Subsidizing the tragedy of the commons: Fuel subsidies modify fishing behavior and drive overfishing

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This version: June 17, 2025

Abstract

Fuel subsidies in fisheries are regarded as a leading cause of overfishing, but there is little empirical evidence to substantiate this claim. Here, we assembled and analyzed nine years of high-resolution data on fisher-level fuel subsidy allocations, fishing activity, and fisheries production in Mexico's shrimp trawl fleet to empirically test whether fuel subsidies drive overfishing. By leveraging year-to-year variations in the subsidy policy, we find that when an economic unit receives a fuel subsidy, it increases its fishing effort by 31.4%, fished area by 11.2%, and landings by 59.5%. Moreover, a 1% increase in the subsidy amount causes a 0.1% increase in fishing hours, a 0.04% expansion of fishing grounds, and a 0.15% increase in landings. Overall, fuel subsidies explain at least 23.7% of total annual fishing time, 7.9% of fished area, and 47% of reported landings in Mexico's industrial shrimp trawl fleet. We also identify fishing grounds that are disproportionately exploited as a result of the subsidy program, showcasing the spatial implications of a non-spatial policy. Our results lend support to calls to eliminate fuel and other input subsidies in fisheries worldwide.

Significance Calls for fishery subsidy reforms exist in Target 14.6 of the Sustainable Development Goals and Target 18 of the Kunming-Montreal Global Biodiversity Framework, and have been discussed and generally agreed on at the World Trade Organization. Our ability to predict the social and environmental outcomes of such proposals hinges on our understanding of how much fishing is attributable to subsidies, a quantity that has remained elusive. Our study addresses this knowledge gap by estimating the ways and magnitudes in which fuel subsidies drive overfishing. Our insights allows us to form expectations about the potential benefits of a global subsidy reform.

1 Introduction

Fuel subsidies to the world's fishing fleets lower the cost of fishing and are thought to be one of the leading causes of fisheries over-exploitation[1]. Scientists, practitioners, and politicians worldwide have called for eliminating or reducing fuels subsidies as part of a global concerted efforts to rebuild fish stocks[2, 3]. However, our ability to predict the social and environmental outcomes of a reform hinge on the answer to two crucial and as-of-now unanswered questions: "How much additional fishing effort is caused by fuel subsidies?" and "How does this additional effort, if any, manifest in the world?" If the amount of overfishing induced by fuel subsidies is relatively large, then the reforms could have large upsides. However, if the amount is small relative to other sources of overfishing (*e.g.* by-catch or illegal, unreported, and unregulated fishing), then it may be better to focus management efforts on addressing those. Here, we use high-resolution vessel tracking data from Mexican shrimp trawlers and long-term administrative data on vessel-level subsidy allocations to provide the first causal estimates of the effect of fuel subsidies on overfishing and fishing behavior.

Subsidizing an input such as fuel generally leads to a socially inefficient over-use of that input. When the input usage creates an externality (like carbon emissions or overfishing [4, 1]), the subsidy leads to two sources of lost economic efficiency (or deadweight losses). The first is the usual cost associated with a market distortion; this arises because resources are being misallocated. The second is associated with greater production of the externality itself. This is an under-studied topic, but is of pivotal importance to the sustainability of agriculture, fisheries, mining, and other natural resource use settings, and implicitly underpins recent policy efforts to curb subsidies in these sectors [2, 3]. This paper focuses on this second type of deadweight loss in the context of fuel subsidies in industrial fisheries. As we will show, economic units receiving a fuel subsidy spend more time fishing and increase the spatial footprint of their fishing activities. These individual behavioral responses add up to large amounts of additional fishing that disproportionately affect some fishing grounds more than others.

Fisheries subsidies are prevalent in most coastal nations and are believed to be one of the main drivers of overfishing [1]. In 2018 alone, nations provided a total of USD $35.4 billion in fisheries subsidies, USD $7.7 billion of which were granted as fuel subsidies. These large numbers have prompted calls for global subsidy reforms[2, 3], and particular focus has been placed on cost-reducing and capacity-enhancing subsidies such as fuel subsidies and vessel modernization programs. Although there is broad consensus about the potential threats and damages posed by fuel subsidies in fisheries, empirical evidence on their social and environmental costs remains limited to just a few studies. For example, Sakai [5] showed that subsidies that reduce costs may have negative effects when extraction of fish is not limited. Recent work by Englander et al. [6] shows that fuel subsidies to China's distant water fishing fleet have a large impact on the fleet's fishing effort, and that biological overfishing could be greatly reduced in several regions if China were to half fuel subsidies to it's distant water fleet. And, finally, Revollo-Fernández et al. [7] studied Mexico's subsidy program and found a positive relationship between annual government expenditure on fuel subsidies and annual fisheries production, but the coarse nature of their data prevented them from identifying vessel-level changes in fishing behavior and production. Our work makes a direct contribution to this literature by using long-term and high-resolution data on vessel-level subsidy allocations and behavior to identify changes in vessel- and fleet-level fishing behavior, and their environmental consequences.

Subsidizing fuel may be particularly damaging to the environment because it reduces the cost of fishing, which can incentivize fishers to fish more than they would without a subsidy[1]. However, two crucial aspects remain unknown: 1) the channel through which a fisher's behavioral response to a subsidy deteriorate the environment, and 2) the magnitude of these changes to fishing behavior.

When subsidized, a captain may consider the following options: spend more time fishing in their fishing grounds, search for –and exploit– other fishing grounds, or some combination of both. Furthermore, these changes likely result in higher harvesting rates. As an example to motivate our analysis, Figure 1 shows how fishing activity by one economic unit changes when they receive a fuel subsidy of MXN \$231,543 (about USD \$12,388). The patterns suggest that the fuel subsidy increases both fishing hours (from 513 hrs/yr to 2,880 hrs/yr) and the extent of fishing grounds (from 8,395 Km^2 to 12,572 Km^2). Of course, this is just an example from a single economic unit in our data, and it does not account for other time-varying factors that could drive the change in time and extent of fishing (*e.g.* changes in the price of fuel or environmental conditions). However, it highlights how the level of environmental degradation will depend on the channel, as well as on the magnitude of the increases in each (*i.e.* how much more fishing and how much more area fished). These unknowns (the channels and their magnitudes) limit our ability to accurately predict the sustainability benefits of a subsidy reform. Thus, understanding the behavioral underpinnings of these responses and the environmental implications of fuel subsidies is paramount to fostering sustainable fisheries.

Studying the effect of subsidy policies in fisheries is difficult because subsidies are often opaque and allocated to small-scale actors who are notoriously heterogeneous and hard to monitor. Mexico, however, provides a relevant and interesting empirical context in which to study the effect of subsidies on fishermen behavior. Mexico is the world's 11^{th} largest fishing nation, and produces around 1.5M tonnes of seafood from capture fisheries[8]. Importantly, Mexico's well-developed fishing industry has a long-history of being subsidized by federal programs [9, 10, 7] that have evolved through time.

The fuel subsidy program relevant to our period of analysis (2011 - 2019[1]) is administered as follows: Mexico's fishery management agency (CONAPESCA) maintains a limited-entry roster of economic units (fishers or fishing companies) eligible to receive a fuel subsidy in any given year. An economic unit can only "enter" the roster if another unit "exits" the roster, either voluntarily or as a penalty (*i.e.,* failure to carry a working vessel monitoring system). Subsidized economic

[1]Note that the fuel subsidy program was discontinued after its 2019 iteration, and was replaced by a program that provides direct cash transfers to all fishers. See El Sudcaliforniano: Pega a pescadores la falta de apoyos for a news report and a letter by Senator Cecilia Sánchez García denouncing the removal of fisheries subsidies in 2023.

