11/25

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Firm size and environmental effort under spatial externalities: Evidence from Norwegian salmon farming

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SNF Working Paper No. 11/25

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SNF Project No. 10030:
DistRes – Distribution and resource rent in fisheries

The project is financed by The Research Council of Norway
(Project No.: 295197)

CENTRE FOR APPLIED RESEARCH AT NHH
BERGEN, DECEMBER 2025
ISSN 2704-0380 (Online)

Firm size and environmental effort under spatial externalities: Evidence from Norwegian salmon farming

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Abstract

Managing spatial externalities in natural resource industries poses regulatory challenges. We examine whether ownership structure shapes private incentives for environmental management in Norwegian salmon aquaculture. Sea lice-parasites that damage fish health and reduce growth-disperse among farms via ocean currents. Delousing at one farm benefits neighbors, while the treating farm bears the cost alone. We test whether firms controlling a larger share of local production are more likely to undertake treatments, in line with internalizing spillover benefits. Using microdata on 250,000 farm-week observations (2012–2021), we find strong support: a five percentage-point increase in local firm share is associated with a 0.4 percentage-point increase in weekly treatment probability – for a typical nine-farm cluster, roughly one to two additional treatments annually. The effect appears at distances matching lice dispersal biology (25–75 km) but disappears at 100 km. These findings suggest that aligning ownership structure with the spatial extent of externalities could complement regulation by harnessing private incentives.

Keywords: Spatial externalities; Aquaculture; Intra-firm spillovers; Natural resource management.

JEL classification: D62, L22, Q22, Q52

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1 Introduction

In marine aquaculture, production sites are biologically connected by ocean currents that transport parasites and pathogens across farms, generating spatial externalities that extend far beyond individual sites. As a result, mitigation at one farm reduces infection pressure for neighboring farms, while inadequate control increases the risk of contamination throughout the system. In Norwegian salmon farming, the parasitic salmon louse (*Lepeophtheirus salmonis*) is the dominant and most costly manifestation of this coordination problem.

Despite extensive regulatory intervention, lice outbreaks remain endemic and impose substantial economic costs. Lice-related growth losses reduce farm revenues by 3–16 percent depending on location, with total annual damages estimated at approximately $436 million (2011 USD) for the Norwegian industry (Abolofia et al., 2017). These figures underscore that lice externalities are not a marginal environmental concern, but a central constraint on production and profitability.[1]

A key driver of these economic losses is the characteristically large spatial scale at which marine aquaculture externalities operate. Salmon lice larvae disperse tens of kilometers via ocean currents, with empirical estimates indicating dispersal ranges of 10–80 km, and core exposure typically clustering around 10–30 km (Asplin et al., 2020; Samsing et al., 2017). In contrast, most terrestrial agricultural externalities, such as livestock disease transmission, pesticide drift, and invasive pests, operate over distances of a few kilometers or less.[2]. As a result, marine parasite spillovers span far larger spatial domains, expanding the relevant domain of interaction from a handful of immediately adjacent farms to dozens of biologically connected neighbors. This scale fundamentally alters the nature of the coordination problem faced by producers.

Whether parasite mitigation is privately optimal under such extensive spillovers depends critically on how production is distributed across firms within biologically connected areas. Lice control is costly, and since delousing efforts reduce infection pressure for nearby farms, mitigation constitutes a local public good. When firms do not internalize the spillover benefits of their delousing actions, mitigation effort falls below the social optimum. In addition, because mitigation efforts are strategic substitutes, there is a free-riding problem: producers have an incentive to reduce their own efforts when nearby farms increase theirs.

[1]Similar parasite- and disease-driven spillovers are a pervasive challenge for aquaculture worldwide. For example, concerns related to sea lice and disease transmission have led the Government of Canada to announce a ban on open net-pen salmon farming in British Columbia beginning in 2029. Similar disease spillovers have been documented in Vietnamese shrimp aquaculture, where movement of contaminated water between ponds facilitate transmission of pathogens across farms (Suzuki et al., 2025).

[2]Spatial externalities in agriculture vary by transmission mechanism. Most livestock diseases transmit within 1 km through direct contact or aerosols (Boender & Hagenaars, 2023), and pesticide drift extends 0.1–0.75 km from treated fields (Ward et al., 2006). Even far-reaching terrestrial externalities remain far more localized than marine lice: wind-borne viral diseases (foot-and-mouth disease, avian influenza) reach 1–10 km, while vector-borne diseases such as bluetongue spread 10–50+ km via wind-dispersed midges (Boender & Hagenaars, 2023).

The severity of this coordination failure depends on how production is distributed across firms within biologically connected areas. Firms controlling a larger share of local production internalize a greater fraction of the benefits from reduced lice pressure and therefore face stronger incentives to invest in mitigation. By contrast, when production is fragmented across many firms, each firm captures only a small share of the spillover benefits, amplifying free-riding incentives and weakening aggregate mitigation. As a result, mitigation decisions depend not only on local environmental conditions at the farm, but also on the firm's local production footprint in surrounding waters.

In this paper, we formalize this mechanism and test its implications in the context of Norwegian salmon aquaculture. We develop a stylized model in which the firm chooses costly delousing effort that reduces local lice density and benefits all farms within a biologically connected area. The model implies that mitigation efforts are strategic substitutes and that firms with larger local production shares exert greater effort. This yields a clear, testable prediction: within a given biologically connected area, farms owned by firms with larger local biomass shares delouse more frequently.

We test this prediction using detailed weekly farm-level data on salmon production, lice counts, and delousing events, combined with time-varying ownership records and precise farm locations. For each farm-week, we construct measures of firm-level biomass shares within biologically relevant distance buffers and estimate how these shares relate to the probability of delousing. These shares vary within farms over time due to production cycles and across farms due to spatial location, allowing us to directly link local industry structure to environmental effort in a setting where externalities operate over unusually large distances.

The Norwegian salmon farming industry provides a well-suited empirical setting for studying this mechanism. Production occurs in open-net pens, allowing parasites to disperse between farms as ocean currents carry them over distances spanning tens of kilometers. These spatial links are well documented in the scientific literature and regulatory oversight mandates standard data collection for all farms along the coast. At the same time, the industry exhibits substantial heterogeneity in local ownership concentration across regions, creating meaningful variation in firms' exposure to spatial spillovers.

Previewing our main findings, we document a robust positive relationship between firms' local production shares and delousing frequency. This relationship is stable across alternative specifications and distance buffers, with effects concentrated at spatial scales consistent with known lice dispersal patterns. Importantly, the effect is not explained by differences in lice pressure or farm capacity: farms belonging to firms with larger local biomass shares engage in more frequent mitigation even when these factors are held constant. These findings align with the theoretical prediction that greater internalization of spillover benefits increases environmental effort.

This paper sits at the intersection of several strands of the literature. First, it contributes to the literature on spatial externalities and public goods by providing empirical evidence on how ownership structure shapes mitigation incentives when spillovers are spatially extensive (Asche et al., 2022; Costello & Polasky, 2008). In aquaculture, the ecological and economic costs of lice to farmed and wild fish are well documented (e.g., Abolofia et al., 2017; Torrissen et al., 2013), and lice transmission between farms is inherently spatial (Jansen et al., 2012; Kragesteen et al., 2019). More broadly, empirical studies in agriculture (e.g., on pesticide drift, Waterfield & Zilberman, 2012), water quality management (e.g., Sigman, 2002), forestry (e.g., Atallah, 2025; Ollikainen, 2016), and fire prevention (e.g., Crowley et al., 2009) show that spatial spillovers across adjacent land parcels complicate individual incentives. This literature emphasizes that when spillovers are spatially structured, incentives for mitigation depend not only on regulation, but also on how production is distributed across space. Our paper brings this insight to a marine setting where the spatial scale of interaction is substantially larger than in most terrestrial production systems.

