Matching property rights and transboundary ecological processes: The case of Norwegian salmon aquaculture

Adams Ceballos-Concha, Frank Asche, Andrew Ropicki, Conner Mullally, and Jordan Moor.

Abstract

Transboundary ecological processes, such as the spread of pests and diseases, require management strategies that align property rights with the spatial scale of these processes. The existing literature is predominantly based on theoretical models and qualitative case studies, and has posited that coordinated management can often mitigate spatial externalities. However, robust causal assessments of the effects of coordinated management remain scarce. To address the issue empirically, we differentiate between the probability of an initial salmon lice infestation (the extensive margin) and the severity of infestation once it occurs (the intensive margin) using a uniquely comprehensive dataset from Norwegian salmon aquaculture. The findings reveal that while ownership concentration does not significantly alter the likelihood of infestation, it substantially reduces severity by enabling coordinated management practices. This divergence demonstrates that firm incentives vary across these two dimensions. Although the empirical setting focuses on salmon lice in salmon aquaculture, the findings carry broader implications for industries facing similar spatial-dynamic externalities. In particular, ownership consolidation can encourage coordinated investments and interventions, potentially reducing the underinvestment typically observed when multiple firms share biologically connected resources.

Keywords: Aquaculture, externalities, ownership concentration, property rights, salmon farming, spatial-dynamic, transboundary externalities.

JEL codes: Q22, Q28

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The spread of pests, diseases, and invasive species across property boundaries undermines individual efforts to sustain productivity and protect ecosystems, posing a significant challenge to environmental management. This issue is particularly acute in food production, where biological processes associated with pests and diseases typically cross property boundaries, affecting nearby and more distant producers through complex ecological feedback (Epanchin-Niell and Wilen 2015). For example, airborne diseases in livestock and crop pests such as the European corn borer devastate yields and livelihoods across farms (Capua and Alexander 2004; Hutchison et al. 2010). The nature of these externalities often leads to strategic behavior, where individual producers may underinvest in mitigation efforts, anticipating that others will bear the cost of control measures. Similarly, Singerman, Lence, and Useche (2017) demonstrate that citrus greening spreads across groves due to the mobility of the Asian citrus psyllid, creating incentives for free-riding and underinvestment in area-wide pest control efforts.

Transboundary ecological challenges may persist because effective management requires coordination across property boundaries. However, governance structures and market incentives often fail to facilitate such coordination, particularly in developing countries with limited governance capacity (Naylor et al. 2021). Historical examples, such as the Dust Bowl of the 1930s, illustrate the consequences of fragmented management in the face of large-scale ecological processes. In the Great Plains, small farms operating independently could not mitigate wind erosion and soil degradation, leading to severe environmental and economic impacts (Hansen and Libecap 2004). This failure arose from a mismatch between the scale of management and the spatial dynamics of the ecological processes involved (Chapin, Kofinas, and Folke 2009). Addressing such mismatches requires strategies that align decision-making with the broader ecological processes (Schmidtz and Willott 2003).

In this paper, we utilize a unique dataset on the Norwegian salmon aquaculture sector to investigate the impact of the strongest form of collaboration, ownership, in mitigating the most challenging parasite facing the industry: salmon lice. We quantify ownership concentration across 13 regulatory-created production zones using the Biomass Herfindahl-Hirschman Index (BHHI) and assess its relationship with salmon lice management outcomes. We distinguish between two dimensions of transboundary externalities: (1) the extensive margin, which refers to the likelihood of a salmon lice infestation occurring at a farm, and (2) the intensive margin, which pertains to the severity of the infestation once it has occurred. This differentiation matters because the factors influencing infestation, as well as the farmers' ability to control them, differ from those governing its subsequent spread and severity.

Our findings support the hypothesis that higher ownership concentration significantly lowers salmon lice levels on the intensive margin. Secondly, we find no statistically significant evidence that ownership concentration impacts the extensive margin. These results suggest that while concentrated ownership can internalize externalities that arise once an infestation is present, other factors may be more important in determining the initial outbreak. Importantly, our findings demonstrate that complete control is unnecessary to reduce a pest effectively; rather, sufficient concentration of ownership can significantly reduce the scale mismatch between farm-level decision-making and broader ecological processes like salmon lice dispersal. These findings align with Epanchin-Niell and Wilen's (2015) theoretical work, which suggests that even partial cooperation can yield significant benefits. As we have data on only one form of collaboration, ownership, we do not attempt to investigate how strong the collaboration has to be to be effective.