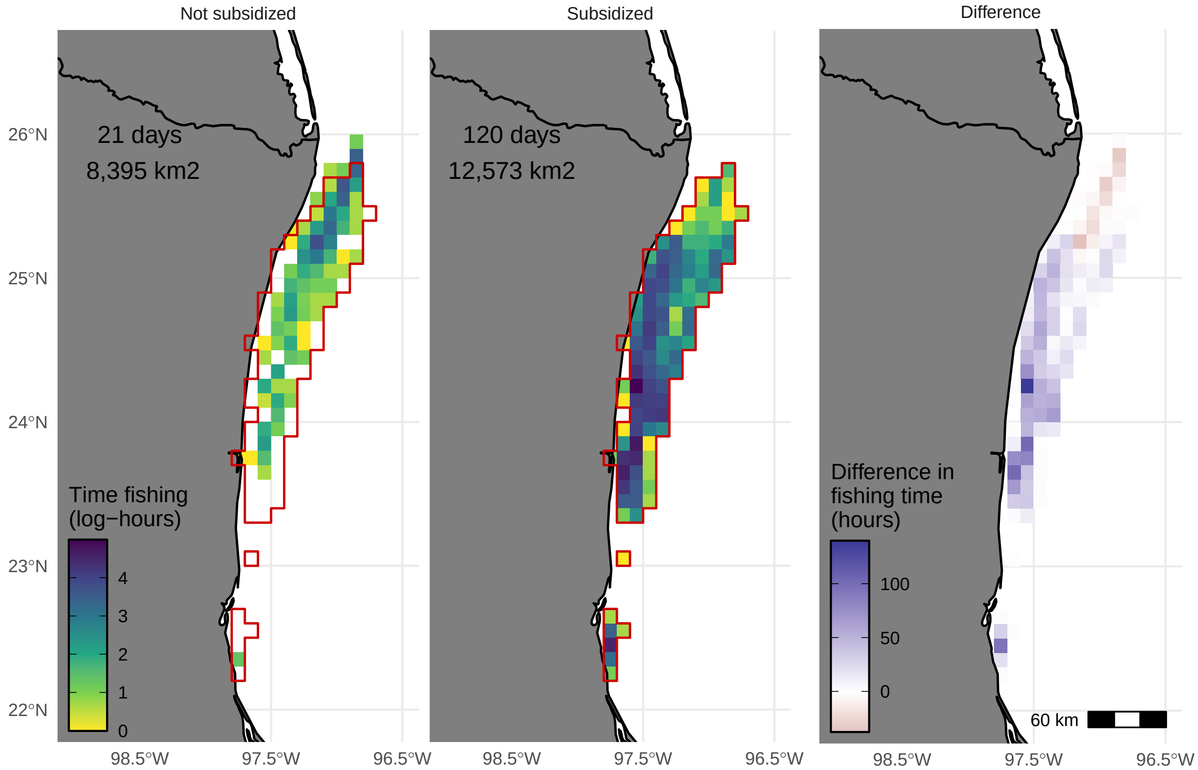

Figure 1: Example of changes in intensive and extensive margins of fishing behavior in relation to subsidy status. Maps show fishing activity by one economic unit in a year without a subsidy (2011, left), a year with a subsidy (2016, middle), and the difference between both (right). The red polygons in the left and middle panels outline the area fished when the economic unit was subsidized. Note that the economic unit spends around five times more time fishing when subsidized than when not (darker pixels), and that the extent and number of its fishing grounds is around 50% larger when subsidized than when not (red polygons show a larger footprint).

units receive money via a government-issued debit card, which can be used at fueling depots. In principle, the subsidy amount is a function of a vessel's engine power, although fisheries managers have the ability to adjust the final allocation based on annual national allocations to the program (For more details, see Supplementary Materials). Any unspent money at the end of the year is reclaimed by CONAPESCA. The program design provides two sources of variation that we will exploit to identify the causal effect of fuel subsidies on fishing behavior: (1) entry and exit from the roster changes a fisher's treatment status (*i.e.*, subsidized or not), and (2) the annual variation in the subsidy formula that responds to program budget introduces unit-level variation in the amount of subsidy allocated to each unit, even for those that are always subsidized (Figure S1).

2 Results

How do fishers respond to fuel subsidies? We used vessel tracking data[11] and a database of landings[11] to calculate annual time fished (hrs), annual area fished (km^2), and annual landed catch (kg) by each economic unit. We first perform a simple comparison of means of these measures across subsidized status for all economic units in our data Figure 2 and find three general patterns. First, subsidized vessels spend more time fishing, fish a greater area, and land more shrimp than vessels that are not subsidized. Second, vessels that are always subsidized consistently fish more than those that are only sometimes subsidized, and *vice versa*. And third, that this pattern persists even for the subset of vessels whose subsidy status changes in time within our sample (labeled "sometimes"). Of course, this graphical analysis cannot account for characteristics of each economic unit as well as other potential confounding variables, but it nonetheless paints a clear picture of the potential effect of subsidies on fishing behavior and fisheries production. A formal analysis of these data is presented below.

Our results are divided into three main sections. We first show the effect of change in subsidy status (*i.e.* subsidized or not subsidized) on our three outcomes of interest. We then present estimates of the elasticity of each outcome of interest with respect to the amount of subsidy received. The final section uses our empirical estimates to ask how much fishing effort could have been avoided had the subsidies never been issued, and where in Mexico's waters we would expect to see the largest benefits of subsidy reforms.

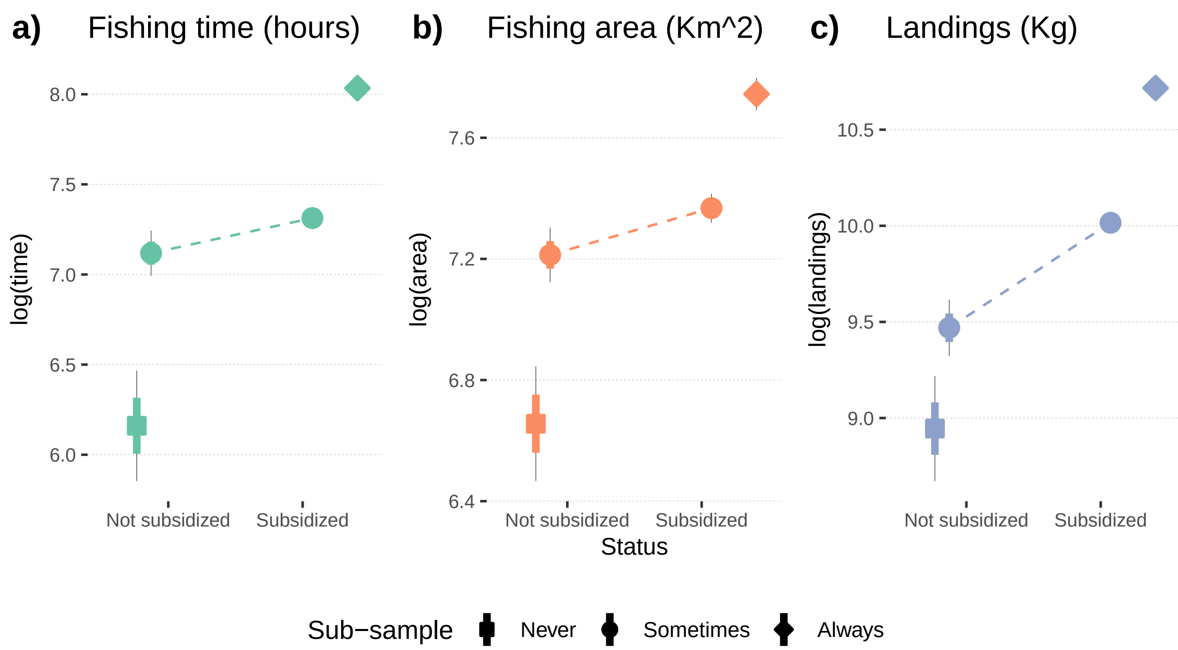

Figure 2: Fishing behavior and production in relation to subsidy status. The x-axis shows the subsidy status and the y-axis shows log-transformed outcome of interest (time fishing, area fished, and landings). Points show mean values, shapes indicate subsidy category with respect to number of times subsidized (never, sometimes, always). The error bars show standard errors (colored portion) and 95% confidence intervals (thin black lines). The dashed line connects the mean values corresponding to vessels that are sometimes subsidized across subsidized status, and the overlaid text shows the % change corresponding to each value (in log-points).

2.1 Responses to change in subsidy status

We can use changes in a subsidy status to test for changes in fishing behavior and fisheries production for economic units whose subsidy status changed at least once between 2011-2019 (N = 1,673). We estimate the semi-elasticity (*i.e.* the % change in an outcome of interest caused by change in subsidy status) of time fishing, fished area, and landings with respect to subsidy status in a two-way fixed-effects regression framework (See Methods). We find that, when an economic unit receives a subsidy, they spend 31.45% more time fishing, expand their fishing grounds by 11.20%, and land 59.44% more shrimp (Table 1). The estimates on hours and landings are significant at the $\alpha = 0.001$ level; changes in area fished are significant at the $\alpha = 0.05$ level. These results are generally robust to different definitions of the sample and model specifications (See Figure S2 and Figure S3).

