	(0.006)
Post-2000 $\times \mathbf{1}$(Above '00 median)	0.158	0.383	0.040	-0.037	0.010	0.052
	(0.165)	(0.179)	(0.005)	(0.007)	(0.016)	(0.006)
Birth decade FE	X	X	X	X	X	X
No. workers	7.532	7.532	7.532	7.532	7.532	7.532
No. small-boat workers	1,210	1,210	1,210	1,210	1,210	1,210
'00 Mean: small boats	5.16	3.93	0.00	1.00	0.705	NA
'00 Mean: large boats	7.96	6.85	0.00	1.00	0.772	NA
Panel C: cross-section of fishery workers each year						
Pre-2000 $\times \mathbf{1}$(Small boat)	0.476	0.402			-0.016	
	(0.128)	(0.138)			(0.012)	
Post-2000 $\times \mathbf{1}$(Small boat)	-1.03	-0.991			-0.016	
	(0.127)	(0.136)			(0.011)	
Panel D: cross-section of fishery workers each year, split by '00 median daily catch						
Post-2000 $\times \mathbf{1}$(Below '00 median)	-1.45	-1.43			-0.029	
	(0.172)	(0.182)			(0.015)	
Post-2000 $\times \mathbf{1}$(Above '00 median)	-0.534	-0.464			-0.001	
	(0.166)	(0.180)			(0.015)	
Birth decade FE	X	X			X	
No. worker-years	161,316	161,316			161,316	
No. small-boat worker-years	18,135	18,135			18,135	

Note: The table shows results from a simple differeince-in-differences of small- and large-boat workers across years, pooling 1993-1999 and 2001-2012 for the pre- and post-years respectively. Panel A is a cross-section of fishing workers each year, highlighting earnings differences within each year. Panel B follows the panel of workers who were in fishing boats in 2000. All specifications include fixed effects for birth decade. Income is measured in million ISK. All monetary values are inflated using the consumer price index for Iceland in January 1, 2020. At that time, the market exchange rate was 122.4 ISK to 1 USD, i.e. 1 million ISK $\approx$ 8,170 USD. "Moved" is an indicator for filing tax returns in a different postal code than in 2000.

Table 3. Statistics by Productivity of Boats

	Below-median treated boat	Above-median treated boat	Control boat
Avg. fishery income, 2000	$31,900	$46,909	$55,775
Avg. fishery income percentile, 2000	37	47	53
Avg. income percentile, Iceland in 2000	59	71	75
Wage bill / revenue in 2000	0.31	0.30	0.21
Average share of income from fishing, 2000	0.71	0.76	0.79
Average share of income from fishing, 2007	0.75	0.72	0.79
Frac. in capital region, 2000	0.20	0.14	0.28
Frac. in capital region, 2007	0.22	0.07	0.25
Frac. foreign, 2000	0.08	0.01	0.02
Frac. foreign, 2007	0.21	0.18	0.07
Avg. age, 2000	36.9	37.9	36.2
Avg. age, 2007	39.0	37.2	37.7

Note: The table shows some key summary statistics by the three groups tracked in the reduced-form analysis. The first two columns show statistics for he treated boats in 2000 (small and medium boats that are put into a permit market) split at the median catch per man-day, a measure of productivity. It tracks some income measures and a measure of labor share (the share of harvest revenue running to the wage bill) in 2000, the year before small boats are placed in the permit market. It also tracks a series of demographic characteristics in 2000 and 2007 (many years after permit trading) to show that the demographics of fishery workers changed starkly, particularly on small boats.

Table 4. Parameters of interest

Description	Symbol	
Production		
Expected daily revenue	R_{id}	regression of realized daily revenue on observed characteristics
Daily cost	c_d	$c_{id} \sim$ Log normal(μ_c, σ_c), where each parameter is a function of size and gear mix.
Mean daily cost	μ_c	from aggregate choice of days to meet quantity goal
Variation of daily costs	σ_c	from likelihood of choosing particular day given its revenue and the quantity goal
Permit market		
Shock to marginal cost	Δ_i	$\Delta_i \sim$ Log normal$(\mu_\Delta, \sigma_\Delta)$, from variation in wedge Π'/r for similar boats and allocations
Transaction costs: base cost	α	allows for increased marginal cost as permit choice grows from allocation $\bar{q}$.
difference when selling	β	how relationship between wedge and allocation differs under selling vs buying permits
curvature	η	sensitivity of relationship between wedge and allocation to magnitude of trade.

Note: The table shows the key parameters of interest in the model. The production parameters determine each boat's harvest profit function. The market parameters allow for transaction costs that increase as producers choose permits away from their allocation.

Table 5. Structural estimates for three years

	1999		2001		2003	
Panel A: Average cost per unit and average unit revenue (ISK per kg) across boats						
	Cost per kg	Revenue per kg	Cost per kg	Revenue per kg	Cost per kg	Revenue per kg
Overall	13.7	109.7	20.2	136.1	16.3	133.6
Handline	11.4	108.5	22.0	131.1	12.4	133.2
Hand-longline	15.5	107.5	23.9	127.2	22.3	126.4
Net-hand-longline	12.9	115.0	7.08	147.7	30.0	143.5
Longline	22.1	107.3	21.5	129.3	14.1	129.2
Gillnet	3.57	121.0	22.3	161.7	26.0	154.0
Seiner	12.6	155.5	13.5	144.3	16.5	140.2
Trawler	18.0	97.3	17.3	118.6	9.4	120.9
Small boat	16.3	109.6	22.3	131.1	14.3	132.4
Medium boat	11.6	112.6	19.7	139.8	19.7	136.1
Large boat	12.5	106.9	17.9	138.3	15.6	132.7
Panel B: Market parameters						
$E[\lambda]$	0.995		1.17		1.82	
$Var(\lambda)$	0.048		0.050		0.104	
$\hat{\alpha}$	-0.280		-0.085		-2.47	
$\hat{\beta}$	-62.3		-50.4		-47.5	
$\hat{\eta}$ (curvature of $TC(\cdot)$	-1.80		-1.77		-0.91	

Note: Panel A shows the average unit cost and average unit revenue for different boat types, i.e. average total costs per kg quantity for each boat. Panel B shows estimates of the residual variation in the wedge between marginal profits and permit price λ as well as the parameters of the transaction cost function. See Table 4 for details. All monetary values are inflated using the consumer price index for Iceland in January 1, 2020. At that time, the market exchange rate was 122.4 ISK to 1 USD, i.e. 1 million ISK $\approx$ 8,170 USD.

Table 6. Regression of wage bill

	(1)	(2)
Revenue	0.162	0.186
	(0.053)	(0.055)
Revenue × log(boat size)	0.017	0.007
	(0.002)	(0.002)
Revenue × indicator for...		
Hand-longliner	-0.085	-0.022
	(0.076)	(0.077)
Handliner	-0.157	0.224
	(0.281)	(0.403)
Longliner	0.036	0.049
	(0.053)	(0.054)
Other	0.066	0.091
	(0.056)	(0.056)
Seiner	-0.118	0.060
	(0.053)	(0.054)
Trawler	0.121	0.094
	(0.053)	(0.054)
Year fixed effects	X	X
Firm fixed effects		X
R^2	0.8883	0.9083
N	14,893	14,293

Note: This table shows the results of a regression of fishery firm's total wage bill on the firm's annual harvest revenue. It interacts the coefficient on revenue with the (log) boat size and the gear mix. When a firm has multiple boats, I pick the size and gear mix of the smallest boat. The first column reports results for a specification with no firm fixed effects; the second column reports results with firm fixed effects, showing how the wage bill changes as revenue changes across years.