Second, the paper contributes to work on strategic behavior under spatial regulation in aquaculture. Much of the existing literature focuses on infestation outcomes, such as lice levels, rather than mitigation effort itself. Because outcomes reflect both exogenous ecological dynamics and the aggregation of treatment decisions across connected farms, they do not cleanly identify firms' behavioral responses to incentives. Mitigation effort, by contrast, directly captures strategic choice. As a result, outcome-based analyses may mask strategic free-riding behavior even when firms' effort allocations differ substantially. The economics literature has only recently begun to model and empirically analyze firm behavior and strategic interaction in aquaculture. For example, Oglend & Soini (2020) show that entry restrictions introduced to address lice externalities can generate regulatory rents and shift behavior toward unregulated margins, highlighting how industry responses depend on how the benefits and costs of mitigation are distributed across firms and space. Our analysis complements this work by focusing directly on mitigation decisions rather than outcomes.

Third, the paper contributes to the literature on ownership structure and property rights under externalities. Building on classic theories of public goods and common-pool resources (e.g., Bergstrom et al., 1986; Ostrom, 1990; Schlager & Ostrom, 1992), recent work on property rights shows that spatial configuration and fragmentation of ownership play a central role in determining economic outcomes under externalities (e.g., Leonard & Plantinga, 2024; Leonard & Parker, 2021; Winikoff & Parker, 2024). Previous studies in aquaculture have primarily emphasized regulatory design and the biological efficacy of controls (e.g., Oglend & Soini, 2020), but have not examined how variation in local ownership structure affects **realized mitigation behavior**. A related study, Ceballos-Concha et al. (2025), considers ownership concentration at coarse spatial units and focuses on infestation outcomes rather than effort, limiting its ability to identify firm-level incentives.

To our knowledge, this is the first empirical study to test whether local ownership concentration, measured at the spatial scale over which treatment externalities operate, affects mitigation effort in aquaculture or other marine resource industries. We show that firms owning larger biomass shares within biologically relevant distances engage in more frequent delousing. By examining treatment decisions rather than lice outcomes, we isolate strategic responses to ownership incentives, addressing calls to better understand firm behavior under spatial externalities in aquaculture (Asche et al., 2022; Oglend & Soini, 2020). More broadly, our findings underscore the role of spatial industry structure in shaping incentives for environmental mitigation, and are informative for discussions of how coordination across biologically connected producers – whether through ownership patterns or other institutional arrangements – can complement regulation.

The remainder of the paper is structured as follows. Section 2 presents the theoretical model and derives predictions for empirical testing. Section 3 introduces the case we study in the empirical analysis. Section 4 describes the data and variable construction, before outlining the empirical approach in Section 5. Section 6 presents the results, while Section 7 concludes with a discussion of policy implications.

2 Model and predictions

We consider a fjord with N salmon farming firms, indexed by $i = 1, \dots, N$. All firms produce according to licensed capacity and face the same lice population, which reduces the value of production through convex damages. Firms choose costly delousing efforts $e_i \geq 0$, which reduce the lice infestation on its stock of fish, and thus the local lice density. Hence, delousing efforts contribute to a local public good.

Let the gross value of production for firm i be V_i. Lice infestation reduces this value according to a convex damage function $D(E) = d(Q) - \theta E$, where $E = \sum_{j=1}^{N} e_j$ is the total delousing effort in the fjord, $d(Q) > 0$ is the baseline loss without mitigation, which depends on the total production in the fjord $Q = \sum_j q_j$, and $\theta > 0$ measures the effectiveness of mitigation. We assume diminishing marginal benefit of mitigation, which implies that $D'(E) < 0$ and $D''(E) > 0$. In addition, we assume that salmon production is sufficiently profitable for all firms to produce at full capacity, an assumption that is justified by the fact that salmon farming licenses sell at high prices. Hence, we can write $d(Q) = d > 0$.

The benefit of mitigation to firm i is proportional to its production capacity q_i (or local biomass share $s_i = \frac{q_i}{Q}$):

$$B_i(E) = s_i \cdot f(E), \quad f'(E) > 0,\ f''(E) < 0, \tag{1}$$

where $f(E)$ represents the reduction in damages from total delousing effort E. In addition, we assume a quadratic cost of delousing effort $C_i(e_i) = \frac{c}{2}e_i^2$ with $c > 0$.

Firm i chooses e_i to maximize net benefit:

$$\max_{e_i} \; s_i f(E) - \frac{c}{2}e_i^2. \tag{2}$$

The first-order condition is:

$$s_i f'(E) - c e_i = 0. \tag{3}$$

Since E depends on all e_j, each firm's best response is:

$$e_i = \frac{s_i}{c} f'\left(e_i + \sum_{j \neq i} e_j\right). \tag{4}$$

With $f''(E) < 0$, the marginal benefit $f'(E)$ decreases with the effort of others, making delousing efforts *strategic substitutes.* An increase in one firm's effort reduces the optimal effort of all others.

2.1 Comparative statics

The model allows us to examine how the number of firms in the fjord and the distribution of production capacity across them affect equilibrium delousing efforts.

First, consider the case of symmetric firms, where $s_i = 1/N$ for all i. In this case, the first-order conditions imply that the optimal effort per firm is decreasing in N: As the number of firms increases, each firm's share of the total benefit from low lice levels falls, and thus each firm contributes less. This is the standard free-riding result in public good provision.

Second, consider an asymmetric case with one large firm and $N - 1$ identical smaller firms. The large firm has a higher s_i and therefore internalizes a larger share of the benefit from total effort. It will therefore choose a higher delousing effort than in the symmetric case. By contrast, each small firm, facing a lower s_i, will choose a lower effort than in the symmetric benchmark. Although the large firm's increase in effort partially offsets the reduced efforts of the smaller firms compared to the case of symmetric firms, the total effect on aggregate effort depends on the size difference. When the large firm's share is sufficiently big, total delousing effort in the fjord will exceed the symmetric benchmark.

Finally, consider the effect of consolidation. Merging two or more firms into a single entity increases the s_i of the merged entity and reduces the number of independent decision-makers in the fjord. Both effects contribute to raise aggregate delousing effort: The merged entity has a stronger incentive to protect its now larger share of production, and the reduction in the number of separate players yields less opportunity for free riding. In economic terms, consolidation partially internalizes the positive externality of delousing, raising total mitigation and, under our assumptions, total production value.

These comparative statics summarize the central theoretical prediction: All else equal, farms belonging to firms with a larger share of total production in the relevant interaction zone will delouse more. This provides a clear testable implication for the empirical analysis.

2.2 Testable prediction

The comparative statics imply that, within a biologically relevant interaction zone such as a fjord, farms own by firms with a larger share of total production will undertake more delousing. Larger local shares strengthen firms' incentives to protect their own production, as they internalize a greater fraction of the spillover benefits from reduced lice pressure. The magnitude of this relationship depends on the degree of strategic substitutability in delousing efforts across farms.

In the empirical analysis, we measure each firm's local share as the proportion of total biomass within a given buffer around each farm, and we use the observed probability of delousing in a given week as a proxy for mitigation effort. We then estimate how the likelihood of delousing varies with local share, controlling for lice levels, farm and firm characteristics, and spatial and temporal factors.

3 Institutional and environmental setting

This study examines spatial externalities and strategic mitigation behavior in Norwegian salmon aquaculture. The sector provides an ideal empirical setting: it is large enough for externalities to matter economically, yet sufficiently geographically concentrated for strategic interactions among firms to be observed, and is characterized by comprehensive administrative data.

Aquaculture is among the fastest-growing food production sectors globally and an increasingly important source of animal protein. Farmed Atlantic salmon is the dominant species within marine finfish aquaculture, accounting for 32.6 percent of marine and coastal finfish aquaculture by volume, with global production reaching approximately 2.7 million tonnes in 2020 (Food and Agriculture Organization of the United Nations, 2022). Global salmon farming is highly concentrated, with Norway, Chile, and Scotland together accounting for the majority of world output. This concentration, combined with biological and regulatory constraints on rapid supply expansion, limits short-run substitution across regions and amplifies the economic relevance of environmental pressures in major producer countries.

Norway is the world's largest producer of farmed Atlantic salmon, supplying roughly half of global output. Norwegian salmon exports increased from 0.995 million tonnes in 2012 to approximately 1.3 million tonnes in 2021, an expansion of 28.9 percent over the period, and continued to reach record levels in subsequent years (Statistics Norway, 2026; Norwegian Seafood Council, 2025). The industry is strongly export-oriented, making it a key contributor to Norway's trade balance and exposing producers directly to global demand conditions. Growth over the past decade reflects both productivity improvements and sustained international demand for farmed salmon.