Table 1: Effect of receiving a subsidy on intensive and extensive behavioral margins, and fisheries production. Identification comes from quasi-random inclusions / exclusions from the roster.

	Fishing time	Fishing area	Landings
Subsidized	0.317***	0.134***	0.493***
	(0.053)	(0.037)	(0.071)
% Change	37.28%	14.33%	63.71%
N	1673	1668	1479
R2 Adj	0.717	0.761	0.753

* p <0.1, ** p <0.05, *** p <0.01

The unit of observation is an economic unit by year. All models include fixed effects by economic unit and by region-year. Numbers in parentheses are panel-robust standard errors (Newey-West with a 1yr lag). Differences in sample size across columns are due to missing coordinates on some VMS messages or missing landings data.

2.2 Responses to change in subsidy amount

Our dataset has three types of economic units: units that are never subsidized, units that are subsidized for at least one year, and units that are subsidized every year in the sample period. For the later two types, the *amount* of subsidy they receive varies by year (See Figure S1). This annual variation is due to budgetary constraints that arise when CONAPESCA receives different amounts of funding in the annual federal budget or when funds are allocated to other programs (*e.g.* aquaculture development as described in Leal Cota and Rolón Sánchez [10]). These year-to-year changes in the amount of subsidy received are due to changes in administrative budgets and as such plausibly uncorrelated with the unobserved determinants of the outcomes of interest. Thus we can use this year-to-year variation in subsidy amounts to test for changes in fishing behavior and fisheries production for economic units who were subsidized at least twice between 2011-2019 (N = 2,750).

We now estimate the elasticity (*i.e.* the % change in outcome of interest caused by a 1% change in the amount of fuel subsidy received) of time fishing, fished area, and landings with respect to the amount of subsidy that economic units receive. Again, we use a two-way fixed-effects regression and find that, for every 1% increase in the subsidy an economic unit receives, they increase fishing time

Table 2: Effect of increasing subsidy amounts on intensive and extensive behavioral margins, and fisheries production. Identification comes from exogenous variations in the amount of subsidy allocated toe ach economic unit.

	Fishing time	Fishing area	Landings
log(subsidy amount[MXP])	0.124***	0.065***	0.168***
	(0.019)	(0.015)	(0.018)
% Change	0.12%	0.06%	0.17%
N	2750	2744	2722
R2 Adj	0.863	0.868	0.881

* p <0.1, ** p <0.05, *** p <0.01

The unit of observation is an economic unit by year. All models include fixed effects by economic unit and by region-year. Numbers in parentheses are panel-robust standard errors (Newey-West with a 1yr lag). Differences in sample size across columns are due to missing coordinates on some VMS messages or missing landings data.

by 0.1% ($p \leq 0.001$), fished area by 0.04% ($p \leq 0.05$), and landings by 0.15% ($p \leq 0.001$). These results are also robust to different definitions of the sample and model specifications (Figure S4).

2.3 Aggregate effects of fuel subsidies

We have shown that subsidized economic units fish more, and that the amount of additional fishing increases with the amount of subsidy received. What do those *individual* responses amount to in terms of*aggregate*, fishery-wide impacts? How much of total historical effort is attributable to fuel subsidies? Vessels are not identical, are not homogeneously distributed in space, and subsidies are not equally distributed (neither among vessels nor space). To answer these questions, we leverage our yearly vessel-level data to derive who is subsidized, how much subsidy they receive, and where they fish. In this section we quantify the portion of historical fishing activity (hours) that is attributable to fuel subsidies. We then identify areas that are disproportionately subject to subsidized fishing effort.

2.3.1 Historical impacts of subsidies

In the context of fuel subsidies, total annual fishing activity can be divided into three categories: 1) activity by economic units that were not subsidized, 2) activity by economic units who were subsidized but that would have occurred even in the absence of the subsidy, and 3) activity by subsidized economic units and that is attributable to a subsidy. Data shows that between 2011 and 2019, Mexican shrimp trawlers spent between 1.26 and 1.68 million hours fishing per year, and that 1.15 to 1.60 million hours were spent by economic units who received a subsidy (Figure 3a). We apply our semi-elasticity estimates to identify each of the three categories of fishing activity described above, and find that between 0.36 and 0.5 million hours can be attributed to fuel subsidies, depending on the year. As a whole, subsidies cause between 23.7% and 30.34% of total annual fishing hours. The total area fished by the fleet fluctuates between 1.15 and 1.36 million km^2, with 0.88 to 1.31 million Km^2 of these being exerted by subsidized economic units (Figure 3b). The modest semi-elasticity that we estimated for this response implies that between 0.09 and 0.14 million Km^2 of these area are trawled due to economic units expanding their fishing grounds when they receive a subsidy. Thus, subsidies increase area trawled by 7.91% to 10.79% overall. The fleet also lands between 16.34 and 21.70 tons of shrimp per year; between 15.95 to 21.29 thousand tons are landed by economic units who receive a fuel subsidy (Figure 3c). Here, between 9.5 and 12.6 tons of annual shrimp landings are attributable to subsidies. Subsidies thus induce a 47-58% increase in annual landings.

These results suggest that removing subsidies would result in large upsides, by reducing the amount and extent of fishing. However, removing fuel subsidies altogether may be politically challenging or undesirable, so we repeat the analysis but this time use our elasticity estimates to calculate the *percent* reduction in fishing time, fishing area, and landings that would result from different subsidy reduction policies (*i.e.* reductions of 10, 30, 50, and 90%). For example, a policy that removes 50% of fuel subsidies could reduce fishing time by a mean of 86.6 thousand hours per year, cumulative fished area by 282 thousand km^2 per year, and landings by 1.88 thousand tons per year (Figure 3d-f).

2.3.2 Spatial implications of a non-spatial policy

Mexico's fuel subsidy policy, and its allocation, has no explicit spatial component. However, fishing vessels are not homogeneously distributed in space, resulting in hotspots of fishing effort [12] (Figure 4a). If all vessels operated by subsidized economic units happened to fish in a subset