Table 7. Decomposing the Gains from Trade

	Gains from trade (million USD)	Total transaction volume (million kg)	Average gain (USD per kg)
Both	103.5	529.8	0.20
Requirement	109.4	515.3	0.21
Segment	121.7	608.5	0.20
No limits	127.8	606.5	0.21

Note: The table shows the gains from trade under four permit market designs, pooling years from 2001 onward. It compares the efficient benchmark ("no limits") to including market segmentation, imposing the harvest requirement, and the actual design that implements both trading limits. It then shows the gains from trade: the difference in total profits under the permit market versus all boats harvesting their permit allocation. This is decomposed into the total trade volume and the average gain per trade. It shows that segmentation impacts the average gain from trade, while the requirement impacts the total transaction volume. The requirement has a larger efficiency impact because it constrains more production relative to the efficient benchmark.

Table 8. Comparing the Two Trade Limits: Which Workers Gain?

	Gain (million USD)	Lose (million USD)
Segmentation		
Which workers?	Small-boat	Large-boat
Total transfer to workers	2.4	-4.7
Total transfer to their owners	-3.6	2.7
Harvest requirement		
Which workers?	High sellers	Everyone else
Total transfer to workers	12	-17
Total transfer to their owners	-28	15

Note: The table summarizes which workers and boat owners gain from the implementation of trade limits in Iceland's fisheries permit market. It compares total earnings to different groups of workers and firms when each trading limit is implemented, relative to a counterfactual market without trade limits. It emphasizes how each limit targets different workers: small-boat labor in the case of segmentation and labor on high-selling boats in the case of the harvest requirement. It also emphasizes that owners of non-targeted boats gain on average through changes in the permit price, namely because permit prices increase and this transfers surplus from buyers to sellers.

Table 9. Comparing the Two Trade Limits: Redistribution and Increase in Labor Demand

	Segment	Harvest requirement	Both
Income change, workers < median income (million USD)	0.90	2.98	3.95
Profit change, owners < median profits (million USD)	-1.90	4.85	3.62
Increase in labor demand (thousand person-days)	6.21	0.98	8.22
Cost (foregone gains from trade) (million USD)	6.17	18.5	24.3
Cost per $1 increase to low-income labor	6.82	6.19	6.15
Cost per 1,000 person-day increase in labor demand	0.99	18.9	2.9

Note: The table shows how each trade limit impacts both total labor demand and the distribution of income in Iceland's fisheries. It shows how four key economic outcomes change relative to a permit market with no trade limits: total income to the lower half of the fishery worker income distribution, total profits to the lower half of the boat owner profit distribution, the total labor demand in person-days, and the profits (i.e. the change in gains from trade). It then divides the change in profits by the change in earnings to low-income workers to get the cost of redistribution via each limit. It compares three market counterfactuals: segmenting the market only, only implementing the harvest requirement, and the actual design that implemented both limits. Segmentation mainly increases labor supply, while the harvest requirement is the better redistributive policy. Implementing both limits increases labor demand and promotes redistribution, while also shifting the incidence of the trade limits onto the owner of higher-profit boats.

Appendix

A Details on Framework

A.1 Implementing the profit-maximizing allocation

The profit-maximizing allocation assigns production to firms to maximize aggregate surplus, as if one agent controls all firms' production choices:

$$\max_{q_i} \sum_i \Pi(q_i, \mathbf{z}_i) \text{ subject to } \sum_i q_i \leq \bar{Q} \tag{44}$$

Under the solution, all firms equalize marginal profits to the marginal shadow cost λ:

$$\frac{\partial}{\partial q_i} \Pi(q_i, \mathbf{z}_i) = \lambda, \quad \forall i \tag{45}$$

where the marginal shadow cost λ is the Lagrange multiplier from the aggregate production cap.

Implementing the profit-maximizing allocation with a permit market. The seminal result underpinning environmental permit markets is that this profit-maximizing allocation is implementable by allocating permits to produce and allowing those permits to be traded in a market in competitive equilibrium (Crocker 1966; Dale 1968; Montgomery 1972). Let $\bar{q}_i$ be the allocation to firm i, such that $\sum_i \bar{q}_i = \bar{Q}$.

Assumption 1. *Firms take permit prices as given.*

Assumption 2. *There are no search or hassle costs in the permit market, such that the marginal cost of a permit is summarized by the permit price.*

Assumption 3. *Firms harvest all permit holdings q_i. They choose the permits to hold to maximize total profits, given the production profit function and permit allocation $\bar{q}_i$.*[33]

The final component of the competitive equilibrium determines the equilibrium permit price:

[33] In this simple setting, choosing permits or choosing production is equivalent. When production is uncertain or there are other provisions like banking, this is no longer the case.

Assumption 4. *The permit market clears such that aggregate permit choice is equal to the total number of permits available:*

$$\sum_i q(r, \mathbf{z}_i) = \sum_i \bar{q}_i = \bar{Q} \tag{46}$$

Under the optimization problem in (1) and market-clearing in (46), the market equilibrium implements the profit-maximizing allocation, i.e. a traditional First Welfare Theorem argument.[34] The permit price will be equal to the shadow marginal cost of production characterized in (45).

A.2 Details of day selection process

The selection process is as follows:

1. Define daily profits of boat i on day t as

$$\pi_{it} = E[R_{it}|\mathcal{I}_i] - c_{it} \tag{47}$$

2. Denote the ordered set of **positive** daily profits by $\{\pi_{i(k)}\}$, where

$$\pi_{i(1)} \geq \pi_{i(2)} \geq \cdots \geq \pi_{i(n)} \text{ and } \pi_{i(k)} \geq 0, \forall k$$

   Here, $k = 1, 2, \ldots, n$ indexes the ordered days, and $t_{(k)}$ is the original day corresponding to the k-th highest profit, i.e., $\pi_{i(k)} = \pi_{it_{(k)}}$.

3. Denote the corresponding expected harvests denoted by $\{q_{i(k)}\}$, where

$$q_{i(k)} = E[q_{it_{(k)}}|\mathcal{I}_i]$$

4. Let $\mathcal{S}(q_i, \mathcal{I}_i, c_i)$ be the set of days of highest profit until harvests equal permit holdings:

$$\mathcal{S}(q_i, \mathcal{I}_i, c_i) = \{t_{(1)}, \ldots, t_{(k)} \mid \sum_{m=1}^{k} E[q_{i(m)}|\mathcal{I}_i] \leq q_i\} \tag{48}$$

   which depends on c_i through the arrangement of days $t_{(k)}$.

[34] A set of theoretical work has confirmed how market power or transaction costs change the ability of the permit market to implement the profit-maximizing allocation (Hahn 1984; Stavins 1995).