The scale mismatch and coordination challenges highlighted by our findings are rooted in classic property rights theory. The Coase theorem (Coase 1960) suggests that if transaction costs were negligible, private bargaining among resource users would lead to an efficient outcome. However, in fragmented production systems with many independent actors, the transaction costs of negotiating, monitoring, and enforcing collective agreements are often prohibitively high. This leads to the well-documented problem of underinvestment in mitigation; when pests or diseases migrate across property boundaries, damage control investments create positive spillovers for neighboring properties, but individual decision-makers will focus solely on their private returns, weighing the cost of treatment against the damage prevented to their own stock (Lichtenberg and Zilberman 1986). This issue is exacerbated by scale mismatches, where ecological processes, such as pest dispersal, occur on a larger spatial scale than individual decision-making units (Bhat, Huffaker, and Lenhart 1993; Sanchirico and Wilen 1999; Epanchin-Niell and Wilen 2012, 2015; Schmidtz and Willott 2003).

Spatial-dynamic models demonstrate that cooperative strategies, whether through property-rights consolidation (Kaffine and Costello 2011), which reduces the number of decision-makers and thus lowers the transaction costs of coordination, or coordinated cost-sharing (Epanchin-Niell and Wilen 2015), can internalize these externalities, improve management efficiency, and reduce long-term control costs. But, much of this literature relies on laboratory experiments or simulations (Pincinato et al. 2025). The lack of farm-level data on treatment effectiveness and costs constrains the ability to evaluate the feasibility of these strategies, leaving open questions about their implementation and effectiveness. We contribute to this literature by demonstrating that ownership concentration can promote the mitigation of pest outbreaks in a real-world setting using a credible empirical approach.

We organize the paper as follows. Section "Salmon Aquaculture, Dynamics of Salmon Lice Spread, and Ownership Concentration" describes the Norwegian industry, the data, and the

Biomass HHI. Section "Empirical Specification" presents the empirical model and identification strategy. Section "Results" reports the estimates. Section "Conclusions" concludes.

Salmon Aquaculture, Dynamics of Salmon Lice Spread, and Ownership Concentration

Globally, salmon is the second largest aquaculture species by production value (Garlock et al. 2022). Norway is by far the largest producer, with a production share between 50% and 60% (Pandey et al. 2023). Norway's aquaculture production of Atlantic salmon increased from 1.2 million tons in 2012 to 1.28 million tons in 2017 and further to 1.52 million tons in 2023 (Directorate of Fisheries 2025). Over 95% of this production is exported (Straume et al. 2024). The export value grew significantly during this period, from approximately 5.34 billion USD in 2012 to 7.37 billion USD in 2017, reaching 10.65 billion USD in 2023, as prices increased strongly. The ten largest companies account for approximately 70% of total production (Directorate of Fisheries 2025). While concentration levels at the national scale remain moderate (Pandey et al. 2023), ownership is more concentrated within specific production regions.

The marine phase of salmon aquaculture, also known as the grow-out phase, is what is typically referred to as salmon production (Anderson et al. 2025). A production cycle begins with juvenile fish being transferred to sea pens, where they are fed to a market weight of around 5 kg. Each production cycle takes between 14 and 22 months, and before a new generation can be released, a period of fallowing is undertaken to restore the benthic fauna at the sea bottom below the farm.

Salmon lice, a parasite, pose a significant challenge to the Norwegian salmon farming industry, causing both economic and ecological impacts, and are a key focus in the regulatory system (Jensen, Tveterås, and Nielsen 2024). Salmon lice spread through the water column into the open sea cage systems and onto migrating wild salmon. Salmon lice exhibit a ten-stage life cycle; during the first three planktonic stages, the larvae are carried by currents and winds and can travel up to 30 km (Jevne et al. 2021; Jones and Beamish 2011). This dispersal creates spatial externalities, as untreated farms can serve as reservoirs that reinfect neighboring farms (Aldrin et al. 2013), providing incentives for coordinated control. Moreover, larval concentrations tend to form in patches, and their abundance is lower in farms located in low-salinity areas, where environmental conditions limit their growth and distribution (Thorstad et al. 2015).