The seafood sector, dominated by salmon aquaculture, is Norway's second-largest export sector (by value) after petroleum. Total seafood exports reached NOK 175.4 billion approximately USD 16.3 billion at 2024 average exchange rates) in 2024, and the sector generates about 2.3 percent of mainland GDP (Norwegian Seafood Council, 2025; Iversen et al., 2024). The sector invested NOK 1.5 billion (approximately USD 139 million) in research and development in 2023, placing it among the ten most R&D-intensive industries in the country, ahead of food manufacturing and comparable to sectors such as refined petroleum and chemicals (Statistics Norway, 2024). These research efforts are motivated both by productivity improvements and by environmental challenges, most notably salmon lice.

Aquaculture accounts for approximately 1.5 percent of Norwegian employment (Statistics Norway, 2025) and is geographically concentrated, with a small number of coastal counties[3] hosting the majority of aquaculture activity. This concentration makes local labor markets and regional economies particularly sensitive to conditions in the sector. Because industry growth is subject to environmental regulation and spatially linked production processes, salmon aquaculture occupies a central position in Norwegian policy debates where environmental externalities and economic outcomes are tightly intertwined.[4]

3.1 Norwegian aquaculture regulation

These policy concerns are reflected in a regulatory framework that has increasingly tied production capacity to environmental performance. The Aquaculture Act of 2005 prioritized industry profitability and competitiveness, treating environmental sustainability primarily as a boundary condition. Between 2005 and 2017, mounting evidence of salmon lice impacts on wild salmon populations exposed tensions between continued capacity expansion and environmental limits. These tensions culminated in a major regulatory shift with the introduction of the Traffic Light

[3]Production is concentrated in five coastal counties – Nordland, Vestland, Troms og Finnmark, Møre og Romsdal, and Trøndelag – which together account for approximately 88 percent of aquaculture employment.

[4]Of total aquaculture-related employment, approximately 15,141 positions (about 0.5 percent of national employment) are in direct production, while the majority are in upstream supplier industries such as feed manufacturing, equipment, logistics, and specialized services (approximately 33,000 positions) (Statistics Norway, 2025; Iversen et al., 2024).

System in 2017, which linked capacity adjustments to area-level environmental outcomes and marked a transition from site-specific compliance toward collective, region-based accountability.

Production License. Production licenses are issued by the Ministry of Trade, Industry and Fisheries, with administration delegated to the Directorate of Fisheries. Licenses are scarce and transferable subject to regulatory approval and determine the total biomass a firm may operate. Importantly, licenses are legally distinct from sites (locations): while licenses define how much biomass may be produced, site approvals determine where production may occur.

Maximum Allowed Biomass (MAB). A capacity-based licensing system established under the Aquaculture Act (Akvakulturloven, 2005). Production licenses function as transferable production capacity rights and define maximum Allowable Biomass (MAB), which sets an upper limit on the total quantity of live fish biomass (in tonnes) that may be held at any point in time. MAB is a stock constraint rather than a measure of annual output and directly shapes stocking density, harvest timing, and growth trajectories over the production cycle. During the early 2010s, a standard commercial salmon license corresponded to an MAB of approximately 780 tonnes, making MAB the binding quantitative constraint on production.

Farm site location approval. Permission to operate at a specific site requires approval through a multi-agency administrative process. Site applications are evaluated by the County Governor (environmental impacts), the Norwegian Food Safety Authority (fish health and welfare), the Norwegian Coastal Administration (navigation and coastal use), and the relevant municipality (spatial planning), with coordination by the Directorate of Fisheries. Firms must hold both a valid production license and an approved site to operate.

Operation. Once acquired, a license's associated MAB may be deployed across one or multiple approved sites owned by the firm, provided that site-specific approvals are in place and that aggregate biomass across sites does not exceed licensed capacity. Licenses are not permanently tied to specific locations and may be reassigned across sites subject to regulatory approval, allowing firms to reallocate production spatially in response to biological and operational conditions while keeping total production capacity fixed at the license level.

Operational compliance with capacity constraints is ensured through the Regulation on the Operation of Aquaculture Facilities (Driftsforskriften, 2008), which specifies production standards and mandates systematic monthly reporting of biomass, mortality, and fish health. These reporting and inspection requirements make production capacity observable and enforceable in practice and form the institutional foundation upon which subsequent environmental regulations and capacity-adjustment regimes are built.

Environmental regulations. Salmon aquaculture generates a range of environmental externalities, including waste dispersal, nutrient accumulation, fish escapes, and disease transmission. While most of these externalities are addressed through site-level environmental assessments and operational standards, sea lice (*Lepeophtheirus salmonis*) have become the primary focus of environmental regulation in the industry. Scientific evidence linking farm-origin lice to elevated mortality among wild salmon smolts during their seaward migration shifted lice management from a production efficiency concern to a central regulatory priority. Sea lice disperse via ocean currents during a planktonic larval stage lasting several weeks, creating spatial externalities: lice produced at one farm can infest neighboring farms and wild fish populations on the order of tens of kilometers.

Lice management is governed by regulations under the Food Act (2003) and enforced by the Norwegian Food Safety Authority (Mattilsynet). Farms are required to conduct weekly lice counts following standardized protocols and to report adult female lice levels to the authorities. Regulatory thresholds specify maximum permissible lice levels, measured as average adult female lice per fish, which trigger mandatory treatment obligations when exceeded. These thresholds apply uniformly across farms regardless of ownership or operational characteristics, and compliance is subject to inspection and enforcement. Between 2009 and 2017, lice regulation was progressively strengthened through tighter monitoring requirements, more stringent thresholds, and increased enforcement, reflecting growing regulatory emphasis on limiting the impacts of farm-origin lice on wild salmon populations.

Regulatory evolution of lice thresholds. The regulatory treatment of sea lice thresholds underwent three major phases between 2009 and 2017, progressively tightening monitoring requirements and establishing more stringent, temporally differentiated threshold levels.

Under the 2009 lice regulation[5], farms were required to monitor lice counts bi-weekly when water temperatures exceeded 4°C and report monthly to the Norwegian Food Authorities. Treatment was mandatory within 14 days of exceeding regulatory threshold levels. The regulation emphasized coordinated spring delousing campaigns across neighboring farms to minimize lice exposure during the critical period when wild salmon smolts migrate seaward. However, threshold levels were applied uniformly throughout the year without explicit differentiation based on wild salmon migration timing, and enforcement relied primarily on monthly aggregated reports rather than real-time monitoring.

In December 2012, a new regulation took effect (January 1, 2013). The regulation introduced

[5] in Norwegian:Forskrift om bekjempelse av lus i akvakulturanlegg nr. 1095

explicit provisions for combating treatment-resistant lice populations and expanded the Norwegian Food Authorities' authority to establish regulatory zones and impose coordinated treatments when voluntary compliance proved insufficient. While the 14-day treatment requirement remained in place, reporting shifted to weekly and formalized coordination marked a transition from reactive, site-specific enforcement toward proactive, area-based management.

In March 2017, a critical amendment established time-specific lice thresholds that explicitly differentiated regulatory stringency based on wild salmon migration patterns. The amendment set a stricter threshold of 0.2 adult female lice per fish during peak smolt migration periods – defined as weeks 16-21 (approximately mid-April to late May) in southern and central Norway (Nord-Trøndelag and southward), and weeks 21-26 (late May through June) in northern regions (Nordland, Troms, and Finnmark). Outside these critical windows, farms were permitted up to 0.5 adult female lice per fish, acknowledging reduced risk to wild populations while maintaining year-round control obligations. These threshold reforms set the institutional stage for the Traffic Light System introduced later in 2017, which would extend the principle of science-based, temporally and spatially differentiated regulation to encompass zone-level capacity adjustments.

Traffic Light System (TLS). The Traffic Light System (TLS), introduced in 2017 through the Production Area Regulation[6], fundamentally reoriented Norwegian aquaculture regulation by linking production capacity directly to zone-level environmental performance. The system divides the Norwegian coastline into 13 designated production areas defined by hydrographic conditions and salmon lice dispersal patterns. Environmental performance is assessed biennially based on scientific evaluations of sea lice-induced mortality among wild salmon smolts during their spring seaward migration.