5. Then the **day choice vector** $\mathbf{d}_i$ indicates which days are in $\mathcal{S}(q_i, \mathcal{I}_i, c_i)$:

$$\mathbf{d}_i = \{d_{it}\}_{t=1,\dots,T}, \text{ where} \tag{49}$$

$$d_{it} = \begin{cases} 1 & \text{if } t \in \mathcal{S}(q_i, \mathcal{I}_i, c_i) \\ 0 & \text{if } t \notin \mathcal{S}(q_i, \mathcal{I}_i, c_i) \end{cases} \tag{50}$$

6. The total number of days is

$$D(q_i, \mathcal{I}_i, c_i) = \sum_t d_{it} \tag{51}$$

A.3 Identifying revenue and quantity expectations

First, I assume that I perfectly specify the boat's information set at the time of day choice when forming quantity and revenue expectations:

Assumption 5. *Boats form expectations over daily revenue R_{it} and daily harvests q_{it} as a function of boat characteristics $\mathbf{z}_i$ and day characteristics $\mathbf{z}_t$. Therefore the set of chosen days depends on these characteristics: $\mathcal{S}(q_i, \mathcal{I}_i, c_i) = \mathcal{S}(q_i, \mathbf{z}_i, \mathbf{z}_t, c_i)$*

Any deviation between observed realized revenue and the expected revenue is the forecast error of a boat:[35]

Definition. *The **forecast error** of a boat i for day t is observed as*

$$\xi^R_{it} = R_{it} - E[R_{it}|\mathbf{z}_i, \mathbf{z}_t] \tag{52}$$

$$\xi^q_{it} = q_{it} - E[q_{it}|\mathbf{z}_i, \mathbf{z}_t] \tag{53}$$

such that I change the notation of the set of days of highest profits up until q_i so that it depends on these forecast errors: $\mathcal{S}(q_i, \mathbf{z}_i, \mathbf{z}_t, c_i, \xi^R_i, \xi^q_i)$.

Forecast errors are considerable in fisheries, since there is great uncertainty in the location and quantity of fisheries in different locations at particular times. Plugging into the inequalities above shows that beliefs over both quantities and revenues play a role in day

[35] This error term would also include measurement error in revenue. I observe fish prices as averages of species-size-gear mix-region-month bins, in both fish auctions and from contracts for vertically integrated boats, not the boat-specific prices directly. The major determinant of fish price is gear mix and month, since these influence the size and wholeness of the fish when landed, both of which I can control for. I observed quantities caught and registered by each fishing boat in Iceland, so I am not concerned about unobserved quantities that contribute to revenue.

choice:

$$d_{it} = 1 \implies R_{it} - \xi_{it}^R > c_{it}, \text{ and } t \in \mathcal{S}(q_i, \mathbf{z}_i, \mathbf{z}_t, c_i, \xi_i^R, \xi_i^q) \tag{54}$$

$$d_{it} = 0 \implies R_{it} - \xi_{it}^R < c_{it}, \text{ or } t \notin \mathcal{S}(q_i, \mathbf{z}_i, \mathbf{z}_t, c_i, \xi_i^R, \xi_i^q) \tag{55}$$

The following independence assumption is therefore crucial to identify cost characteristics separately from differences in expectations:

Assumption 6. *Forecast errors ξ_i^R and ξ_i^q are independent of daily production costs c_{it}, conditional on boat characteristics $\mathbf{z}_i$, day characteristics $\mathbf{z}_t$, and determinants of permit holdings q_i.*

Therefore boats do not systematically under- or over-predict with different quantity constraints or as days happen to be more or less costly. Moreover, I rule out dynamic dependence: early forecast errors do not change expectations later in the year. Under Assumptions 5 and 6, I can identify daily revenue and quantity expectations for all days t—whether boats went fishing or not—by regressing realized revenues and quantities on $\mathbf{z}_i$ and $\mathbf{z}_t$.

A.4 Identifying the crew size function

Assumption 7. *Let crew size be a flexible function of characteristics $\mathbf{z}_i$:*

$$L_{it} = L(\mathbf{z}_i) + \epsilon_{it}^L \tag{56}$$

where unobserved determinants of crew size ϵ_{it}^L are independent of q_i and $\mathbf{z}_i$.

The assumption rules out that variation in crew size conditional on $\mathbf{z}_i$ implies different profitabilities. It is not as strong as it appears in the fisheries context, so long as there is enough heterogeneity in $\mathbf{z}_i$. Crew sizes might vary because trainees are aboard, for example. I do not model gear choices, assuming they are fixed for the production process of a boat in a year, so the assumption implies that the total days at sea scale proportionally between the multiple gears they use. The assumption implies that average crew size across production days does not change with quantities, controlling for $\mathbf{z}_i$, a fact that holds true in the data. I can then estimate $L(\mathbf{z}_i)$ via regression of crew sizes on $\mathbf{z}_i$.

For the wage bill, I consider only single-boat firms and, with sufficient heterogeneity in $\mathbf{z}_i$, can relate harvest revenues to the wage bill by regression. This assumes taht unobserved determinants of the wage bill are

Assumption 8. *Total labor earnings or wage bill w_i depends on a share $\phi \in (0,1)$ of total realized harvest revenue $R_i = \sum_t R_{it}$:*

$$w_i = \alpha(\mathbf{z}_i) + \phi(\mathbf{z}_i) \cdot R_i + \epsilon_i^w \tag{57}$$

where unobserved determinants of the wage bill ϵ_i^w are independent of revenue forecast errors $\sum_t \xi_{it}^R$, conditional on $\mathbf{z}_i$.

I can then estimate the parameters of the revenue-sharing relationship $\alpha(\mathbf{z}_i)$ and $\phi(\mathbf{z}_i)$ via regression of wage bill on realized revenue, among single-boat firms.

I can then identify the ex-ante labor demand and ex-ante wage bill, i.e. how labor outcomes before within-year shocks are realized, using the day and revenue functions that I have identified. That is, expected labor demand for a quantity goal q_i is

$$\ell(q_i, \mathbf{z}_i) = L(\mathbf{z}_i) \cdot D(q_i, \mathbf{z}_i) \tag{58}$$

and the ex-ante wage bill is

$$w(q_i, \mathbf{z}_i) = E[w_i | q_i, \mathbf{z}_i] = \alpha(\mathbf{z}_i) + \phi(\mathbf{z}_i) \cdot \left(R(q_i, \mathbf{z}_i) - \sum_t \underbrace{E[\xi_{it}^R | q_i, \mathbf{z}_i]}_{=0} \right) \tag{59}$$

where the expected aggregate forecast shock $\sum_t E[\xi_{it}^R | q_i, \mathbf{z}_i]$ is zero by the independent assumption on forecast errors.

B Data Construction

B.1 Summary of fishery data sources and administrative data

The labor market data consists of three major datasets. All are at the annual level:

1. Old pay-slip data from 1981 through 1997. These were digitized by Sigurdsson (2021) and give some basic demographic information (e.g. gender) as well as earnings information for each firm at which an individual worked in a year.

2. New pay-slip data from 1993 through 2021. These are collected by Statistics Iceland and give some basic demographic data as well as earnings information for each firm at which an individual worked in a year.

3. Tax returns from 1989 through 2021. These give more detailed demographic information (highest degree, marital status, number of children, postal code of residence, born abroad/in Iceland) as well as total taxable earnings (labor income), tax burden, and a series of government transfers like pensions and unemployment assistance.

I receive all information from these datasets for individuals who ever worked on fishing boats (defined below). I also receive a random cross-section of 10% of the remaining observations, i.e. a random set each year of individuals who never worked on fishing boats. Thus it is not a panel of individuals.