Salmon lice are a listed disease under Norwegian law. A mere suspicion of an outbreak triggers an immediate and strict ban on moving any live fish from the affected farm site (§ 28, FOR-2008-06-17-819; Animal Health Act § 19). Regulations have been in place to limit salmon lice levels since 1997, and these rules have undergone several updates. To prevent the spread of disease, fish are only infrequently moved between farms for operational reasons, and movement due to disease or parasite infestations is prohibited. During the period covered by our dataset, production sites are required to maintain lice levels below 0.5 adult female lice (or three mobile lice) per fish from January 1 to August 31. From September 1 to December 31, the thresholds increase to 1 adult female (or five mobile lice) per fish, as there are no migrating wild salmon. Exceeding these limits requires remedial measures, including medical treatments or, if necessary, reducing biomass through early harvesting.

The economic costs of salmon lice management are significant, with total losses estimated at 9% of farm revenues annually due to treatment expenses and production losses (Abolofia, Asche, and Wilen 2017). Ecologically, salmon lice affect wild salmon populations by reducing the survival rates of migrating smolts by up to 50% (Thorstad et al. 2015). This externality is currently the primary constraint in the regulatory system (Jensen, Tveterås, and Nielsen 2024). Addressing this challenge requires coordinated management strategies that incorporate the dynamics of the salmon lice lifecycle, their dispersal across farms, and the interconnected nature of aquaculture systems to mitigate both economic and ecological consequences.

The regulatory system divides Norway's coast into 13 production zones[1] (Figure 1). Production zones were designed to manage industry capacity while minimizing environmental impacts, with a particular focus on the spread of salmon lice (Anon 2015; Gullestad et al. 2011). These zones are designed to account for water currents and the spread of contaminants and parasites, allowing each production zone to operate as a unit with minimal external contamination. This approach implies that lice released from farms within one production zone are less likely to infest farms in another, making each production zone an independent management unit (Ådlandsvik 2015).