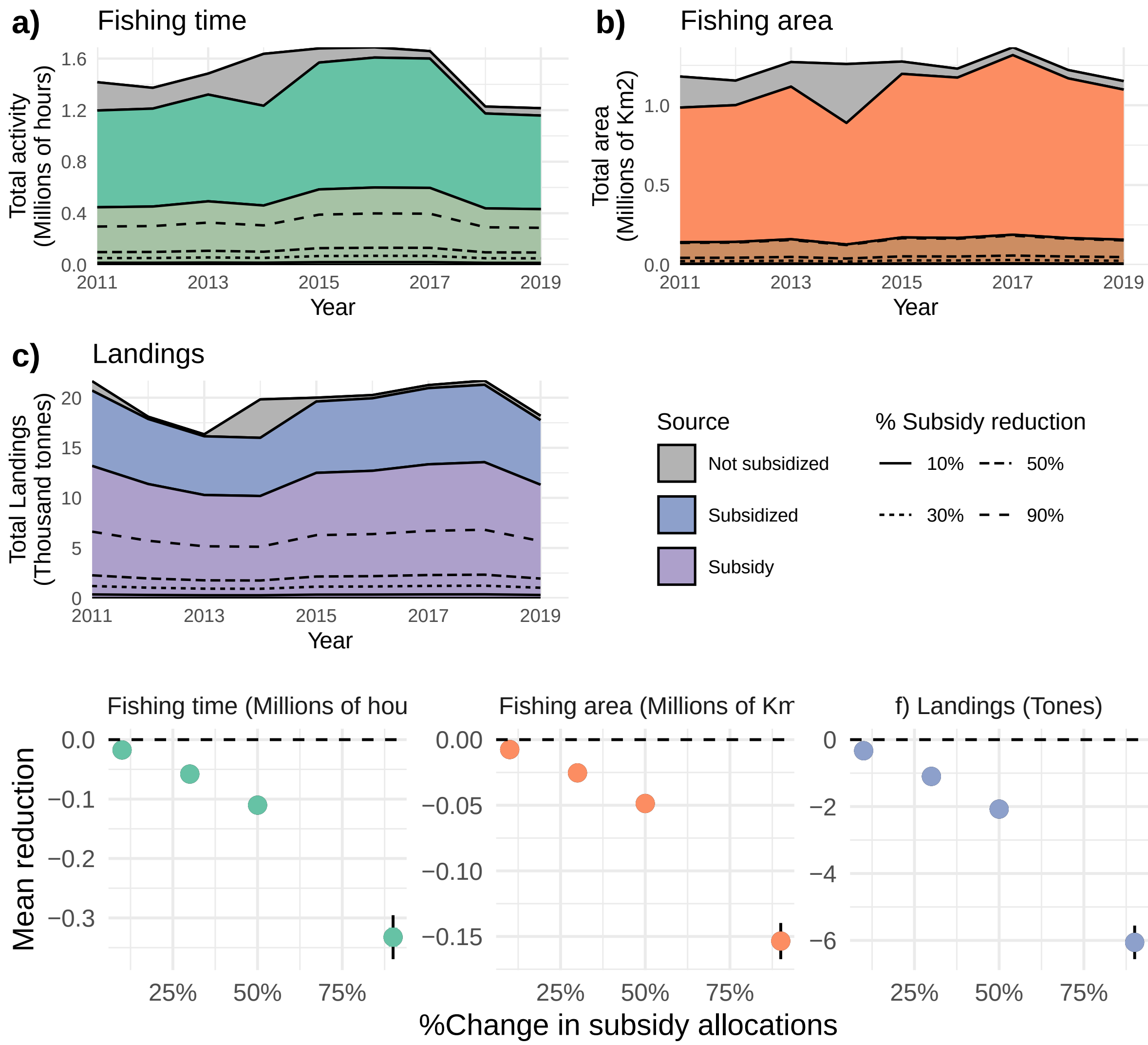

Figure 3: Aggregate effects of fuel subsidies on fishing activity, fished area, and landings. Panels a-c show area-stacked time-series of fishing time, fishing area, and landings. The gray portion is activity and production from economic units that were not subsidized in a given year. The colored portion corresponds to activity and production by economic units that were subsidized. The bottom stack of each panel shows the portion of effort or production by subsidized economic units that is attributable to the subsidy, as indicated by our semi-elasticity estimates (Table 1). The different line types show the portion of effort that could have been removed had the subsidies been reduced by different amounts. Panels d-f show the mean annual reduction in fishing time, fishing area, and landings expected from four different subsidy reduction policies (estimated as mean of all activity between 2011-2019). Black error bars show 95% confidence intervals and the colored portion shows standard errors. **NOTE: Landings are thousand tons, not million tons; figure needs to be updated**

of fishing grounds, then eliminating fuel subsidies would have large and localized environmental upsides. On the other hand, if vessels operated by subsidized economic units operate in more or less the same areas as non-subsidized economic units, then subsidies reform would have a more modest but spatially widespread impact. This tension between large and local vs modest and widespread upsides begs the question: is subsidy-induced fishing effort homogeneously distributed in space?

We follow the same process as before, where we use our semi-elasticity estimates to calculate a counterfactual amount of fishing activity in the absence of subsidies, but this time we do it along a 0.1°x0.1° grid (roughly 11 km by 11 km at the equator). Pixels that are only fished by economic units that are not subsidized will show no change, while pixels that are exclusively fished by subsidized economic units will show the largest change. Using data from the most recent year (2019, with 366 economic units, and 309 of them subsidized), we find that the subsidized fishing activity is heterogeneously distributed in space, but that this heterogeneity matches the baseline distribution of fishing activity by unsubsidized economic units.

Mexico divides its coastline into six broad management areas (Figure 4). The Gulf of California (region II) and Gulf of Mexico (region V) sustain the highest levels of fishing activity and subsidized fishing activity (Figure 4a-b). Eliminating fuel subsidies would lead to up to 31% reduction in fishing activity, across all fishing regions. However, the potential conservation gains would be largest for the Campeche bank (between regions V and VI) and the Eastern coastline of the Gulf of California (region II; Figure 4c-d). This analysis also reveals that fishing activity in areas of particular conservation concern, such as the upper Gulf of California (northernmost section in region II and home to the critically endangered Vaquita [13, 14]) and the recently protected Alacranes Reef[15] (in region VI) is mainly exerted by economic units that are not subsidized.

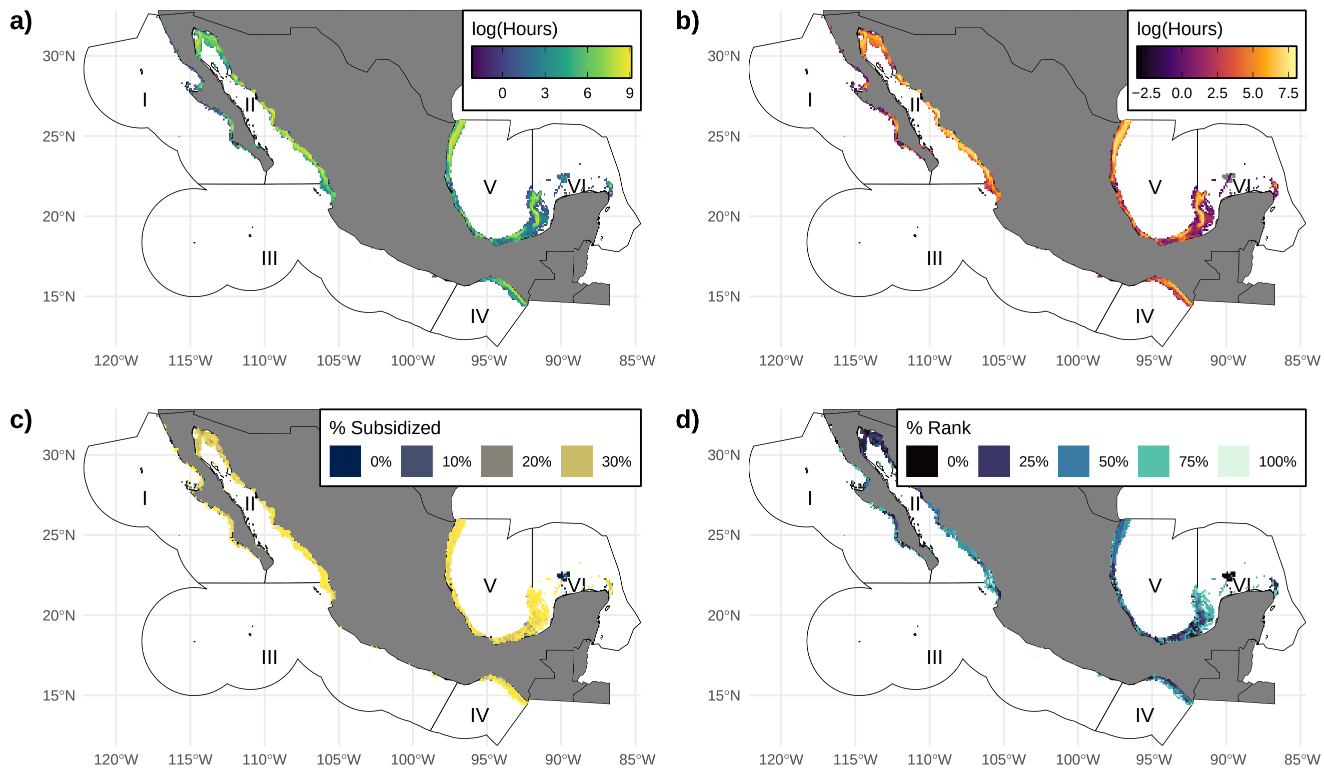

Figure 4: Spatial distribution of the effects of fuel subsidies on fishing activity. Panel a) shows a map of total fishing hours for 2019. Panel b) shows a map of total fishing hours attributable to fuel subsidies. Panel c) shows the per cent of fishing effort that is attributable to fuel subsidies, and panel d) shows the percentile ranking of each pixel. Polygons in the ocean show Mexico's Exclusive Economic Zones, divided into six management regions utilized by Mexico's fishery management agency.

3 Discussion

We find robust empirical evidence that fuel subsidies induce overfishing, and that modest individual behavioral responses by fishers add up to have important aggregate implications for fisheries management and subsidy reform. Our estimates show that up to 30% of historical fishing activity, 10% of fished area, and around 50% of landings are attributable to fuel subsidies. And, because subsidized economic units are not homogeneously distributed in space, fuel subsidies result in a patchwork of over-exploitation. Here we discuss potential limitations of our analysis, expand on the mechanisms behind and implications of these insights, and finalize with concluding remarks.