B.2 Identifying the set of fishery workers

The fishery workers are identified in tax data using their national identification numbers (*kennitala*) from the following sources:

1. The crew registry kept by the Icelandic Transport Authority (*Samgöngustofa*), which registers individuals by their personal identifiers on the days on which they are at sea. This registry becomes more comprehensive over time. Ranked positions (captain, first mate, engineers) on the largest boats (> 50 gross tonnes) are tracked starting in 1981. All crew-members on large boats are added in 1986. The registry requirement decreased its size threshold in 1992, such that all crews for large boats (> 6 GT) were tracked in the 1990s. Ranked positions on small boats (< 6 GT) were added in 2001. The crew registry covered every person on a fishing boat starting in 2011.

2. Annual pay-slips given by each firm on their workers, which I received from Statistics Iceland from 1981 through 2021. Those pay-slips separately record earnings from fishing boats.

3. Annual tax returns for all workers, which I received from Statistics Iceland from 1988 through 2021. From 1988 through 1994 and 1997 through 2014, there was a tax exemption for workers on fishing boats. In 1995, the tax returns flagged the days at sea for fishing boat workers, which were used that year for tax exemption calculations.

Any individual ever recorded in the crew registry, receiving fish earnings, or receiving the tax exemption are flagged as ever working in the fishery. For these workers, I receive all years they appear in the labor market datasets mentioned above, regardless of whether they are working in the fisheries.

Individuals appearing in the crew registry can be linked directly to each fishing trip on each boat. Those linked using the tax exemptions—including small-boat workers for my period of study—are linked by firm identifiers in the tax and payslip data.

B.3 Constructing cod-equivalent harvests

The Icelandic fisheries management scheme consists of many species, each with their own cap. To allow for the exchange of species permits, the government has instituted species exchange rates (*þorskígildisstuðlar*) that convert a kg of each species permit to cod-equivalent units (*þorskígildi*). These exchange rates are set by the Fisheries Ministry for each regulatory year t, which starts September 1. It is based on the average unit price of each species relative to that of cod from May 1 of the previous calendar year to April 30 of the current calendar year t. For example, if the average unit price of cod was 120 Icelandic krónur per kg (i.e. total revenue divided by total harvests), and the average unit price of haddock was 60 ISK per kg, then each kilogram of haddock in permits or harvests is 0.5 cod-equivalent kilograms.

Importantly for my analysis, the harvest requirement binds at the cod-equivalent level: boats must harvest half their permit allocation in cod-equivalent units. Therefore harvest and permit quantities throughout the analysis are in cod-equivalent kg or metric tons (1,000 kg).

I collect species exchange rates from the website of the Iceland Fisheries Authority (*Fiskistofa*) and, for earlier years, from regulatory announcements by the Fisheries Ministry in the Icelandic government register (*Reglugerðarsafn*). I then multiply the quantities of each species by these exchange rates to create cod-equivalent harvests and permit amounts.

B.4 Constructing annual permit rental price

Permits are traded throughout the year in markets for different species. The structural model, however, assumes one period of trading in the year, and I consider uni-dimensional quantities in cod-equivalent units. Therefore, my measure of each year's permit rental price is the average permit price across all transactions in all species, weighted by the transaction amount in cod-equivalent kilograms.

The model therefore does not account for price dispersion in the year, which, along with the presence of brokers, is an indication of search frictions. The average permit market at the species-year level has a coefficient of variation of 0.335, with an average of 0.111 in cod permit markets where most transactions take place. The coefficients of variation are on average 37% higher in small-boat permit markets. These are similar in magnitude to other markets where search frictions have been studied: 0.19 to 0.25 (retail wine), 0.20 to 0.24 (waste hauling), and 0.22 (prescription medication) (Sorensen 2000; Jaeger and Storchmann 2011; Salz 2022). Comparing another environmental market, Shapiro and Walker (2024) calculate a coefficient of variation of 1.04 in the average pollution offset market they study, larger by an order of magnitude.

C Details on Estimation

C.1 Estimating day choice: method of simulated moments

Here is an outline of the method of simulated moments. Recall that the mean and variance of the daily cost distribution are gear-mix-specific functions of boat size. If g is the gear mix of the boat, then

$$\mu(\mathbf{z}_i) = \alpha_1^g + \alpha_2^g \cdot \log(\text{boat size}) \tag{60}$$

$$\sigma(\mathbf{z}_i) = \alpha_3^g + \alpha_4^g \cdot \log(\text{boat size}) \tag{61}$$

For any proposed cost parameters $\{\hat{\alpha}\}$,

1. Calculate $\hat{\mu}_i = \hat{\alpha}_1^{g_i} + \hat{\alpha}_2^{g_i} \cdot \log(\text{boat size}_i)$ and $\hat{\sigma}_i = \hat{\alpha}_3^{g_i} + \hat{\alpha}_4^{g_i} \cdot \log(\text{boat size}_i)$, given boat i's gear mix g_i and its boat size.

2. Take S draws of the cost shock vector, where, for each simulation $s \in S$, there is a vector $c_i(s)$ of T draws from $c_{it} \sim^{iid}$ Log-normal$(\hat{\mu}_i, \hat{\sigma}_i)$. T is the total possible days at sea. For each simulation s,

   (a) Use the realized cost vector $c_i(s)$ to calculate the vector of daily profits $\pi_i = \{\pi_{it}\}_{t=1}^T$, where $\pi_{it} = \hat{R}_{it} - c_{it}$, where $\hat{R}_{it}$ is the result of the regression on daily revenues.

   (b) Form the ordered set of days $\{t_{(k)}\}$ by ranking all days with $\pi_{it} \geq 0$ by their daily profits π_{it}. Denote the corresponding expected harvests as $\{q_{i(k)}\}$. Denote the corresponding expected revenues as $\{\hat{R}_{i(k)}\}$.

   (c) Take the set of most profitable days until expected harvests are equal to permit holdings: $\sum_{m=1}^k q_{i(m)} = q_i$, where q_i is post-trading permit holdings for boats in the permit market and is the total cod permits for boats under non-tradeable cod permits (small boats before 2000). Call this set $\mathcal{S}_i^s$.

   (d) Re-order the set of expected daily revenues $\{\hat{R}_{i(k)}\}$ from highest to lowest among days in $\mathcal{S}_i^s$. Call this the marginal revenue curve $\hat{R}_i^s = \{\hat{R}_{i(n)}\}$, i.e. the expected daily revenues of the chosen days and (n) denotes the ranking from highest to lowest revenue.

3. Collect the simulated moments $g(\hat{\alpha})$:

   (a) The expected daily revenue of the 1st through T'th highest revenue days: $R_{i(n)}(\hat{\alpha}) =$

$\frac{1}{S}\sum_s \hat{R}^s_{i(n)}$ for all ranks (n). These represent T moments, which can be zero. The empirical counterpart is $\hat{R}_{i(n)}$.

(b) The total number of days at sea: $D_i(\hat{\alpha}) = \frac{1}{S}\sum_s |\mathcal{S}^s_i|$. The empirical counterpart is $\hat{D}_i$.

4. The objective function is the squared distance between the simulated moments and the empirical moments:

$$Q(\hat{\alpha}) = [g(\hat{\alpha}) - \hat{g}]W'[g(\hat{\alpha}) - \hat{g}] \tag{62}$$

where W is a weighting matrix.