Production areas are classified as green, yellow, or red following each assessment cycle, based on advice from an expert scientific group using monitoring data and epidemiological models. Final regulatory decisions are made by the Ministry of Trade, Industry and Fisheries and implemented by the Directorate of Fisheries. Area classifications determine capacity adjustments applied uniformly to all licenses within each production area: green areas permit capacity growth, yellow areas impose a freeze on growth, and red areas require mandatory capacity reductions. Adjustments apply to firms' total licensed Maximum Allowable Biomass (MAB) within each area and are implemented on a biennial basis.

The TLS establishes collective accountability for environmental outcomes within production areas. All firms operating in the same area face identical capacity consequences regardless of individual farm-level lice counts or compliance histories. Because salmon lice disperse across farms via ocean currents over biologically relevant distances comparable to the spatial scale of

[6](*Produksjonsområdeforskriften*, FOR-2017-01-16-61)

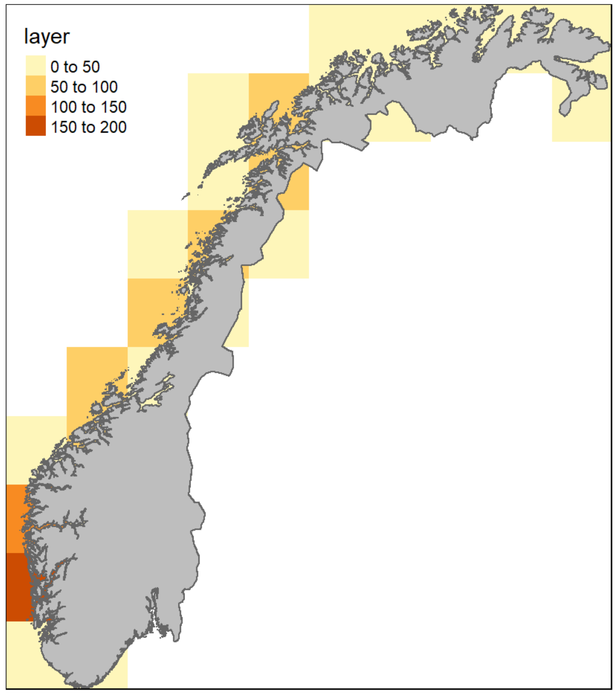

Figure 1: Density in number of farms by raster grids of 200 km-by-200 km. (Data: Norwegian Aquaculture Registry)

production areas, environmental outcomes and regulatory constraints are inherently shared among neighboring operators. By replacing site-specific compliance with area-level capacity adjustments, the TLS embeds spatial ecological connectivity directly into the regulation of production capacity.

3.2 Production geography, biology, and mitigation

Production predominantly occurs in open-net pens in fjords and sheltered coastal waters, with grow-out cycles typically lasting 14–22 months depending on location and seasonal temperature. Farm density is highest in western Norway, where environmental conditions such as sea temperature and the abundance of sheltered coastal waters are particularly favorable for salmon production, and is lower in the far north and south. The density and scale of salmon farming vary substantially across regions, affecting both biological connectivity and the potential for spatial externalities. Figure 1 shows the geographic distribution and density of farms across Norway, based on raster grids of 200 km by 200 km, illustrating both the spatial concentration of production and the heterogeneity in farm density. The western coast has the highest concentration, while the opposite for the north.

Biological connectivity & externalities. The main environmental and production challenge in Norwegian aquaculture is the salmon louse (*Lepeophtheirus salmonis*), a naturally occurring parasite that harms both farmed fish and wild salmonids[7]. The rapid expansion of salmon farming since the 1970s has increased the number of hosts by several orders of magnitude, elevating the lice pressure in coastal ecosystems. The adult female lice finds a salmonid host to feed on before releasing eggs in the water column. Salmon lice hatch from eggs into planktonic nauplius larvae, which remain free-swimming for about 100–150 degree-days (roughly 10–15 days at 10^{o}C), before developing into the infectious copepodid stage. During this period, dispersal is primarily driven by variable current conditions, influenced by wind, freshwater runoff, tides, and density gradients (Institute of Marine Research, 2020). These dynamics result in spatial externalities: A lice outbreak at one farm can elevate infection pressure tens of kilometers away, while treatment at one site can reduce pressure for others. Although some lice may travel over 100 km, the bulk of infectious copepodids typically remain within 10–80 km of the source, with spread patterns varying by geography, season, and prevailing currents (see e.g. Asplin et al., 2014, 2020). Lice control is therefore not only a private cost but also a public good, with strategic interdependence among farms. While other pathogens, including viral and bacterial diseases, also exhibit spatial transmission, salmon lice is the main regulatory and economic constraint, and thus the focus of our analysis. However, our framework applies to similar externalities from other parasites and diseases.

Delousing technologies. Active delousing methods fall into two main categories used in official reporting: chemical (medicinal) and mechanical (non-medicinal). First, chemical treatments include chemotherapeutant baths, and in-feed medications. Second, non-chemical treatments include mechanical removal, thermal treatment using warm water at 28–34°C, and freshwater baths (in well-boats). While chemical treatments dominated the industry through the mid-2010s, they were largely replaced by mechanical and thermal methods (Overton et al., 2019) following evidence of lice resistance (Fjørtoft et al., 2020) to chemotherapeutants and concerns about environmental impacts on non-target species, particularly crustaceans (Parsons et al., 2020). We address this shift in treatment types by testing pre and post samples.

A complementary biological control strategy involves stocking pens with cleaner fish (wrasse, lumpfish), which continuously feed on lice. Unlike chemical or mechanical delousing, cleaner fish function as a preventive, ongoing control measure rather than an acute or episodic treatment. The presence of cleaner fish signals the intent of mitigation, and is used as a control binary variable in our econometric specification

[7]Other salmon aquaculture externalities such as escapes and nutrient accumulations are outside the scope of this article

Treatment incentives & spillovers. Norwegian regulations set seasonal thresholds on lice abundance in salmon farms, defined as a maximum average number of adult female lice per fish, with mandatory treatment required when these limits are exceeded. Farms may also treat preemptively based on expected lice pressure. Approved treatments – such as mechanical removal, thermal baths, or chemical use – involve direct costs, operational disruptions, and risks of stress or mortality to the fish, so farmers weigh expected lice pressure against the costs and benefits of intervention. Because a substantial share of the benefits from treatment, in the form of reduced lice pressure, accrues to neighboring farms, the spatial distribution of ownership can shape incentives. Our theoretical framework predicts that when a firm controls a larger share of local biomass, it internalizes more of these benefits and thus may have a stronger incentive to act. In more fragmented ownership settings, the incentive to free-ride on others' treatments is expected to be greater.

The Norwegian regulatory framework mandates comprehensive reporting of production, biomass, lice counts, and treatment activity, generating high-frequency administrative records that allow farm-level behavior to be observed within biologically and institutionally relevant spatial units. These features make it possible to relate variation in local ownership structure and environmental exposure to observed mitigation effort, motivating the data construction and empirical approach described below.

4 Data

Our empirical analysis combines several administrative and registry datasets that provide complete coverage of Norwegian salmon farming at the farm-week level over the period 2012-2021. Our dataset includes information on production volumes, ownership, farm locations, lice counts, treatment events, and environmental conditions, allowing us to construct measures of both local ownership share and mitigation effort.

Monthly production data at each licensed site are obtained from the Norwegian Directorate of Fisheries. These reports include fish numbers and biomass which are the key capacity measures in our empirical analysis. It also contain details on smolt releases, harvests, and mortality, as well as inputs such as feed use and outputs such as fish sold. Using this production dataset along the geographic coordinates of each site, we compute each farm's *local weekly biomass share*: the proportion of the total biomass within a specified buffer distance that is owned by the same firm. This variable is the empirical analogue of the ownership parameter s_i in our theoretical model, and can change both because of weekly changes in local stock levels (due to growth, mortality, and harvest) and yearly changes in ownership (i.e., which firm operates the farm).