No observational study is immune to shortcomings and limitations. In our setting, we believe our estimates of the effect of subsidy on fishing behavior are plausible due to a key features of our study design. First, subsidy amounts are largely determined by country-wide administrative budgets which are unlikely to be impacted by individual fisher's economic incentives to fish (e.g., global demand for shrimp). Second, fishers have little to no control over how these data are observed because they do not control their VMS transponders. Both support our interpretation of estimates as causal effects of subsidy allocations on fishing behavior in the short run. However, our (semi)elasticity estimates of the effect of subsidies on landings should be interpreted with caution. For one, "landings" is not the same as "catch". Catch is the amount of biomass extracted, landings are the portion of the catch that is retained, offloaded in port, and *reported* to the fishing authorities. Second, economic units who are subsidized are also required to report their catch. Failure to do so would exclude them from next year's subsidy roster. Although others have noted a generally positive trend between fuel subsidies and landed catch [7], our estimates of the effect of fuel subsidies on landings should be interpreted as an upper-bound that includes the combined effect of increased catch due to additional subsidy-induced effort and an increased incentive to report said catch in order to remain in the roster. Interestingly, this suggests that fuel subsidies may result in an unexpected social benefit through the provision of more accurate catch data, a crucial component of stock assessments.

Our results show that subsidizing fuel alters fishing activity. But how managers allocate and disburse fuel subsidies also defines the way in which fishers respond. Mexico's fuel subsidy program limits the quantity of subsidized fuel any fisher can obtain because, although there is considerable year-to-year and fisher-to-fisher variation, the allocation rule establishes a 2-peso per liter price subsidy over the first 40-70% anticipated fuel consumption of an economic unit (DOF 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018). These subsidies are disbursed as lump-sum transfers that can only be used for fuel. Fishers use this cash to pay for fuel until funds are exhausted (i.e. the first few liters are "free" as they are paid-for by the government). This results in a price structure similar to an increasing block rate pricing scheme, often used to price electricity and water. In those markets, there is evidence that consumers react to the "average price" rather than the marginal price [16]. Using the allocation rule and a median price of diesel fuel of 16.2 pesos per liter, we calculate that Mexico's fuel subsidies result in a 4.9-8.6% reduction in the average price of fuel (similar to the 8.2% calculated by Revollo-Fernández et al. [7]). Our empirical results suggest that this is enough to induce a behavioral response.

Our aggregate calculations show that up to 30% of historical fishing effort is attributable to subsidies. We also show that some areas (*e.g.* the bank of Campeche and Eastern boundary of Gulf of California) are disproportionately impacted to subsidy-induced fishing. These observations imply that subsidy reform could have large but localized environmental benefits. Limited availability of stock assessment data preclude us from making precise statements about the potential upsides for all relevant stocks, but we can at least put this number into perspective for some. For example, the biomass of the heavily fished blue shrimp (*Litopenaeus stylirostris*) stock in the Gulf of California [17] is estimated to be 30% below the target biomass that would yield maximum sustainable yields (i.e. $\frac{B}{B_{msy}} = 0.7$; [17]). It is therefore reasonable to believe that reducing fuel subsidies would result in large upsides and stock rebuilding, at least in the Gulf of California.

We also show that areas known to be important for marine biodiversity (like Alacranes reef and Upper gulf of California) are mostly targeted by economic units that are not subsidized. This suggests that subsidy reform would have little to no direct implications for these areas. Other fishery management and conservation measures, such as fully protected marine protected areas, may be a more suitable approach if the objective is to curtail fishing effort over sensitive and important habitat.

Overall, our findings suggest that subsidy reform could have a spatially disperse response, with some areas benefiting more than others (in biological terms, at least). However, it also important to consider the social implications of subsidy reform, since some ports or fishing communities may be more reliant on subsidies than others. Previous work in Mexico and elsewhere has shown that even perfect management designed to maximize long-term yields would not be enough to raise fisher's income past the poverty line [18, 19]. Instead, some have suggested that money spent on harmful fuel subsidies could be allocated to social programs designed to raise fisher's income [20], although the proposal lacks details on a path forward. This tension between biological upsides and the political costs of a subsidy reform may underpin nation's hesitation to reform fisheries subsidies, and highlights an important opportunity to study the distributional implications of this policy.

We conclude that fuel subsidies induce overfishing, that the amount of overfishing is non-trivial, and that its effects are spatially localized. These findings support calls for subsidy reforms [2, 3], but we note that managers should manage expectations accordingly. Our findings are directly relevant to Mexico, and to other coastal nations considering reducing or removing fuel subsidies to their industrialized fishing fleets.

4 Declarations

Data and code - All data and code used in this manuscript is available on GitHub and will be posted on Zenodo.

Funding - This project was funded by the PEW charitable foundation. Funders had no say on the design and direction of the research.

Aknowledgements - We appreciate feedback provided by Andrés Cisneros-Mata and Enrique Sanjurjo on an earlier version of the paper. We also thank Sara Chávez and Eduardo Rolón for providing the fuel subsidy allocations dataset, and Edaysi Bucio for providing clarifications on how fuel subsidies are allocated.

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Christopher Golden, Line Gordon, Hugh Govan, Rowenna Gryba, Benjamin S Halpern, Quentin Hanich, Mafaniso Hara, Christopher D G Harley, Sarah Harper, Michael Harte, Rebecca Helm, Cullen Hendrix, Christina C Hicks, Lincoln Hood, Carie Hoover, Kristen Hopewell, Bárbara B Horta E Costa, Jonathan D R Houghton, Johannes A Iitembu, Moenieba Isaacs, Sadique Isahaku, Gakushi Ishimura, Monirul Islam, Ibrahim Issifu, Jeremy Jackson, Jennifer Jacquet, Olaf P Jensen, Jorge Jimenez Ramon, Xue Jin, Alberta Jonah, Jean-Baptiste Jouffray, S Kim Juniper, Sufian Jusoh, Isigi Kadagi, Masahide Kaeriyama, Michel J Kaiser, Brooks Alexandra Kaiser, Omu Kakujaha-Matundu, Selma T Karuaihe, Mary Karumba, Jennifer D Kemmerly, Ahmed S Khan, Patrick Kimani, Kristin Kleisner, Nancy Knowlton, Dawn Kotowicz, John Kurien, Lian E Kwong, Steven Lade, Dan Laffoley, Mimi E Lam, Vicky W L Lam, Glenn-Marie Lange, Mohd T Latif, Philippe Le Billon, Valérie Le Brenne, Frédéric Le Manach, Simon A Levin, Lisa Levin, Karin E Limburg, John List, Amanda T Lombard, Priscila F M Lopes, Heike K Lotze, Tabitha G Mallory, Roshni S Mangar, Daniel Marszalec, Precious Mattah, Juan Mayorga, Carol McAusland, Douglas J McCauley, Jeffrey McLean, Karly McMullen, Frank Meere, Annie Mejaes, Michael Melnychuk, Jaime Mendo, Fiorenza Micheli, Katherine Millage, Dana Miller, Kolliyil Sunil Mohamed, Essam Mohammed, Mazlin Mokhtar, Lance Morgan, Umi Muawanah, Gordon R Munro, Grant Murray, Saleem Mustafa, Prateep Nayak, Dianne Newell, Tu Nguyen, Frederik Noack, Adibi M Nor, Francis K E Nunoo, David Obura, Tom Okey, Isaac Okyere, Paul Onyango, Maartje Oostdijk, Polina Orlov, Henrik Österblom, Dwight Owens, Tessa Owens, Mohammed Oyinlola, Nathan Pacoureau, Evgeny Pakhomov, Juliano Palacios Abrantes, Unai Pascual, Aurélien Paulmier, Daniel Pauly, Rodrigue Orobiyi Edéya Pèlèbè, Daniel Peñalosa, Maria G Pennino, Garry Peterson, Thuy T T Pham, Evelyn Pinkerton, Stephen Polasky, Nicholas V C Polunin, Ekow Prah, Jorge Ramírez, Veronica Relano, Gabriel Reygondeau, Don Robadue, Callum Roberts, Alex Rogers, Katina Roumbedakis, Enric Sala, Marten Scheffer, Kathleen Segerson, Juan Carlos Seijo, Karen C Seto, Jason F Shogren, Jennifer J Silver, Gerald Singh, Ambre Soszynski, Dacotah-Victoria Splichalova, Margaret Spring, Jesper Stage, Fabrice Stephenson, Bryce D Stewart, Riad Sultan, Curtis Suttle, Alessandro Tagliabue, Amadou Tall, Nicolás Talloni-Álvarez, Alessandro

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6 Methods

We are interested in studying how fuel subsidies affect fishing activity and production. Here, our unit of observation are "economic units", a term used by the Mexican fisheries agency (CONAPESCA) to refer to an individual or firm that participates in a fishery. We combine administrative datasets on subsidy allocations by economic unit and vessel tracking data to construct a unique panel of annual subsidies and fishing activity by economic unit. The following subsections provide further details on data procurement, filters, and sample construction.