I then search for cost parameters α that minimize $Q(\alpha)$. I use the two-step optimal weight matrix for W.

C.2 Constructing the profit functions

For each gear mix (which impacts costs and revenue/quantity expectations) and region (which impacts revenue/quantity expectations),

1. Set a grid of boat sizes and quantities, namely an even grid of values from the minimum to maximum for boats with that gear mix in that year.

2. Simulate cost draws using the estimates of the cost distribution $\hat{F}_{c|\mathbf{z}}$. Save total profits, i.e. $\Pi^s_i = \sum_t \pi_{it}$ for chosen days under the cost draw s. Also save the total days at sea D^s_i as before. Labor earnings rely on harvest revenues, so I sum these up separately as well: R^s_i.

3. Average across all simulations to find harvest profits $\Pi(q_i, \mathbf{z}_i)$, day choice $D(q_i, \mathbf{z}_i)$, and revenues $R(q_i, \mathbf{z}_i)$ for this gear mix-size-quantity combination.

4. Interpolate across quantity-size grid points with cubic splines.

5. Calculate marginal profits as the numerical derivative $\partial\Pi(q_i, \mathbf{z}_i)/q_i$ using the interpolation.

C.3 Estimating market parameters: F_Δ and the transaction cost function

For a guess of parameters $\theta = (\mu_\Delta, \sigma_\Delta, \alpha, \beta, \eta)$,

1. Calculate $\frac{\partial}{\partial q_i} TC(\bar{q}_i - q_i)$ for each boat i using the permit allocation and post-trade permit holdings.

2. If i's permit holdings q_i are not in the bunching range (defined as 50%-60% of permit allocation $\bar{q}_i$),

   (a) Calculate

   $$\Delta_i = \frac{1}{r_i}\left(\frac{\partial}{\partial q_i}\Pi(q_i, \mathbf{z}_i) - \frac{\partial}{\partial q_i} TC(q_i, \bar{q}_i)\right) \tag{63}$$

   where r_i is the weighted average permit price for the year for i's permit market, where weights are the transacted volume of permits in cod-equivalent units.

   (b) Standardize the value to $\tilde{\Delta}_i = (\exp(\Delta_i) - \mu_\Delta)/\sigma_\Delta$

   (c) Then i's individual likelihood is

   $$p_i = \Pr(\Delta_i|\theta) = \phi(\tilde{\Delta}_i) \tag{64}$$

   where ϕ is the probability density function of the standard normal.

3. If i's permit holdings are in the bunching range,

   (a) Calculate the threshold

   $$\bar{\Delta}_i = \frac{1}{r_i}\left(\frac{\partial}{\partial q_i}\Pi(\bar{q}_i/2, \mathbf{z}_i) - \frac{\partial}{\partial q_i} TC(\bar{q}_i/2)\right) \tag{65}$$

   (b) Standardize the threshold to $\tilde{\bar{\Delta}}_i = (\exp(\bar{\Delta}_i) - \mu_\Delta)/\sigma_\Delta$

   (c) Then i's individual likelihood is

   $$p_i = \Pr(i \text{ bunches}|\theta) = \Phi(\tilde{\bar{\Delta}}_i) \tag{66}$$

   where Φ is the cumulative distribution function of the standard normal.

4. Then calculate the log likelihood

   $$\mathcal{L}(\theta) = \sum_i \log p_i \tag{67}$$

I then find θ that maximizes $\mathcal{L}(\theta)$.

C.4 Parameter estimates

Tables C1 and C3 give the cost and market parameter estimates, respectively.

C.5 Model fit

In this section, I summarize a series of model fit exercises. First I focus on two variables in the production process: the days at sea and the daily revenue curve. Figure C1(a) plots the number of days at sea; the model-implied values match closely, though with a slight underprediction at the top. A regression of the actual days on the model-implied days gives an R^2 of 97%. Figures C1(b) and (c) then compare the expected daily revenue of each chosen day in the data and model, where (b) plots every day while (c) shows the binned scatter-plot compared to the 45-degree line. The model fit is close on average, though sub-figure (b) shows that the model predicts that boats choose higher-revenue days than they actually do in the data. This could be because of unobserved cost differences across days (e.g. wintery conditions) that I do not currently control for.

I next turn to the fit of the permit market decisions. Table C4 shows the model-implied non-trading rates (defined as post-trading permit holdings within 99.5%-100.5% of permit allocations) and the bunching rate (defined as having post-trading permit holdings within 50%-60% of permit allocations). This is among boats in the permit market and therefore excludes small boats before 2001. In most years, the model under-predicts the share of boats that do not trade, though the non-participation rates overall are small. It also under-predicts the bunching rate in most years.

Figure C1(d) plots the model-implied permit choice against the permit holdings in the data. It shows the line of best fit for values about $q = \exp 9$ to emphasize that the fit is sensible except for boats with small permit holdings in the data. Among these boats, the model vastly over-predicts the permit holdings. This is not an artifact of ignoring boats under 50% of the permit allocations, since I only estimate the market parameters on boats above the 50% cutoff (assuming that those below are exiting and are not affected by the rule). A regression of the log of model-implied pemrit holdings on actual log permit holdings has an R^2 of 74% overall and 81% at higher levels. Sub-figures (e) and (f) show the binned scatter plot of permit choice (both model-implied and actual) against permit allocation. These emphasize two facts: first, that the model over-predicts permit choices for boats of low allocations by an entire log point. This indicates that the small estimated transaction costs do not fit the data at the bottom of the distribution. Second, the model under-predicts permit choices for small boats across the entire distribution. This could be because the determinants of permit choice are not market-specific and do not relate to size; that is, the Δ_i and transaction cost function $TC(\bar{q}_i - q_i)$ have no relation to boat characteristics.

In line the over-prediction of permit demand among small boats, the model implies aggregate permit demand (at the observed permit prices) within 5% of actual aggregate permit demand in the big-boat market (1.79 vs. 1.70 million tons across all years). In the small-boat market, however, I over-predict aggregate permit demand by 57% (246 vs. 156 thousand tons).

D Details on Construction of Counterfactuals

D.1 Finding counterfactual equilibrium permit prices

Here I outline the algorithm by which I calculate new equilibrium permit prices. Let

$$\bar{Q}^0 = \sum_{i \in n} \tilde{q}(r_n, \mathbf{z}_i, \bar{q}_i)$$

be the aggregate number of permits chosen in the model at the observed permit price r_n for market n (small- vs large-boat vs unified permit market). For the unified market counterfactual, use the aggregate number of permits across boat markets. For the no harvest requirement counterfactual, use the unconstrained permit choice function $q(r_n, \mathbf{z}_i, \bar{q}_i)$. Starting at the observed price r_n,

1. Consider a new candidate price r'. Aggregate each boat's permit choice to find aggregate permit choice $\bar{Q}(r')$.

2. If $\bar{Q}(r') > \bar{Q}^0$ (excess demand), find a new candidate price $r'' = r' + s$. If $\bar{Q}(r') < \bar{Q}(r')^0$ (excess supply), find a new candidate price $r'' = r' - s$. Find the new aggregate choice $\bar{Q}(r'')$. Then,

   (a) If $|\bar{Q}(r'') - \bar{Q}(r')| < \text{tol} \cdot \bar{Q}^0$, stop. I set tol to 0.001, i.e. 0.1% of the actual aggregate number of permits.