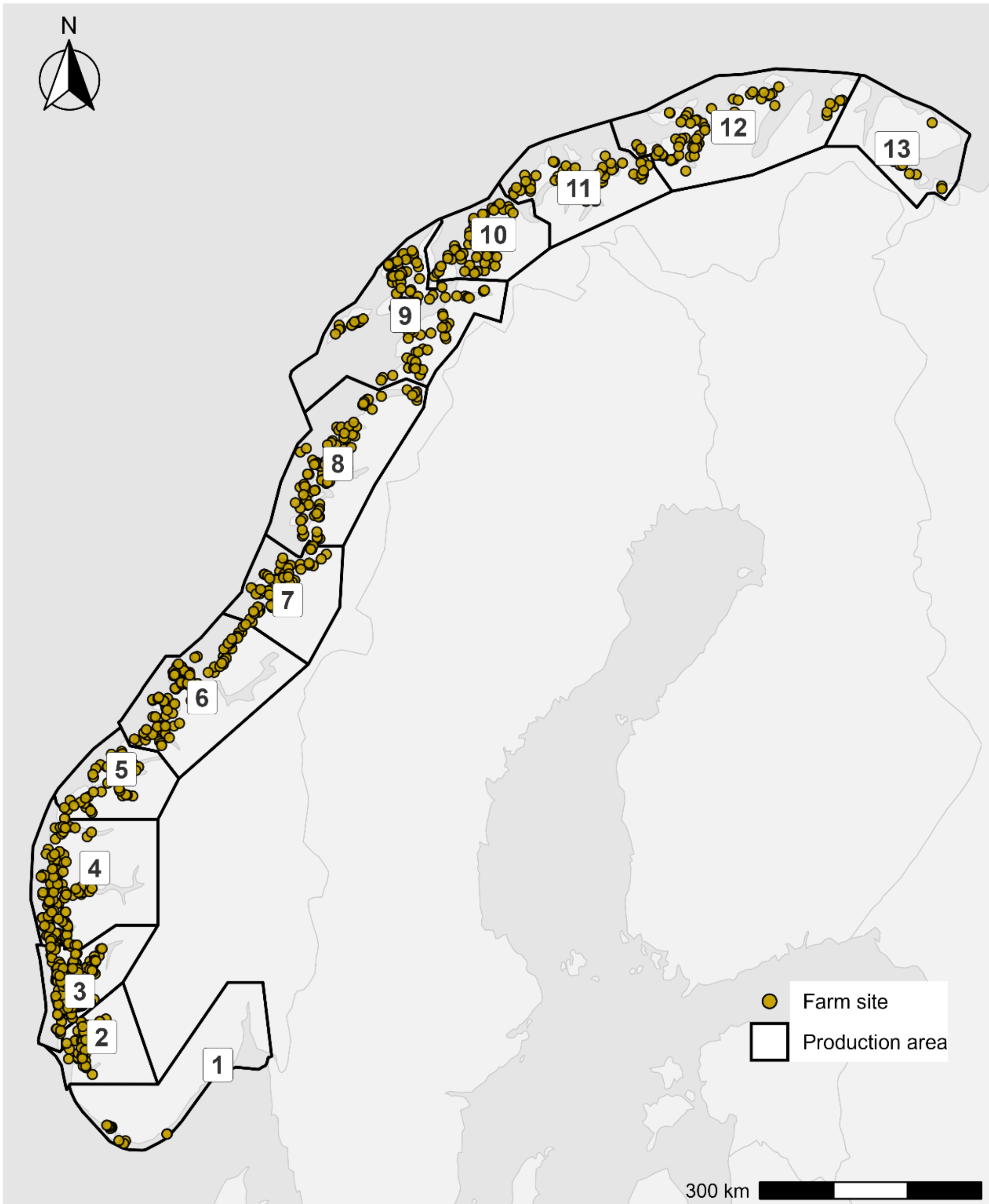

Figure 1: The 13 aquaculture production zones along the Norwegian coast.

To analyze the impact of ownership concentration on salmon lice prevalence, we utilize a monthly farm-level panel for Norway's salmon industry from 2012 to 2017. The outcome variable, salmon lice level, is measured monthly throughout each active production cycle. Our primary independent variable, the Biomass Herfindahl-Hirschman Index (BHHI), captures the ownership concentration of all biomass held by firms (corporate entities) at farms within a given production zone. Thus, our model investigates the effect of zone-level ownership structure on farm-level ecological outcomes.

Values for the BHHI are calculated according to the following definition:

Let q_{ipt} be the biomass in kg, where $i \in [1, \dots, n_p]$ is the i-th firm operating time t, measured in months, $p \in [1, \dots, 13]$. The biomass share, s_{itp} for the i-th firm operating in the production zone p in the month t is given by:

$$s_{ipt} = \frac{q_{ipt}}{\sum_{i=1}^{n_p} q_{ipt}}, \quad i = 1, \dots, n_p \qquad (1)$$

Then, the BHHI for the production zone p in time t is defined by:

$$BHHI_{pt} = \sum_{i=1}^{n_p} \left(s_{ipt}\right)^2 \qquad (2)$$

Figure 2 and Figure 3 illustrate the temporal variation in BHHI and average salmon lice levels across different production zones (note that the y-axis scales differ between these figures). Table 1 presents the variation of BHHI among the various production zones over the entire study period. 2012-2017. Each panel in Figures 2 and 3 corresponds to a specific production zone, with the BHHI as a black line and salmon lice as a blue line. Finally, the red horizontal lines at 0.15 and 0.25 on the BHHI scale point to the thresholds used to categorize concentration levels: below 0.15

indicates a low concentration, between 0.15 and 0.25 indicates moderate concentration, and above 0.25 indicates a high concentration.[2] Higher BHHI values are considered proxies for potential coordination, as concentrated ownership simplifies the synchronization of treatments and biosecurity measures. There is no trend in the BHHIs over time, indicating limited consolidation activity.

Table 1: Summary of Ownership Concentration (BHHI) by Production Zone for 2012-2017

Production zone[a]	Mean	SD	Minimum	Maximum
1	0.77	0.10	0.56	1.00
2	0.27	0.03	0.21	0.34
3	0.11	0.01	0.10	0.14
4	0.13	0.01	0.10	0.16
5	0.38	0.03	0.30	0.44
6	0.26	0.01	0.24	0.30
7	0.20	0.02	0.15	0.26
8	0.21	0.03	0.13	0.27
9	0.15	0.02	0.12	0.20
10	0.17	0.01	0.15	0.21
11	0.29	0.05	0.20	0.40
12	0.31	0.02	0.27	0.35

[a] The number of production sites is 849, 12 production areas, 81 different firms, 1914 production cycles.

The BHHI and the salmon lice average per 10 fish exhibit seasonal trends, with salmon lice levels showing more pronounced seasonal fluctuations. This fluctuation might indicate that salmon lice prevalence is responsive to short-term environmental and/or operational changes. Since the BHHI is calculated based on the share of biomass each company holds within a production zone, any significant fluctuations in the total biomass or biomass distribution among companies would directly impact the BHHI. Furthermore, as the number of companies has been reduced by only five over the study period, it is reasonable to assume a stable ownership structure. In other words, changes in BHHI over time are more influenced by variations in the biomass managed by firms rather than by changes in ownership.