The spatial range over which sea lice transmission can occur is determined by the drift of

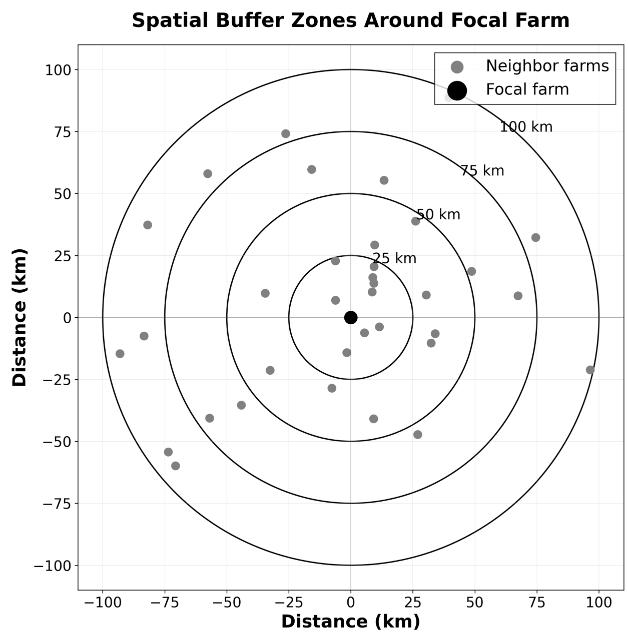

Figure 2: An Example of a Focal Farm and Its Neighbors by Distance Buffers

planktonic larval stages. As mentioned above, larvae may survive and drift over 100 km under favorable oceanographic conditions. However, empirical evidence and hydrodynamic modeling suggest that the risk of infection is greatest over shorter ranges. We therefore construct local stock share measures for four fixed buffer distances: 25, 50, 75, and 100 km. We expect the range between 50 and 75 km to capture most of the economically relevant strategic interaction in delousing decisions, given typical current patterns and larval survival rates.

All active farms (i.e., farms with fish in pens) are required by the Norwegian Food Safety Authority to submit weekly lice and treatment reports. This data is publicly available via the BarentsWatch portal (BarentsWatch, 2026). These reports provide average lice counts per fish at different developmental stages, and environmental variables such as sea temperature at a given depth. Norwegian regulations impose an upper limit on the number of adult female lice per fish; exceeding this threshold triggers mandatory delousing. [8] We therefore use the count of adult female lice per fish as our measure of parasite pressure. Delousing events are recorded in the same reports, with details on the method used (e.g., thermal, mechanical, chemical). We define a delousing event as any lice treatment reported in a given week, regardless of method.

We use a novel, time-varying ownership dataset that tracks the firm that actually owns and controls each farm and license, rather than relying solely on first-level company registration

[8]Thresholds limits vary for two main reasons. First, by seasons, with wild smolts spring migration imposing stricter limits in that period, which is different in the south and the north. Second, by license types, with “Green Licences” subjected to specific lower limits than the general threshold of 0,5 adult female lice per fish. We use the exact threshold imposed for each farm, in each week over the period 2012-2021.

numbers. For example, a holding (main entity) may use different organization numbers (sub-entities) for reporting at farm-level, but ultimately it is the same firm. We also identify ownership of joint ventures by controlling shares (51%+). To our knowledge, this is the first study to precisely measure Norwegian aquaculture industry concentration using actual ownership control by tracking the history of merger, acquisition and other changes of each organization in the Brønnøysund Register Center (Brønnøysund Register Centre, 2026). This allows us to link each farm in each week to its controlling firm and to capture changes due to mergers, acquisitions, and divestments. The number of active firms declined from 79 to 72 over the study period, primarily due to consolidation.

We use historical records on aquaculture licenses and farm locations from the Aquaculture Register (Norwegian Directorate of Fisheries, 2024), a public register established in 2006 and administered by the Directorate of Fisheries. We obtain spatial boundaries from the Norwegian Mapping Authority's Geonorge portal, which provides administrative boundaries and other geospatial data from governmental sources. We also use the 13 salmon production zones defined by the Institute of Marine Research, based on hydrodynamic simulations of lice dispersion, and introduced in 2017 under the Traffic Light System for regulating production growth. We use these zones for mapping and descriptive purposes. We include sea temperature from the lice reports as a control variable in the empirical analysis, reflecting well-established biological evidence that higher temperatures accelerate salmon lice development and reproduction.

Our analysis spans from 2012 to 2021, and the full dataset has 278,117 farm-week observations from 1011 distinct farms over that period. Table 1 reports descriptive statistics for the main variables used in the analysis, drawn from the production and lice datasets. The unit of observation is the farm-week. Monthly biomass reports were interpolated to a weekly frequency to match the lice reporting frequency and treatment decisions. Biomass increases from the moment of release of smolt to the harvest as the fish grow. Stock typically declines during the production cycle due to mortality and other losses. A farm may be partially harvested; for example, 30% of the stock is sold but the remaining fish continue to grow.

The treatment rate is defined as the weekly percentage of active farms reporting at least one treatment method (chemical, mechanical, thermal). Adult lice per fish is the metric used in regulatory thresholds. Biomass, expressed in metric tons, is the main variable of interest used to construct our measure of a firm's local biomass share. The average biomass over all farms and all weeks is 1,346 MT. Stock is measured in thousands of fish.

Table 2 shows statistics by distance buffer around the focal farm. Within a 25 km radius of the focal farm, there are in average about 13 active farms and 5 active firms. Farms that are inactive in a given week, such as during fallowing, are not considered in the calculations. There is a substantial disparity in farm and firm numbers across buffers. Within 25 km, the minimum is 2

Table 1: Focal Farms Summary Statistics

Variable	Min	Mean	SD	Max
Treatment Rate (%)	0.00	12.75	33.36	100.00
Adult Lice (per fish)	0.00	0.16	0.38	29.48
Stock (000s fish)	0	742	463	3481
Biomass (MT)	0	1346	1176	10538
Temperature (°)	0.00	9.08	3.62	24.93

Notes: Weekly observations across all farms in panel. **Treatment Rate** = percentage of farm-weeks with any treatment. **Adult Lice** = adult female lice per fish. **Stock** = number of fish (thousands). **Biomass** = total fish weight (metric tons). **Temperature** = sea temperature in degrees Celsius.

Table 2: Buffer summary statistics

Variable Mean [Min–Max]	25 km	50 km	75 km	100 km
Firm Biomass Share (%)	40.03	25.46	21.09	18.70
	[0.00–100.00]	[0.00–100.00]	[0.00–100.00]	[0.00–100.00]
Number of Farms	13.32	33.82	54.41	73.72
	[2– 52]	[2– 111]	[2– 152]	[2– 184]
Number of Firms	4.52	8.16	11.01	13.81
	[1– 13]	[1– 19]	[1– 23]	[1– 28]
Lice (per fish)	0.153	0.152	0.151	0.150
	[0.00–6.16]	[0.00–3.44]	[0.00–1.75]	[0.00–1.21]

Notes: 2012–2021 weekly observations (N = 278,117) across 1,014 farms. **Firm Biomass Share** = focal firm's share of total biomass within buffer (includes focal farm). **Number of Farms and Firms** include focal farm and firm. **Lice** = mean adult female lice per fish across all farms in buffer (includes focal).

farms (the focal farm plus one neighbor) and the maximum is 52, indicating a dense production area.

Firm local biomass shares exhibit strong spatial decay, from 40.03% (SD = 28.2%) within 25 km, to 25.46% (SD = 20.0%) within 50 km, to 21.09% (SD = 17.6%) within 75 km, and to 18.70% (SD = 15.5%) within 100 km. High standard deviations (15-28 percentage points) reveal substantial heterogeneity across buffer distances: some firms dominate small local areas while others operate across dispersed locations. This monotonic decline with distance is in line with more fragmented ownership at larger geographic scales.

5 Empirical specification

Our goal is to estimate how local firm size within a biologically connected production area shapes farm-level delousing effort. In our empirical setting, sea lice disperse between neighboring farms via oceanic currents; delousing at one farm therefore reduces lice burdens at neighboring farms, creating positive spillover benefits. We measure firm size as each firm's share of biomass within biologically relevant buffer distances around each farm, capturing the proportion of local production the firm controls. The theoretical model predicts that farms owned by firms with larger local biomass shares internalize a greater share of spillover benefits and therefore delouse more frequently.