   (b) Otherwise, if $\bar{Q}(r'') - \bar{Q}(r')$ is the same sign as $\bar{Q}(r') - \bar{Q}^0$, let the new step size be the same: $s' = s$. If it is of opposite sign, halve the step size: $s' = s/2$. Repeat process with new candidate price $r''' = r'' + s'$.

D.2 Calculating aggregate permit supply and demand

To calculate the excess permit supply and demand functions that determine the permit price in competitive equilibrium, I take a grid of permit prices and use the permit choice functions and permit allocations. For any r,

1. Calculate permit choice $q(r, \mathbf{z}_i, \bar{q}_i)$ for all i in the market, under the actual or counterfactual design.

2. Find the excess demand or excess supply of each participant i in the market:

$$q_i^d(r) = \max\{0, q(r, \mathbf{z}_i, \bar{q}_i) - \bar{q}_i\}$$

$$q_i^s(r) = \max\{0, \bar{q}_i - q(r, \mathbf{z}_i, \bar{q}_i)\}$$

3. Aggregate permit demand and supply are therefore

$$\mathcal{D}(r) = \sum_i q_i^d(r)$$

$$\mathcal{S}(r) = \sum_i q_i^s(r)$$

The graphs then trace the two curves for each market.

Appendix Table C1. Cost parameters

Gear mix	Year	α_1^g	α_2^g	α_3^g	α_4^g
1	1999	-0.020	0.149	0.865	0.057
2	1999	0.318	0.134	0.810	0.046
3	1999	-0.624	0.107	0.942	0.061
4	1999	0.169	0.066	0.121	0.086
5	1999	-0.410	0.077	1.647	0.118
6	1999	0.287	0.076	0.546	0.112
7	1999	-4.064	1.437	3.155	-0.415
1	2000	-0.021	0.127	0.715	0.049
2	2000	0.041	0.072	0.539	0.077
3	2000	-0.781	0.088	0.847	0.079
4	2000	0.047	0.057	-0.002	0.083
5	2000	0.699	0.157	10.140	0.403
6	2000	0.622	0.124	1.135	0.099
7	2000	4.381	0.514	1.560	0.025
1	2001	0.311	0.169	0.745	0.065
2	2001	0.563	0.113	0.547	0.078
3	2001	-0.384	0.099	0.742	0.059
4	2001	1.467	-0.551	-2.724	1.521
5	2001	0.303	0.109	1.582	0.138
6	2001	0.713	0.073	0.553	0.115
7	2001	1.194	0.146	7.744	0.306
1	2002	-0.076	0.107	0.510	0.030
2	2002	-0.092	0.079	0.265	0.073
3	2002	-1.784	0.024	1.258	0.090
4	2002	-1.940	1.227	0.230	0.065
5	2002	-1.543	0.596	0.460	0.090
6	2002	-0.541	0.482	4.629	-0.815
7	2002	-3.513	1.346	5.013	-0.690
1	2003	-0.346	0.034	0.219	0.093
2	2003	-0.163	0.075	0.541	0.073
3	2003	-0.941	0.052	0.309	0.074
4	2003	-1.681	0.993	-0.463	0.145
5	2003	-1.501	0.569	0.361	0.065
6	2003	-3.037	0.979	3.061	-0.396
7	2003	-0.370	0.244	6.092	0.270
1	2004	-0.662	0.077	0.682	0.041
2	2004	0.095	0.076	0.333	0.080
3	2004	-1.189	0.069	-0.095	0.057
4	2004	-3.050	1.471	0.346	0.059
5	2004	-0.985	0.463	0.071	0.198
6	2004	-3.031	1.019	4.481	-0.772
7	2004	4.356	0.299	7.790	-1.008

Appendix Table C2. Market parameters

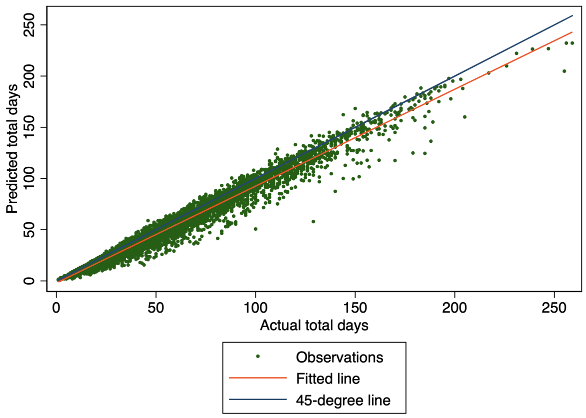
Year	μ_Δ	σ_Δ	α	η	β
1999	-0.60	0.52	-0.93	-2.83	-11.16
2000	-0.52	0.53	0.11	-14.35	-16.64
2001	-0.31	0.29	0.71	-3.96	-15.70
2002	-0.17	0.47	-0.96	-2.04	-17.02
2003	0.12	0.69	-3.17	-1.47	-18.86
2004	1.03	-0.65	1.13	-1.30	4.35

Appendix Table C3. Influence of Designs

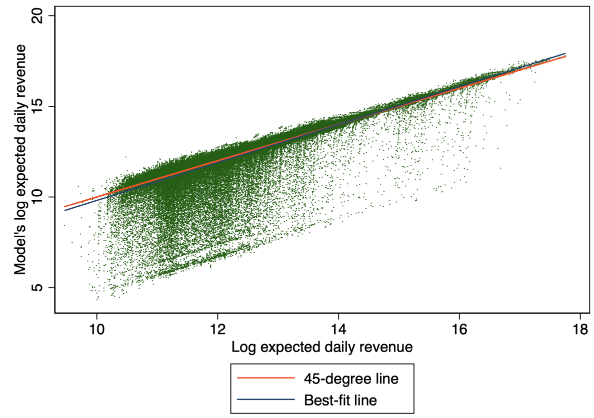
Year	Design	Actual (1)	Segmented, no limit (2)	Unified, with limit (3)	Unified, no limit (4)
1999	Gains from trade (billion ISK)	2.84	3.93	-	-
	Person-days, targeted boats (thousand)	35.36	29.73	-	-
	Wage bill on targeted boats (billion ISK)	1.51	1.24	-	-
	Harvest share of small/medium boats	-	-	-	-
	Harvest profits of small/medium boats	-	-	-	-
	Permit price	77.0	45.1	-	-
2000	Gains from trade (billion ISK)	3.91	5.70	-	-
	Person-days, targeted boats (thousand)	20.77	17.69	-	-
	Wage bill, targeted boats (billion ISK)	1.11	0.96	-	-
	Harvest share of small/medium boats	-	-	-	-
	Harvest profits of small/medium boats	-	-	-	-
	Permit price	100.9	62.5	-	-
2001	Gains from trade (billion ISK)	5.16	5.42	5.59	5.92
	Person-days, targeted boats (thousand)	26.49	20.33	26.50	19.93
	Wage bill, targeted boats (billion ISK)	1.07	0.90	1.07	0.90
	Harvest share of small/medium boats	0.11	0.11	0.10	0.09
	Harvest profits of small/medium boats	3.24	3.25	2.99	2.91
	Permit price	111.1, 84.7	104.8, 77.7	106.6	100.0
2002	Gains from trade (billion ISK)	4.09	5.38	4.13	5.35
	Person-days, targeted boats (thousand)	38.35	32.49	38.38	32.44
	Wage bill, targeted boats (billion ISK)	2.50	2.30	2.50	2.30
	Harvest share of small/medium boats	0.17	0.17	0.15	0.16
	Harvest profits of small/medium boats	4.75	4.83	4.46	4.81
	Permit price	89.9, 69.0	61.2, 60.3	84.7	61.2
2003	Gains from trade (billion ISK)	3.69	4.41	3.96	4.72
	Person-days, targeted boats (thousand)	39.49	29.99	39.50	29.94
	Wage bill, targeted boats (billion ISK)	1.20	0.99	1.20	1.00
	Harvest share of small/medium boats	0.17	0.16	0.15	0.14
	Harvest profits of small/medium boats	4.72	4.80	4.31	4.38
	Permit price	74.0, 49.0	61.5, 41.8	68.4	57.2
Total	Gains from trade (billion ISK)	19.69	24.84	13.68	16.00
	Person-days, targeted boats (thousand)	160.46	130.23	104.38	82.31
	Wage bill, targeted boats (billion ISK)	7.39	6.39	4.77	4.20
	Harvest share of small/medium boats	0.15	0.15	0.13	0.13
	Harvest profits of small/medium boats	12.71	12.88	11.76	12.10