6.1 Datasets and their sources

We make use of six types of data to study the effects of fuel subsidies on fishing behavior. Historical subsidy allocations and a vessel registry allow us to identify subsidized economic units and their characteristics. Then, we use vessel tracking data and historical fisheries production data to derive our three main outcomes of interest: fishing time, fishing extent, and fisheries production. Finally, we also use historical diesel fuel prices and monthly indices for El Niño Southern Oscillation to include fuel costs and environmental variation as covariates. Each of these is described in detail below.

6.1.1 Subsidy allocations

Data on subsidy allocations to each economic unit come from CausaNatura, an NGO whose mission is to compile, procure, and make available administrative datasets relevant to environmental and natural resource management. We use the "*Padrón de beneficiarios de Combustibles*", which was last updated on June, 2020. This administrative dataset contains information on the annual subsidy cap assigned to economic units fishing in Mexico during the 2012 - 2019 period (n = 4,597). From this information, we assign treatment status (subsidized or not subsidized) to all economic units in our sample (see subsection 6.2), and the amount of fuel subsidy received by each.

6.1.2 Vessel registry

We use an official vessel registry with information for all large-scale fishing vessels that hold a fishing permit in Mexico, which was also provided by CausaNatura. The vessel registry includes unique vessel identifiers and economic unit identifiers (ownership), vessel dimensions (length overall, beam, draught, and gross tonnage), species-specific fishing permits granted, and engine characteristics (*e.g.* total engine power, type of fuel used by the engine, and engine model). The registry contains information for 3,093 vessels owned by 1,093 economic units. From these, 1,415 are licensed to use bottom trawl nets and 1,561 are licensed to participate in the shrimp fishery; 1,368 are licensed to use both (and are owned by 464 economic units).

6.1.3 Vessel tracking data

There are two general types of vessel tracking technologies: Automatic Identification Systems (AIS) and Vessel Monitoring Systems (VMS). AIS is designed as a vessel-to-vessel broadcast system intended to help avoid at-sea collisions between vessels [12]. VMS, on the other hand, is employed by governments to track vessels of interest, and a vessel's position is broadcast directly to a central repository instead of to other vessels [21]. We use VMS data from Mexico's satellite monitoring system of fishing vessels (*i.e.* SISMEP[11]). These data are publicly available and continuously updated at datos.gob.mx. The version we use was downloaded on June 15, 2024. These VMS data contain the timestamp, geographic location (latitude and longitude), and speed of 2,775 vessels between January 1, 2007 and Feb 29, 2024.

It's worth mentioning that Mexico's fisheries regulations require all fishing vessels larger than 10.5 m in length overall and with an in-board motor of more than 80 horsepower to carry a Vessel Monitoring System (VMS)[2]. Failure to comply with this VMS requirement automatically disqualifies a vessel as eligible to receive any type of subsidy.

[2]Regulatory text available at: https://www.monitoreodeembarcaciones.com.mx/monitoreosatelital/QuienDebe.htm

6.1.4 Fisheries production

Fisheries production data come from Mexico's landing receipts, where fishers report their landings. As with the VMS requirement, failure to report catch makes a fisher ineligible to receive a subsidy. The dataset contains information on the identity of the economic unit and vessel landing the catch, the target species, and the amount (Kg).

6.1.5 Fuel prices

We also compile price data for diesel fuel used by these economic units by combining two sources of information. The first one is reported by the Energy Information System ("Sistema de Información Energética"; "SIE") and contains the national annual average price of diesel between 2011 - 2016, when fuels were subject to nation-wide price controls. Price controls were lifted in 2017, and fuel prices were determined by local supply and demand. The Energy Regulatory Commission ("Comisión Reguladora de Energía"; CRE) reports monthly state-level prices after 2017, which we use to calculate annual national averages for 2017 - 2019 period. We use Mexico's consumer price index reported by the OECD to adjust prices to 2019 Mexican pesos.

6.1.6 Environmental covariates

The productivity of shrimp fisheries is known to be influenced by ENSO events [22]. We use the Mean NINO 3.4 index available from NOAA's Physical Sciences Laboratory Climate Indices repository (Monthly Atmospheric and Ocean Time Series). We use monthly means to produce an annual mean value of ENSO 3.4, which we include as a time-varying covariate in some of our regressions.

6.2 Data processing

6.2.1 Sample construction

We limit our data to activity occurring between 2011 and 2019, the years for which subsidy allocation data are available. Additionally, retain vessel tracks ocurring at depths between 0.15 and 100 m deep (as indicated by GMEDs bathymetric dataset) because shrimp trawlers in Mexico are not allowed to fish shallower than 9.15 m deep and they operate at a maximum depth of 100 m [23]. Shrimp trawlers typically operate speeds between 1 and 5 knots[3], so we also filter tracks based on their speed. These filters result in a total of 1,177 vessels belonging to 414 economic units. We further restrict the sample to economic units that are only licensed to fish for shrimp using trawl nets, leaving us with 409 economic units.

6.2.2 Outcomes of interest

Our first outcome of interest is fishing activity. We define it as time (hours) a vessel spent traveling at speeds between 1 and 5 knots in areas between 9.15 and 100 m depth. We calculate an economic unit's total annual fishing hours as the sum of fishing hours across all their vessels.

Our second outcome of interest is the total extent of fishing grounds (km^2) in which these economic units operate. We used a density-based spatial clustering algorithm (DBSCAN) to identify fishing grounds based on individual vessel positions. The algorithm was applied to all positions at the vessel-by-year level. The algorithm clusters points based on their distribution across space, given a minimum number of points per cluster and a maximum distance between points. We used a maximum distance of 50Km and a minimum of 6 points per cluster. Clusters thus represent the group of individual GPS coordinates that are associated with a fishing ground. Points without cluster membership were dropped. We then built a convex hull around each cluster and calculated its area. The total extent of fishing grounds of an economic unit was then calculated as the sum of all fishing grounds used by their vessels. For this portion of the analysis, geographic coordinates were reprojected onto a Mexico Lambert Conic Conformal projection (With EPSG code 6361).

Our third and last outcome of interest is the total amount of catch landed by each economic unit, which we derive from our fisheries production dataset. Our sample is therefore made up of large-scale economic units that target shrimp and carry VMS transponders. This group receives between 48.22% and 67.73.% of the annual subsidies awarded to all industrial economic units fishing in Mexico. The final estimation sample is a panel of annual economic-unit fuel subsidy allocations (in 2019 MXP), time, extent, landings, and control variables such as fuel prices, total horsepower

[3] Catálogo de los Sistemas de Captura de las Principales Pesquerías Comerciales, available at: CONAPESCA

of number of active vessels owned by an economic unit, and environmental indices (*i.e.* NINO3.4 index). These data contain 3,376 observations attributed to 409 economic units between 2011 and 2019. Tables with summary statistics are included in the supplementary materials (Table S1).

6.3 Empirical strategy

6.3.1 Changes in subsidy status

Subsidy allocations are uncorrelated with the outcomes of interest (fishing hours, fishing area, and fisheries production) so we can use these quasi-random changes in subsidy status to test for changes in fishing behavior and fisheries production for economic units whose subsidy status changed at least once in our study period (2011-2019). We estimate the semi-elasticity (*i.e.* the % change in outcome of interest caused by change in subsidy status) of time fishing, fished area, and landings with respect to subsidy status in a two-way fixed-effects regression framework.

$$log(y_{it}) = \beta D_{it} + \chi' X_{it} + \omega' \mathrm{EU}_i + \mu' \mathrm{RY}_{it} + \epsilon_{it} \tag{1}$$

Where D_{it} is a dummy variable that takes a value of 1 if economic unit i was subsidized at time t and 0 otherwise. X_{it} is a vector of time-varying control variables (total engine horsepower and number of active vessels), EU_i is a vector of fixed effects by economic units, RY_{it} is a vector of fixed effects by region-year, and ϵ_{it} is the error term. Our coefficient of interest is β. Our results are robust to alternative specifications where we drop the two-way fixed effects structure and instead include annual diesel prices and ENSO indices, where we also include economic units that were never subsidized, or both (See section 6.3.2 and Figure S2).