We test this prediction using a weekly farm-level panel covering 2012–2021, linked to time-varying ownership records. Our outcome variable is an indicator for whether treatment occurs at a given farm in a given week.

The key explanatory variable, $S_{jit}^{(K)}$, is the firm j's share of the total farmed salmon biomass within a circular buffer of K kilometers around focal farm i in week t, where $K \in \{25, 50, 75, 100\}$. Although lice larvae might drift over longer distances, the majority of infectious larvae (copepodids) remain within 20-80 km of the source. We therefore expect interaction effects to be strongest within 75 km. The dependent variable, Y_{it}, is an indicator for whether any delousing event was reported at farm i (owned by firm j) in week t. We focus on the incidence of the treatment, as treatment decisions are typically binary at weekly frequency given operational constraints. See Section 4 for variable definitions.

We estimate this relationship using a weekly farm-level panel covering 2012-2021. We specify the following equation (5) for focal farm i owned by firm j in week t:

$$Y_{ijt} = \alpha + \beta_1 S_{jit}^{(K)} + \beta_2 L_{i,t-1} + \gamma' \mathbf{X}_{it} + \sigma_i + \delta_t + \phi_j Y(t) + \varepsilon_{it}, \tag{5}$$

where t indexes weeks and $Y(t)$ denotes the year containing week t, $L_{i,t-1}$ is the average number of adult female lice per fish at farm i in the previous week ($t-1$). We include controls as $\mathbf{X}_{it}$ (Stock, AvgWeight, Temperature, etc.). Fixed effects are included for farm σ_i, week δ_t and firm-year $\phi_j Y(t)$.

We estimate equation 5 using a linear probability model (LPM) for ease of interpretation; logit specifications are reported as robustness checks. The interaction term tests whether the internalization effect of ownership concentration is stronger when the parasite pressure is high.

5.1 Identification strategy

Our identification strategy is grounded in a simple internalization mechanism: firms that control a larger share of production within a biologically connected area internalize a greater portion of the spillover benefits from lice mitigation and therefore optimally choose higher delousing effort. We test this mechanism using within-farm, over-time variation in a farm's local firm biomass share, S_{jit}.

Within a given farm, S_{jit} varies over time from three main sources: (i) stocking, growth, and harvest cycles at the focal farm, (ii) similar production and fallow cycles at neighboring farms, and (iii) ownership changes across farms in the vicinity. The first two sources generate high-frequency (weekly) variation, while ownership changes occur infrequently and are observed at an annual frequency. Importantly, farm locations are mostly fixed from historical placement, and thus are exogenous; but ownership assignment via license markets is endogenous (in the long run). These three shifts are plausibly exogenous to the focal farm's short-run delousing decision, as they are driven primarily by longer-horizon production cycles and investment-driven ownership transfers, which are shaped by biological processes and regulatory constraints rather than by contemporaneous treatment choices.

Most high-frequency variation in our weekly panel is mechanically generated bybiomass growth, harvest, fallowing, and neighboring farm activity, not contemporaneous reallocation of firm boundaries. This composition of variation suggests that conditional on controls and fixed effects absorbing systematic consolidation strategies, within-farm changes in S_{jit} reflect plausibly exogenous shifts in local exposure.

Our central identifying assumption is that, conditional on observed lice pressure, time-varying farm- and firm-level controls, and a rich set of farm, temporal, and regional fixed effects, within-farm changes in local share S_{jit} reflect plausibly exogenous shifts in local exposure and are orthogonal to unobserved determinants of delousing effort (such as unanticipated cost shocks or unobserved productivity shifts). Under this assumption, residual differences in delousing frequency can be interpreted as arising from variation in local share of production.

Three features of our control strategy support this identification assumption. First, farm fixed effects absorb all time-invariant heterogeneity in bio-environmental conditions, site quality, and managerial practices. Second, week and region fixed effects net out common regulatory, technological, and market shocks. Third, controlling flexibly for contemporaneous lice pressure and temperature limits scope for reverse causality: farms cannot delouse in response to worse conditions that are unobserved at the time of treatment, since we condition on realized lice counts.

This approach parallels Song et al. (2023), who study spatial externalities from wind farms on grassland quality using county fixed effects combined with zone-year and province-year fixed effects to control for unobserved heterogeneity at multiple spatial scales. Like their setting, where wind turbine microclimate effects extend 10+ kilometers to neighboring areas, sea lice in our context disperse via ocean currents across distances of 50-75 kilometers, creating spatial externalities where one farm's treatment decisions affect neighbors' lice exposure. Following their strategy of controlling flexibly for weather variables (precipitation and growing degree days) to address potential omitted variable bias, we control flexibly for contemporaneous environmental conditions. As in Song et al. (2023), conditioning on realized outcomes – current vegetation quality in their setting and lice counts in ours – limits reverse causality by ensuring treatment decisions respond to observed rather than anticipated conditions.

Under these conditions, we interpret the estimated effect of S_{jit} as evidence that firms with a larger local footprint internalize a greater share of spatial spillovers and therefore undertake more environmental mitigation. Specifically, a higher delousing probability at farms with larger local shares is consistent with firms adjusting mitigation effort in proportion to their exposure to locally generated lice.

Identification is further supported by cumulative evidence from distance gradients, synthetic data–generating process exercises, and placebo diagnostics. Notably, we establish robustness across distance buffer definitions (25, 50, 75, 100 km), confirming that the S_{jit} effect exhibits spatial decay in accordance with externality theory. Also, we conduct synthetic data-generating-process exercises embedding simultaneous determination, bad controls, and correlated shocks, testing our specification and estimator behavior under known challenges. Together, these analyses probe the sensitivity of our results to alternative spatial definitions, simulated endogeneity, and potential feedback dynamics. Consistent statistical significance of the S_{jit} coefficient across all specifications strengthens the cumulative case.

5.2 Remaining identification concerns

Several potential threats to identification merit discussion. A primary concern is that local ownership concentration may itself reflect endogenous firm location choices. Specifically, firms may acquire and retain farms in areas with favorable environmental conditions that both attract investment and facilitate lice control, inducing a spurious correlation between S_{jit} and unobserved locational quality.

However, this concern operates at different timescales. *Farm locations* are mostly fixed from historical placement and are therefore exogenous; the endogeneity problem is that *ownership assignment* via license markets is endogenous in the long run. We address time-invariant location endogeneity through farm fixed effects, which absorb all time-invariant heterogeneity in bio-environmental conditions, site quality, and managerial practices. We address time-varying environmental confounders by controlling flexibly for contemporaneous lice pressure and temperature.

More importantly, most high-frequency variation in S_{jit} is mechanically driven by biomass growth, harvest, fallowing, and neighboring farm activity, rather than contemporaneous reallocation of firm boundaries. Ownership changes in Norwegian salmon farming are infrequent, highly regulated, and driven by long-horizon corporate restructuring. Conditional on firm-level controls and fixed effects absorbing systematic consolidation strategies, the identifying variation primarily reflects plausibly exogenous shifts in local biomass exposure.

A second concern is simultaneity and feedback within interaction zones. Because treatment decisions affect neighboring lice pressure, shocks may be correlated across farms. We address this by clustering standard errors at the production-zone–year level, allowing for correlated shocks across farms within biologically connected areas. Placebo tests (showing future lice can also predict treatment) confirm feedback operates both directions; we isolate causality by focusing on neighbor biomass exposure rather than realized neighbor lice.

A third concern is unobserved complementary mitigation strategies, such as cleaner fish or stocking adjustments. If these complementary actions correlate with local production share, our estimates may capture a broader effect of S_{jit} on lice management rather than delousing alone. This is in line with the theoretical framework, which concerns overall mitigation incentives. To the extent that preventive measures substitute for reactive treatments, this channel would bias the estimated effect downward, making our estimates conservative.

Finally, distance gradients can be misleading if coefficients are not standardized. The expected share of biomass controlled by the firm is dependent on the area size, or buffer distance around the focal farm. Hence, a share of 15% within 25 km is considered small while 15% at 100 km is large. Therefore to compare across distance buffers, we report standardized effects ($\beta \times$ SD) and verify that raw magnitudes are consistent across specifications. We show that the estimated effect decays across buffers, as predicted if identification holds.