Note: The table shows the gains from trade and four key outcomes for the permit market as designed and from simulated markets without the two trading limits I study: the harvest requirement and segmentation. For the harvest requirement, the relevant outcomes are the labor demand and earnings on the targeted boats, i.e. the boats that bunch at 50% of their permit allocation in the actual market. For segmentation, the outcomes are the harvest share and profits of boats in the small-boat market, which includes boats under 6 gross tons that were exempt from permit trading until 2001 and medium-sized boats who were placed in their permit market in 2002. It then sums the values in the final rows.

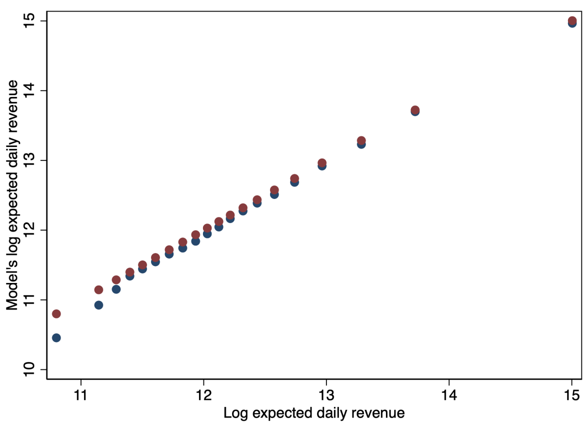
Appendix Figure C1. Model fit: production



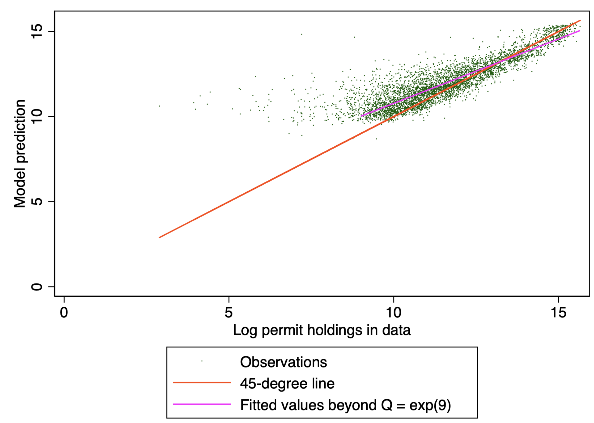
(a) Number of days



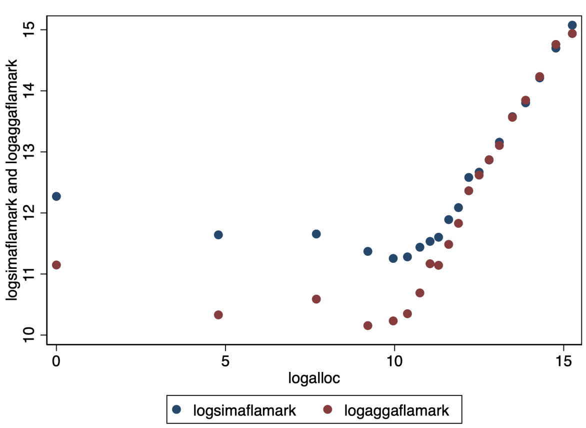
(b) Daily revenue



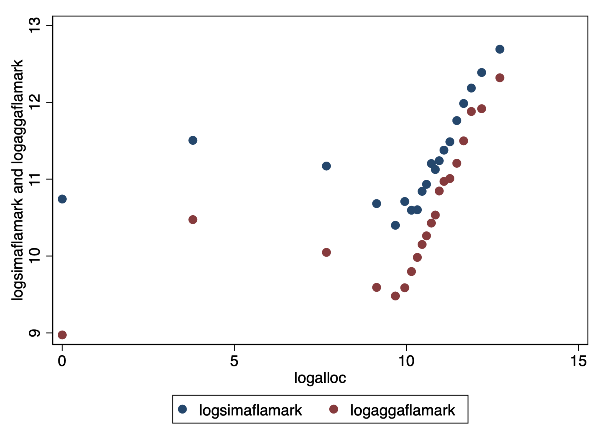
(c) Binned scatter: Daily revenue



(d) Permit choice



(e) Permit choice by allocation, big boats

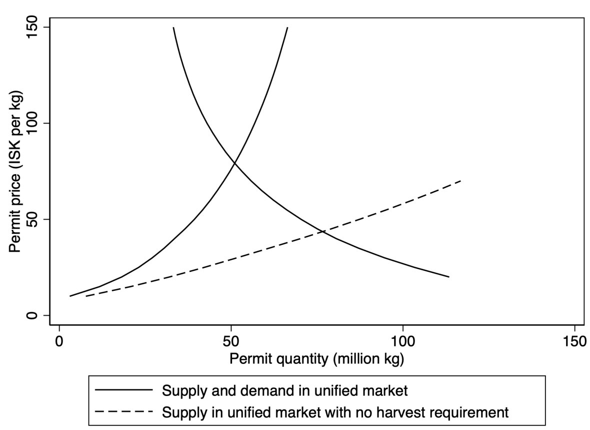


(f) Permit choice by allocation, small boats

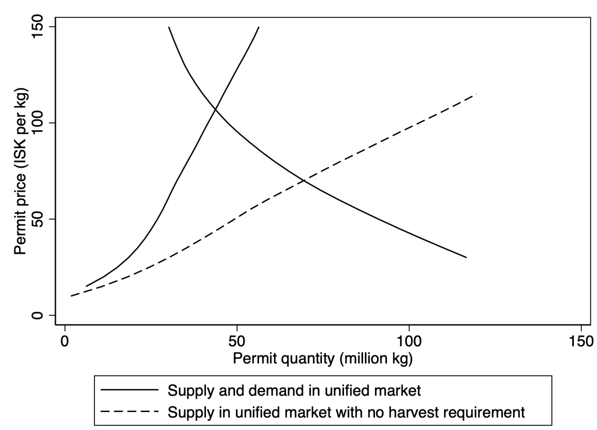
Appendix Table C4. Comparison of Participation and Bunching Rates