Suggestive evidence for the effect of ownership concentration on salmon lice management can be found by examining production zones with differing BHHI values. Zones with high BHHI values, such as zone 1, exhibit more stable and lower salmon lice levels over time. Figure 3 shows that zone 1 consistently achieves lice levels below 0.2 per fish, well within regulatory thresholds. Conversely, fragmented zones, such as zone 4, which has a BHHI below 0.15, show higher and more variable lice levels (Figure 2).

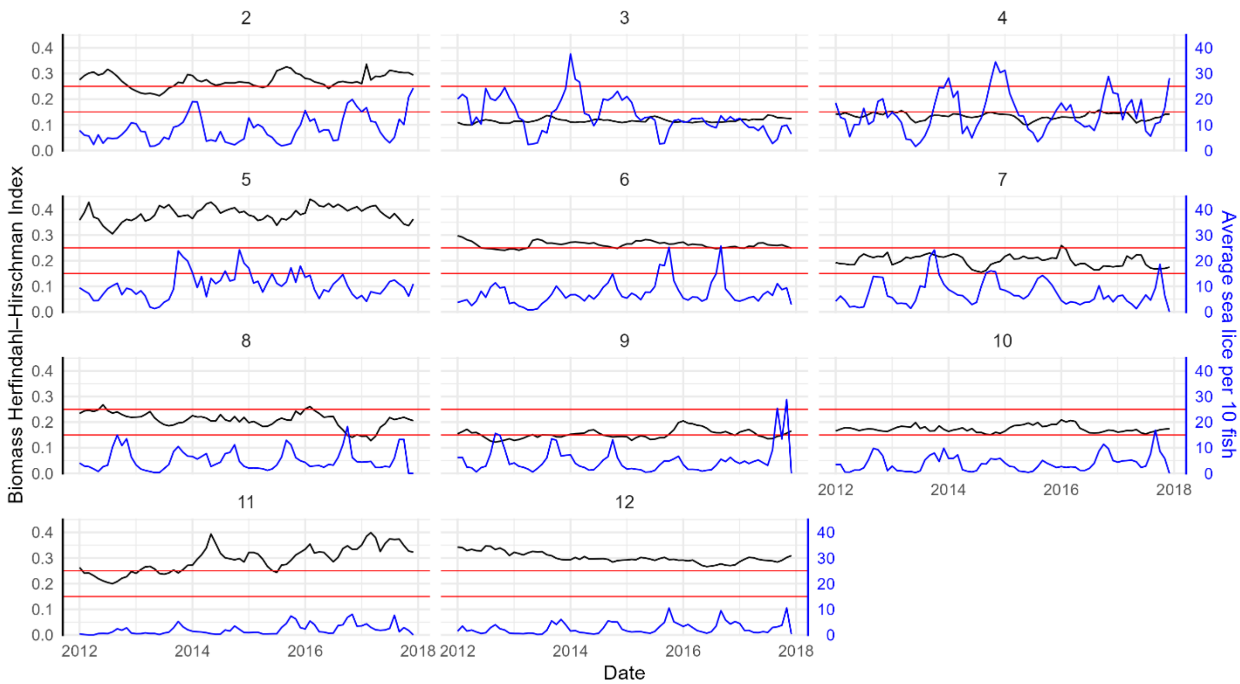

Figure 2: Production Zones 2 to 12: Biomass Herfindahl-Hirschman Index (BHHI, black lines) and salmon lice average per ten fish over time (blue lines).