5.3 Estimation approach

We estimate our baseline specifications using a linear probability model (LPM) with high-dimensional fixed effects. This choice is motivated by three features of our setting:

First, our design requires absorbing farm, week, and firm-year fixed effects in a weekly panel with relatively infrequent treatment events (average circa 12%). In nonlinear binary response models with high-dimensional fixed effects, the incidental parameters problem can lead to biased and inconsistent estimation of the structural parameters when a large number of fixed effects are included (Greene, 2004; Fernández-Val & Weidner, 2016). Following the applied econometrics literature, we therefore use a linear probability model, which differences out fixed effects directly, remains computationally stable, retains the full sample, and delivers consistent estimates of average partial effects even with a binary outcome (Angrist & Pischke, 2009; Chen et al., 2023).

Second, our key regressor is a constructed measure of local spatial exposure, and our identification relies on distance gradients and decompositions of neighboring biomass. The linear model preserves constant marginal effects with respect to each spatial exposure component, enabling transparent decomposition of the treatment effect into own-farm and other-firm contributions.

In logit, the marginal effect of each component would vary with the index and fixed effects, complicating decomposition and gradient interpretation (Wooldridge, 2010; Chen et al., 2023).

Third, the LPM delivers coefficients directly interpretable as percentage-point changes in treatment probability, facilitating transparent interpretation of interactions and translation into policy-relevant magnitudes (Angrist & Pischke, 2009).

6 Empirical results

We examine how firms allocate delousing treatments across their portfolios of farms within biologically connected areas, focusing on whether treatment decisions respond to the share of locally exposed biomass controlled by the firm. The theoretical framework in Section 2 predicts that farms belonging to firms with a larger local biomass share internalize a greater fraction of lice spillovers and therefore face stronger incentives to undertake delousing treatments.

We test this prediction by estimating equation (5) using weekly farm-level data and a linear probability model. The dependent variable, treatment, is a binary indicator equal to one if the focal farm undertakes either mechanical or chemical delousing in a given week, and zero otherwise. Table 3 presents the main results for specifications based on a 50 km exposure buffer, estimated on 244,252 farm-week observations. The sample includes farms with at least one neighboring farm within the 50km buffer. The columns progressively saturate the model with biological controls, farm-scale variables, local structure measures, and fixed effects. Standard errors clustered at the farm, firm, or production-zone level, as indicated, are reported in parentheses.

The baseline model includes farm and week fixed effects, lagged lice pressure, and the focal firm's share of total biomass within the buffer. A one–percentage-point increase in local biomass share is associated with a 0.058 percentage-point higher weekly probability of delousing. The estimate is positive, precisely estimated, and statistically significant at conventional levels, indicating that, within farms over time, greater local firm exposure is associated with systematically higher delousing activity.

The coefficient on lagged adult female lice abundance is positive and highly stable across all specifications, confirming that treatment behavior responds strongly to the primary biological driver. The prior week's lice count serves as the regulatory and biological trigger for treatment, in accordance with mandatory intervention thresholds and with the adverse effects of elevated parasite loads on fish growth and survival. The stability of this coefficient across specifications provides an internal validity check that the model captures economically and biologically meaningful treatment behavior.

Subsequent specifications address potential confounding from firm-level heterogeneity and local market structure. Adding firm–year fixed effects absorbs all firm-specific, time-varying

Table 3: Main Results within a 50 km Buffer

	(1)	(2)	(3)	(4)	(5)
Focal firm share of buffer biomass (0-1) 50km (weekly)	0.0577***	0.0715***	0.0715***	0.0757***	0.0757**
	(0.0171)	(0.0173)	(0.0228)	(0.0259)	(0.0299)
L.Adult female lice per fish (weekly)	0.1536***	0.1553***	0.1553***	0.1553***	0.1553***
	(0.0095)	(0.0096)	(0.0146)	(0.0147)	(0.0122)
Stock (000s fish) (weekly)	0.0000***	0.0001***	0.0001***	0.0001***	0.0001***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Average fish weight in kg (weekly)	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Sea temperature (°C) (weekly)	0.0038***	0.0040***	0.0040***	0.0040***	0.0040***
	(0.0008)	(0.0008)	(0.0011)	(0.0011)	(0.0011)
Neighbor farm count (excl focal) 50km (weekly)				-0.0001	-0.0001
				(0.0006)	(0.0006)
Firm-level HHI biomass-weighted 50km (weekly)				-0.0196	-0.0196
				(0.0251)	(0.0360)
Farm FE	Yes	Yes	Yes	Yes	Yes
Week FE	Yes	Yes	Yes	Yes	Yes
Firm-Year FE	No	Yes	Yes	Yes	Yes
SE Clustering	Farm	Farm	Firm	Firm	Zone
Observations	244,252	244,252	244,252	244,252	244,252
Adjusted R^2	0.098	0.118	0.118	0.118	0.118
Clusters	996	996	102	102	31

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
All models include farm and week fixed effects. Models 3-6 include firm-year fixed effects.
Standard errors clustered at farm level (Models 2-3), firm level (Models 4-5), or coastal zone (Model 6).

characteristics, such as management practices, capital deployment, and strategic reorganization. This addition increases the adjusted R-squared from approximately 0.10 to 0.12, indicating that these factors explain meaningful variation in treatment behavior. Further controls for local farm density and biomass-weighted concentration (HHI) leave the estimated effect of focal firm share stable.

Across these saturated specifications, the estimated ownership effect rises modestly relative to the baseline and remains precisely estimated. This pattern indicates that controlling for firm-level heterogeneity alters the identifying variation, revealing a stronger conditional relationship between local ownership share and treatment probability. The absence of attenuation when additional controls are included provides evidence against positive omitted-variable bias, while the increase upon adding firm–year fixed effects suggests that baseline estimates may understate the conditional association between ownership concentration and mitigation behavior. The coefficient on local HHI is small and statistically insignificant, implying that generic market concentration does not confound the focal ownership effect.

The remaining controls behave consistently with biological and operational expectations. Stock size is positively associated with treatment probability, reflecting greater absolute lice burdens at larger operations. Sea temperature enters positively and significantly, consistent with faster lice reproduction in warmer conditions. Average fish weight has no detectable effect. The coefficient on the number of neighboring farms is close to zero, indicating that farm density alone does not drive treatment behavior, reinforcing the interpretation that ownership, rather than congestion, governs mitigation incentives.

Inference is robust to alternative clustering schemes. Specifications using firm-level and production-zone clustering yield similar standard errors, indicating that results are not sensitive to the level at which spatial correlation is accounted for. We treat the specification with firm–year fixed effects and firm-level clustering as our preferred model, as it accounts for within-firm correlation in treatment decisions while retaining a sufficient number of clusters for reliable asymptotic inference.

Across specifications, the estimated coefficient on focal firm share ranges from 0.058 to 0.076. In the preferred specification Column (4), a one–percentage-point increase in local production share raises the weekly probability of delousing by approximately 0.076 percentage points. While the marginal effect per percentage point is small in absolute terms, variation in local exposure across a firm's portfolio generates economically meaningful differences in aggregate treatment activity. For example, increasing a firm's local biomass share from 15% to 20% raises the expected weekly treatment probability at each affected farm by roughly 0.38 percentage points. Over a 40-week production cycle, this corresponds to about 0.15 additional treatments per farm, or roughly one additional treatment across a five-farm cluster every one to two years. These calculations treat

Table 4: Main Results for All Distance Buffers

	25km	50km	75km	100km
Firm Share	0.0632***	0.0994***	0.1176**	0.0156
	(0.0162)	(0.0356)	(0.0452)	(0.0497)
Lagged Lice Count	0.1762***	0.1765***	0.1768***	0.1765***
	(0.0201)	(0.0202)	(0.0202)	(0.0201)
Stock (000s fish)	0.0001***	0.0001***	0.0001***	0.0001***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Average Weight (kg)	-0.0000	0.0000	0.0000	0.0000
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Temperature	0.0006	0.0008	0.0008	0.0008
	(0.0013)	(0.0014)	(0.0014)	(0.0014)
Neighbor Farms (excl)	-0.0004	-0.0000	0.0001	-0.0003
	(0.0010)	(0.0007)	(0.0004)	(0.0003)
Firms HHI	-0.0508**	-0.0245	-0.0224	-0.0188
	(0.0214)	(0.0370)	(0.0612)	(0.0452)
N	146539	147108	147288	147334
SD (Firm Share)	0.2782	0.1978	0.1752	0.1553
Standardized effect	0.0176	0.0197	0.0206	0.0024
Within R^2	0.0297	0.0296	0.0295	0.0293
Farms	934	934	935	935
Firms	91	91	91	91

weekly probabilities as independent and therefore represent an upper bound if treatments reduce subsequent lice pressure.