6.3.2 Changes in subsidy amount

Recall that our dataset has three types of economic units: those that were never subsidized, those that were subsidized at least one year, and those that were subsidized every year in our dataset. For the later two types, the *amount* of subsidy they receive varies by year (See Figure S1). This annual variation is due to budgetary constraints, which arise when CONAPESCA receives different amounts of funding in the annual federal budget or when funds are allocated to other programs (*e.g.* aquaculture development). These changes in subsidy amounts are uncorrelated with the outcomes of interest (fishing hours, fishing area, and fisheries production), so we can use these quasi-random changes in subsidy amounts to test for changes in fishing behavior and fisheries production for economic units who were subsidized at least twice between 2011-2019. Like before, we estimate our coefficient of interest (this time an elasticity) in a two-way fixed effects framework with our estimating equation taking the form:

$$log(y_{it}) = \beta log(s_{it}) + \chi' X_{it} + \omega' \mathrm{EU}_i + \mu' \mathrm{RY}_{it} + \epsilon_{it} \tag{2}$$

Where s_{it} is the amount of subsidy allocated to a subsidized economic unit, in 2019 Mexican pesos. X_{it} is a vector of time-varying control variables (total engine horsepower and number of active vessels), EU_i is a vector of fixed effects by economic units, RY_{it} is a vector of fixed effects by region-year, and ϵ_{it} is the error term. Our coefficient of interest is β. Our robustness checks for this analysis (See section 6.3.2) test for changes in the estimated coefficient when limiting the sample to vessels subsidized at least 3, 4... 8 times (**??**) or where we use different specifications (Figure S4).

559 # Supplementary Materials

560 ## Supplementary Figures and Tables

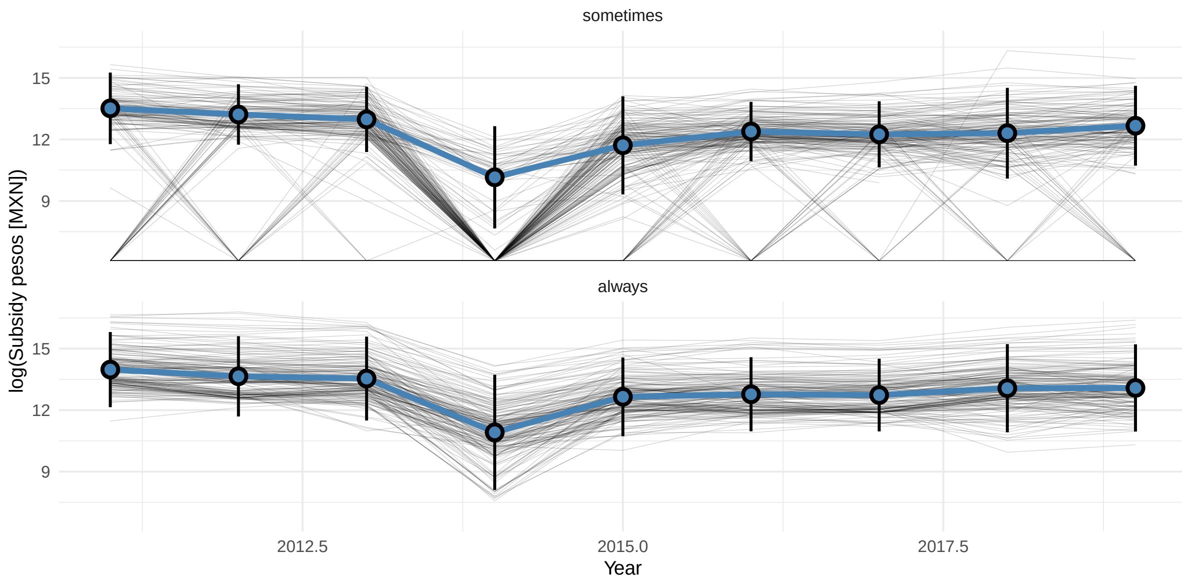

Fig. S1: Change in the subsidy amount (Mexican Pesos) granted to each economic unit between 2011 and 2019. The top panel shows data for economic units that are subsidized at least once, the bottom panel shows data for economic units that are always subsidized in our period of study. Each thin black line corresponds to one economic unit. When a line touches the horizontal axis it implies it is not subsidized in that period. The overlaid points show mean ± sd. The large reduction in 2014 corresponds to CONAPESCA preferentially allocating subsidies towards aquaculture programs that year.

Tab. S1: Summary statistics comparing the mean, standard deviation, and range of subsidy amounts and outcome variables across treatment statuses.

	Treatment status	Mean	SD	Min	Max
Subsidy amount (2019 MXN)	Not subsidized	0.00	0.00	0.00	0.00
	Subsidized	732 869.91	1 412 247.79	730.55	19 633 910.95
Fishing activity (hours)	Not subsidized	2117.75	3186.10	0.02	27 613.03
	Subsidized	4374.22	7357.38	1.15	70 999.48
Fished area (Km^2)	Not subsidized	1882.10	2811.03	0.00	30 962.85
	Subsidized	3602.53	6742.41	0.00	64 566.95
Landings (Kg)	Not subsidized	22 190.89	33 675.53	135.00	285 093.00
	Subsidized	62 328.10	95 041.55	300.00	1 099 556.00

561 # Robustness tests

562 ## Semi-elasticity estimates

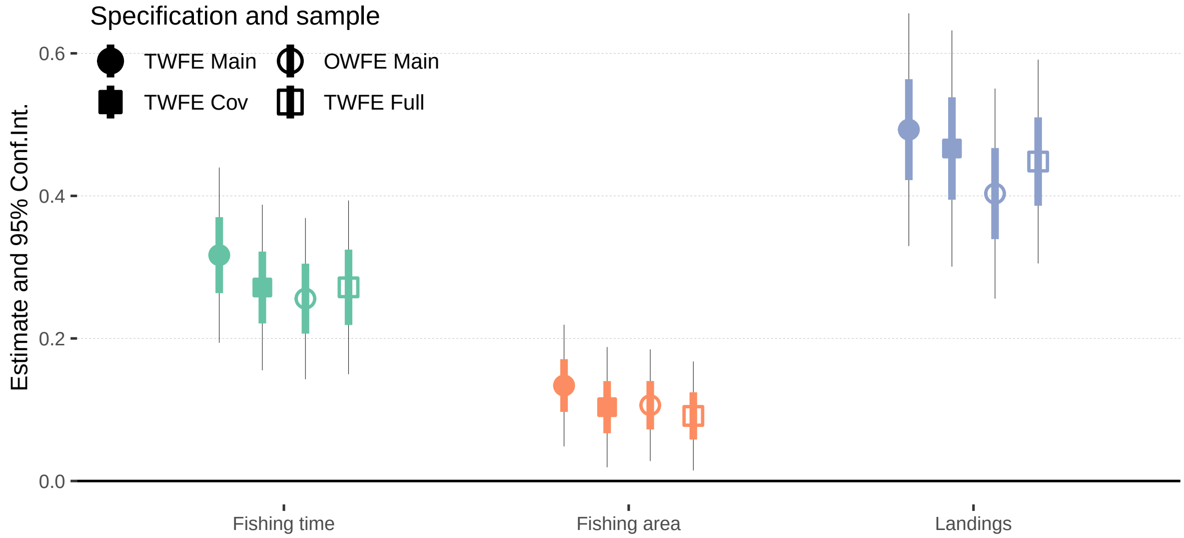

Fig. S2: Coefficient estimates for the semi-elasticities of time fishing, fished area, and landings with respect to subsidy status for different specifications and samples. Points are coefficient estimates, colored lines show standard errors, and black lines show 95% confidence intervals. The main sample excludes economic units never (N = 32) and always (N = 169) subsidized between 2011 and 2019. The full sample includes all economic units, even those for which subsidy status doesn't change between 2011 and 2019. One-way fixed-effect specifications (labeled "OWFE") drop year-by-region fixed effects and use annual log-transformed mean national fuel prices and the NINO3.4 index values.