Year	Model's fraction with no trading	Actual fraction with no trading	Model's bunching rate	Actual bunching rate
1999	0.021	0.037	0.098	0.076
2000	0.020	0.025	0.101	0.048
2001	0.014	0.065	0.044	0.117
2002	0.017	0.055	0.055	0.118
2003	0.008	0.049	0.060	0.155
2004	0.019	0.032	0.070	0.178

Appendix Figure D1. Impact of trading limits: 1999 and 2000

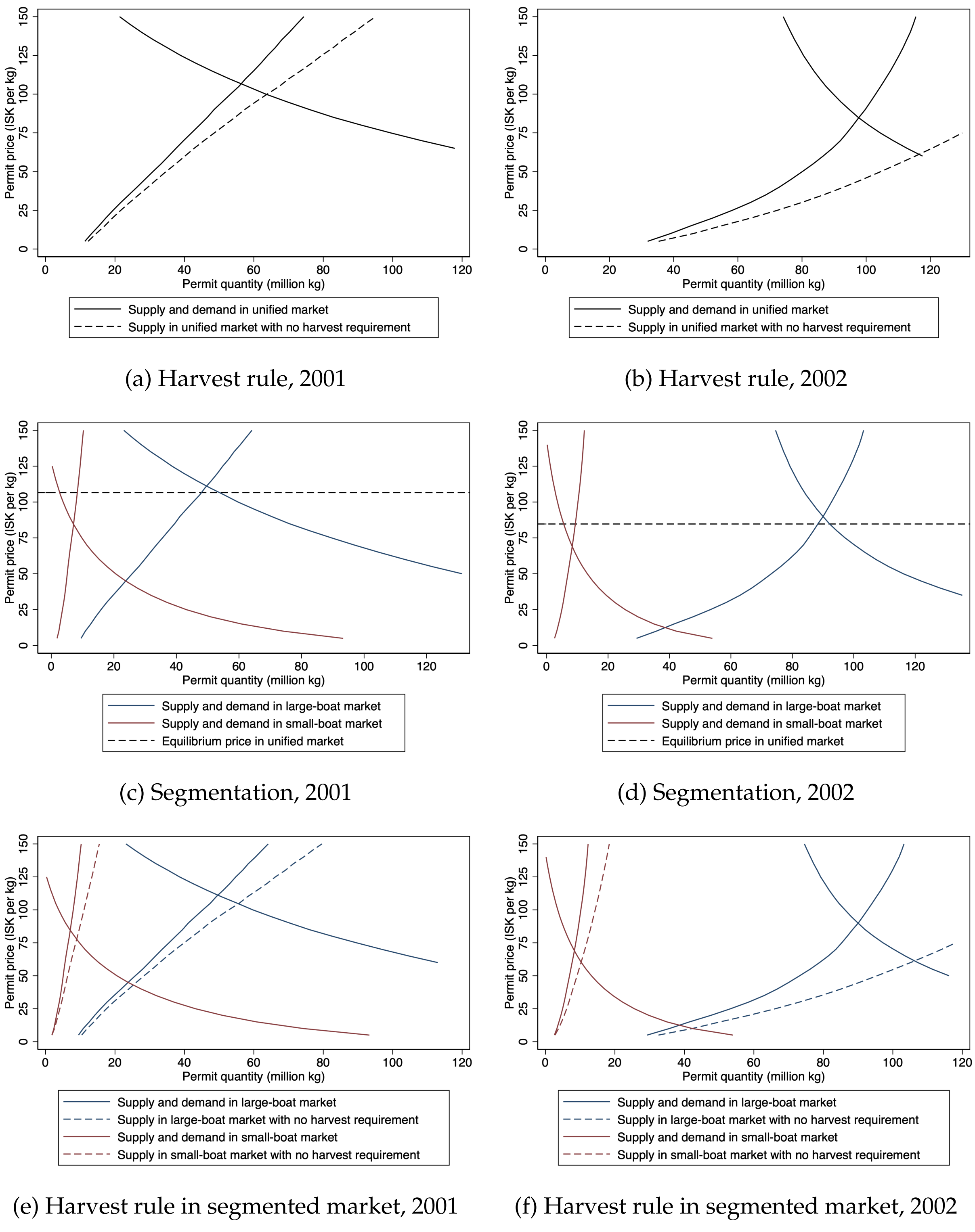


(a) 1999



(b) 2000

Appendix Figure D2. Impact of trading limits: 2001 and 2002



(a) Harvest rule, 2001

(b) Harvest rule, 2002

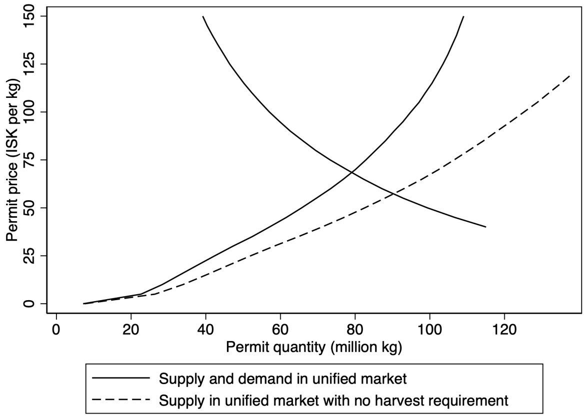
(c) Segmentation, 2001

(d) Segmentation, 2002

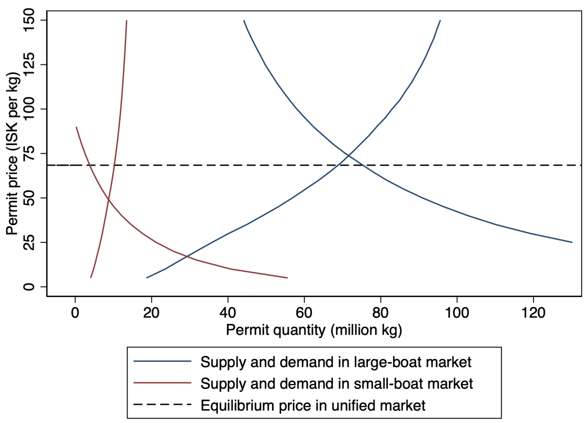
(e) Harvest rule in segmented market, 2001

(f) Harvest rule in segmented market, 2002

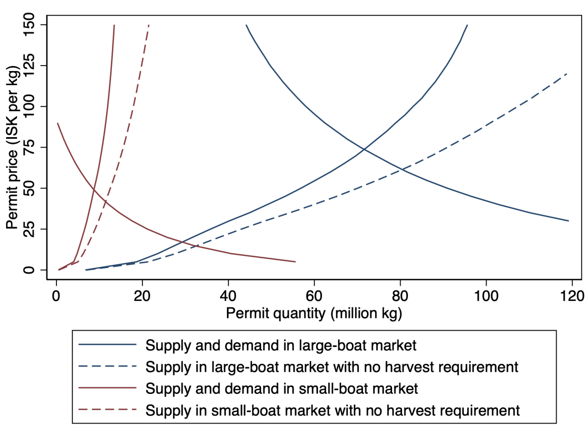
Appendix Figure D3. Impact of trading limits: 2003 and 2004



(a) Harvest rule, 2003



(b) Segmentation, 2003



(c) Harvest rule in segmented market, 2003