Taken together, three patterns support the spatial internalization mechanism. First, delousing responds strongly to biological pressure. Second, the ownership effect survives rich controls for market structure and firm heterogeneity and becomes more pronounced once firm-level confounders are absorbed. Third, the coefficient stabilizes once firm–year fixed effects are included. These findings are in line with firms adjusting mitigation effort in proportion to their exposure to locally generated lice externalities, the central prediction of the spatial internalization framework.

The framework yields a symmetric prediction: as ownership becomes more fragmented within a biologically connected area, individual firms' incentives to mitigate decline. Because lice mitigation is a strategic substitute, aggressive treatment by one firm reduces local lice pressure and lowers neighboring firms' incentives to treat, creating scope for free-riding (Olson Jr., 1965). In practice, such behavior may be tempered by social norms, reputational concerns, or informal coordination mechanisms (Ostrom, 2000).

The internalization framework predicts that firms with larger local biomass shares treat more intensively, which our main results confirm. The symmetric prediction is that treatment declines as ownership becomes more fragmented – when many firms share a buffer, each captures a smaller fraction of local spillover benefits, creating incentives to free-ride on neighbors' mitigation efforts. We test for free-riding in two ways. First, we examine whether local market concentration (HHI) or farm density predicts treatment intensity beyond the focal firm's own share. At 50 km, neither coefficient is statistically distinguishable from zero (Table 3), indicating that generic measures of market structure do not explain treatment behavior once the focal firm's ownership share is controlled. This suggests that the relevant margin is not market-wide concentration but rather the individual firm's stake in local outcomes – in line with the internalization channel dominating at this spatial scale. Second, we test whether free-riding incentives vary across spatial scales. If externalities are more salient at closer distances, strategic behavior may be more pronounced within tighter buffers. We examine treatment patterns across buffer distances of 25, 50, 75, and 100 km in Table 4.

We estimate the same specification as Column (4) of table 3 for all distance buffers. The estimated effect of firm local production share is positive and statistically significant for interaction buffers between 25 and 75 km. Raw coefficients increase with buffer size and peak at 75 km, although these magnitudes are not directly comparable across distances because the scale and dispersion of the firm- share measure change mechanically as the buffer expands. To address this, we also report standardized effects, which remain positive and similar in magnitude across the 25–75 km range (0.018–0.021), with no economically meaningful trend, indicating that the underlying relationship is not driven by rescaling. Across these buffers, a one standard deviation increase in firm biomass share is associated with roughly a 2 percentage point increase in treatment probability – approximately 15% relative to the sample mean of 0.13. At 100 km, both raw and standardized estimates attenuate sharply and lose statistical significance, with the standardized effect falling by an order of magnitude and becoming indistinguishable from zero. This pattern aligns with hydrodynamic models of salmon lice dispersal, which place effective transmission largely within 30–50 km under typical coastal conditions, with weaker connectivity at longer distances (Asplin et al., 2014; Samsing et al., 2017). The peak at 75 km likely reflects that wider buffers capture more farms owned by the focal firm while remaining within biologically connected waters, whereas 100 km extends beyond meaningful parasite linkages. Standard errors increase with buffer size, as expected given reduced within-buffer variation, but the collapse at 100 km reflects substantive attenuation of the signal rather than a loss of statistical power alone. Our buffer grid is coarse (25 km increments), so we cannot pinpoint the exact threshold; finer spatial resolution remains an avenue for future work. Nonetheless, the results are consistent with ownership concentration shaping treatment behavior within biologically relevant interaction zones rather than at scales beyond effective parasite connectivity.

These findings complement those of Winikoff & Parker (2024), who show that fragmented ownership under spatial externalities weakens incentives to internalize local effects. In contrast, our results indicate that greater ownership concentration strengthens internalization incentives within biologically connected production areas. More broadly, the evidence highlights the role of ownership structure in shaping the management of spatial externalities, provided that the spatial scale of analysis aligns with the underlying range of ecological connectivity. When economic interactions are evaluated at biologically relevant scales, the relationship between ownership spatial structure and environmental effort becomes visible.

Local firm biomass shares may evolve endogenously in response to unobserved environmental, biological, or regulatory conditions, which could confound causal interpretation despite the inclusion of rich farm, firm-year, and time fixed effects. While our identification strategy mitigates many sources of time-invariant and common shocks, residual endogeneity arising from anticipatory biomass reallocation or unobserved local trends cannot be fully ruled out. In addition, observed delousing events capture a discrete and regulated response to lice pressure rather than a comprehensive measure of environmental effort. Delousing therefore reflects a specific, policy-relevant margin of mitigation behavior, while other dimensions of effort, such as preventive practices or longer-term technological investments, are not directly observed.

7 Conclusion

This paper provides micro-level evidence that spatial industry structure shapes environmental behavior in settings with externalities. Using comprehensive farm-week data from Norwegian salmon aquaculture between 2012 and 2021, we document a robust positive relationship between a firm's local production share and the probability that its farms undertake delousing. At the sample mean lice level, a one percent increase in local production share within a 50 km buffer is associated with a 0.4 percentage-point increase in the weekly probability of delousing, with stronger effects observed under higher parasite pressure. These findings support the theoretical predictions that greater internalization of spatial spillovers increases incentives to invest in mitigation.

From a policy perspective, the results highlight the limits of environmental regulation that focuses solely on farm-level compliance when biological externalities operate over larger spatial scales. Fragmented local ownership can exacerbate free-riding incentives, weakening collective mitigation and increasing both environmental and economic costs. Policies or institutional arrangements that promote coordination among biologically connected producers may help improve mitigation efforts, and thereby environmental outcomes, without relying exclusively on stricter standards or enforcement.

Evidence from other aquaculture systems underscores the relevance of such approaches. Following a disease outbreak in the early 2000s, the Faroe Islands implemented a "one-company–one-fjord" policy that assigned exclusive production areas to individual operators and mandated coordinated fallowing (Bjørndal & Mrdalo, 2023; Mrdalo, 2023). By increasing local concentration and reducing spatial overlap among firms, this institutional design limited contagion risks and facilitated effective disease control. While not directly comparable, this experience illustrates how spatially coordinated governance can mitigate biologically transmitted externalities in practice.

More broadly, this study contributes to a growing literature on environmental management under spatial externalities by demonstrating how firm boundaries and ownership structure condition mitigation incentives. The insights extend beyond aquaculture to other contexts such as agricultural pest control, invasive species management, and watershed pollution, where environmental outcomes depend on collective action across interconnected units. The results suggest that effective environmental governance requires not only regulating outcomes, but also accounting for how industry structure and spatial organization shape private incentives to internalize shared environmental risks.

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Managing spatial externalities in natural resource industries poses regulatory challenges. We examine whether ownership structure shapes private incentives for environmental management in Norwegian salmon aquaculture. Sea lice-parasites that damage fish health and reduce growth-disperse among farms via ocean currents. Delousing at one farm benefits neighbors, while the treating farm bears the cost alone. We test whether firms controlling a larger share of local production are more likely to undertake treatments, in line with internalizing spillover benefits. Using microdata on 250,000 farm-week observations (2012–2021), we find strong support: a five percentage-point increase in local firm share is associated with a 0.4 percentage-point increase in weekly treatment probability – for a typical nine-farm cluster, roughly one to two additional treatments annually. The effect appears at distances matching lice dispersal biology (25–75 km) but disappears at 100 km. These findings suggest that aligning ownership structure with the spatial extent of externalities could complement regulation by harnessing private incentives.

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