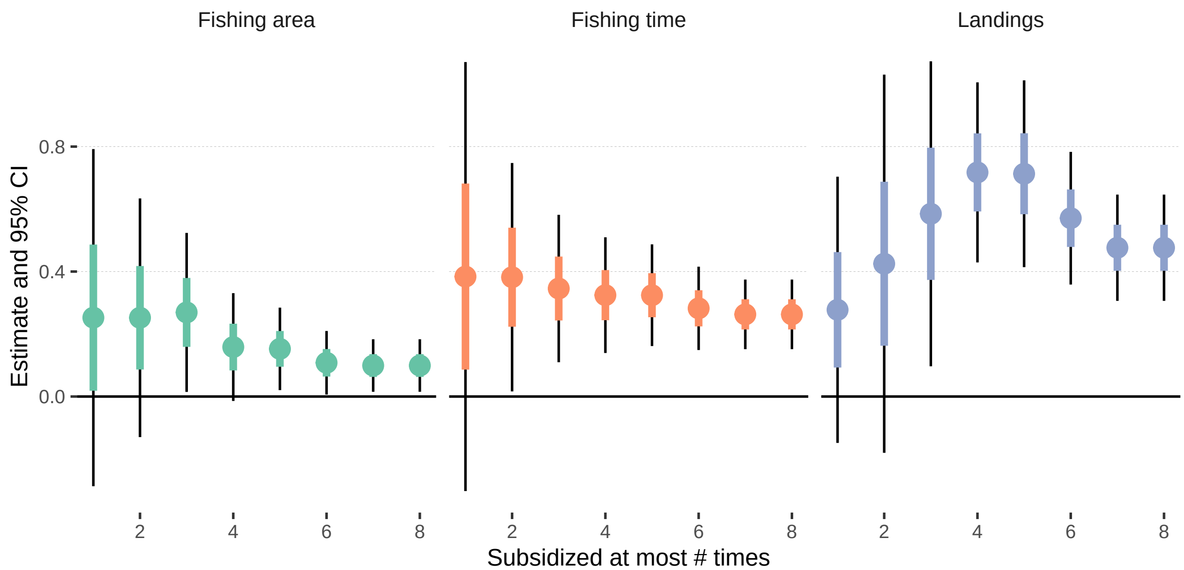

Fig. S3: Coefficient estimates for the semi-elasticities of time fishing, fished area, and landings with respect to subsidy status for different specifications and samples based on subsidy frequency. Points are coefficient estimates, colored lines show standard errors, and black lines show 95% confidence intervals. Each point corresponds to a different sub-sample, where economic units are subsidized at most n times, as indicated by the x-axis. In all cases, the rightmost point (subsidized at most 9 times) corresponds to our main-text estimates.

Elasticity estimates

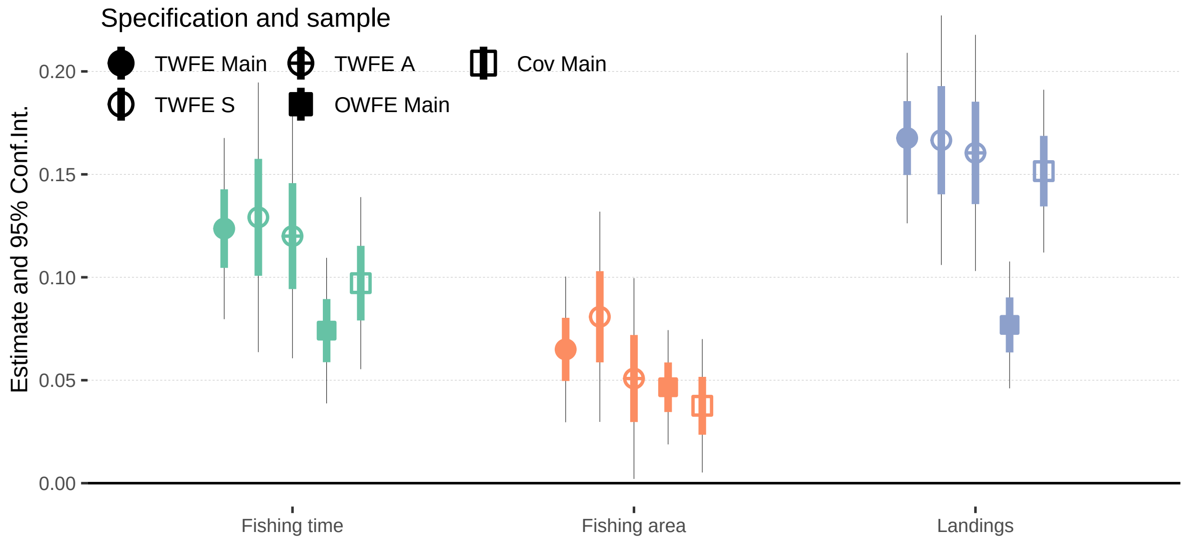

Fig. S4: Coefficient estimates for the elasticities of time fishing, fished area, and landings with respect to subsidy amount. Points are coefficient estimates, colored lines show standard errors, and black lines show 95% confidence intervals. The main sample combines all economic units subsidized at least twice between 2011 and 2019. Alternative samples, labeled "S" and "A", restrict the sample to economic units that are sometime and always subsidized in the same period, respectively. One-way fixed-effect specifications (labeled "OWFE") drop year-by-region fixed effects and use annual log-transformed mean national fuel prices, the NINO3.4 index values, and a dummy variable for 2014.

Supplementary text

Subsidy program description

For the time period analyzed in this study (2011 - 2019), four related fuel subsidy programs in Mexican fisheries have been implemented: *PROCAMPO para vivir mejor* (2011 - 2012), *PROCAMPO Productivo* (2013), *Fomento a la productividad pesquera* (2014 - 2019) and *Subcomponente diesel marino* (2018). The operational rules of the fuel subsidy program in Mexican fisheries are as follows. The fuel subsidy program provides a 2-peso per liter subsidy over a portion of the total fuel used by a vessel, here termed the fuel cap of vessel i ($\hat{Q}_i$). As stated in the program's operational rules[4], the subsidized portion of fuel for any disesel-consuming vessel is calculated using the following formula:

$$\hat{Q}_i = (MDL_i \times DPC_i) \times AF_i \tag{3}$$

Where $\hat{Q}_i$ represents the fuel cap on the subsidy program given to vessel i. MDL_idenotes the"Maximum Daily Liters" of vessel i, and is what the government expects the vessel's fuel consumption to be. DPC_i represents the "Days Per Cycle": the number of days a vessel is allowed to fish during a fishing season. The MDL_i is based on engine size (**??**), while DPC_i is determined by the fishery in which the vessel participates[5]. Finally, AF_i is an exogenous adjustment factor set by CONAPESCA and takes values between 0 and 1. This is independent of fishery, engine power, or stock status and is instead determined by budgetary constraints. The adjustment factor was typically set between 0.4 and 0.7, but local officials may downward adjust it. These variations in adjustment factor provide the source of variation that we will use to identify the effect of fuel fishery subsidies on exacerbating overfishing.

[4]See Section 4.1.2 of Acuerdo por el que se dan a conocer las Reglas de Operación de los Programas de la Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación

[5]A fishery is defined as the combination of species and location. For example a vessel targeting tuna in the Pacific ocean is part of the Pacific tuna fishery.

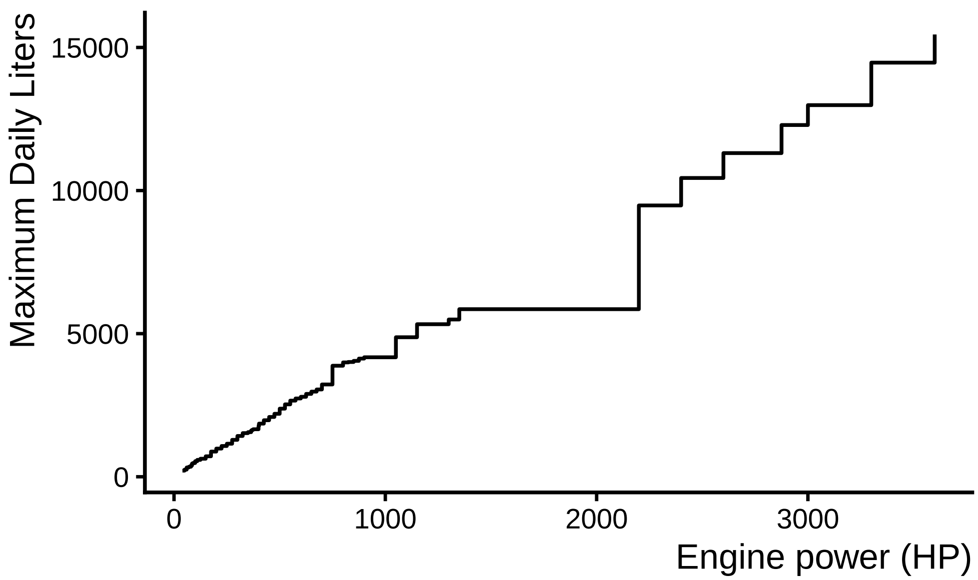

Fig. S5: Expected daily fuel consumption for different engine powers. The x-axis shows engine power bins (in HP) as defined by CONAPESCA's operational rules. The y-axis shows the estimated maximum daily liters of fuel to be consumed for the corresponding engine power bin.