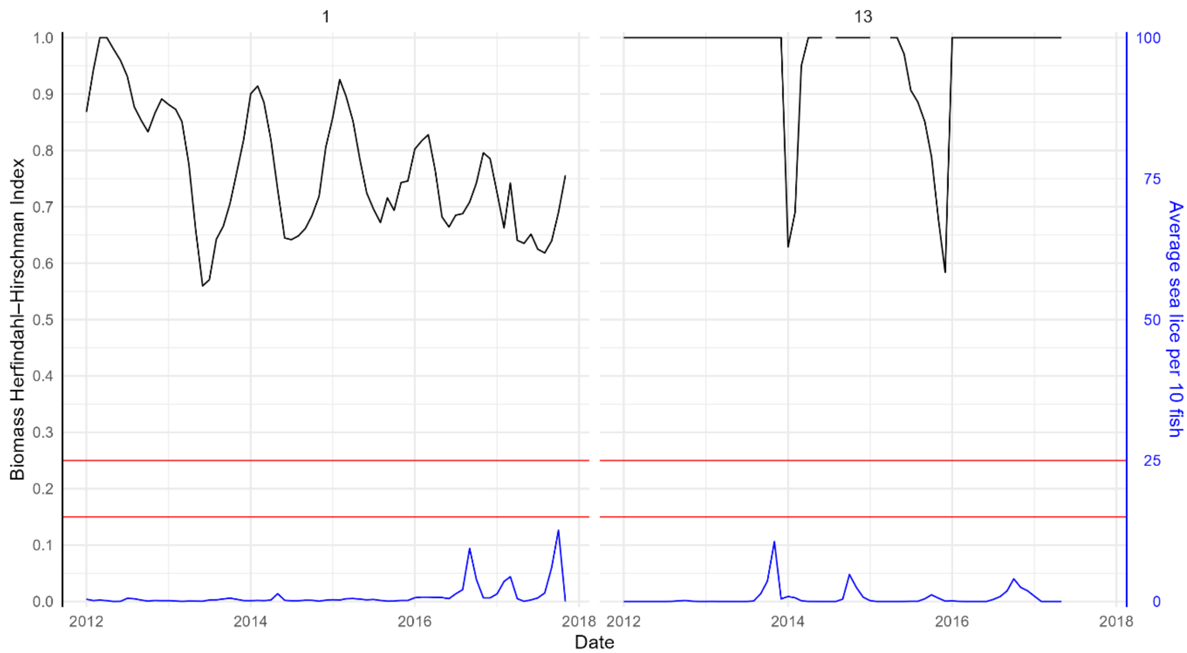

Figure 3: Production zones 1 and 13: Biomass Herfindahl-Hirschman Index (BHHI, black lines) and salmon lice average per ten fish over time (blue lines).

Production zone 13 (see Figure 3) is an atypical zone with extremely high concentration levels approaching one and sporadic production activity. This zone experiences very low water temperatures, which reduces salmon lice concerns, making it less comparable to other production areas. Therefore, we excluded Zone 13 from our analysis. Likewise, Zone 1 also has very high concentration levels and will be omitted due to its potential to influence results heavily and introduce bias due to its unique concentration and salmon lice dynamics.

Greater ownership concentration is expected to lower coordination costs among farms, enabling proactive rather than reactive pest-control strategies. Coordination across neighbouring sites can reduce the transaction costs of monitoring and enforcing joint interventions, easing collective-action problems typical in external pest management (Epanchin-Niell and Wilen 2015). Empirical work in Chile and Norway shows that synchronised treatments (e.g., coordinated immersion baths and joint fallowing schedules) disrupt the salmon-lice life cycle and reduce parasite loads (Arriagada et al. 2017; Guarracino, Qviller, and Lillehaug 2018). Although these studies do not examine ownership, their results suggest that concentrated ownership could internalise the benefits of coordination, fostering practices such as larger smolt production, systematic use of cleaner fish, and calendar-based fallowing (Barrett et al. 2020; Walde et al. 2023).

To assess whether such patterns are observable in Norwegian data before formal econometric testing, Figure 4 presents descriptive comparisons of farm practices across areas with high versus low ownership concentration. Panel A shows that firms operating in highly concentrated zones tend to fallow more frequently, especially large firms, consistent with easier coordination of downtime between cycles. Panel B indicates higher cleaner-fish usage in those same zones, a preventive measure associated with biological lice control and with the findings of

Pincinato et al. (2025). In contrast, firms in less-concentrated areas appear to rely more on reactive treatments: Panel C displays a higher incidence of chemical bath treatments (typically applied only after infestation thresholds are exceeded) in fragmented zones. Finally, Panel D shows greater synchronisation of fallowing and treatment timing where ownership is concentrated, aligning with evidence that coordinated action among neighbouring farms enhances treatment efficacy (Abolofia, Asche, and Wilen 2017; Guarracino, Qviller, and Lillehaug 2018; Pincinato et al. 2025). Because proactive measures are documented to reduce lice prevalence, and we observe greater uptake of those measures in highly concentrated ownership zones, the descriptive evidence is compatible with (though not proof of) the hypothesis that ownership concentration is associated with lower lice intensity through eased coordination.

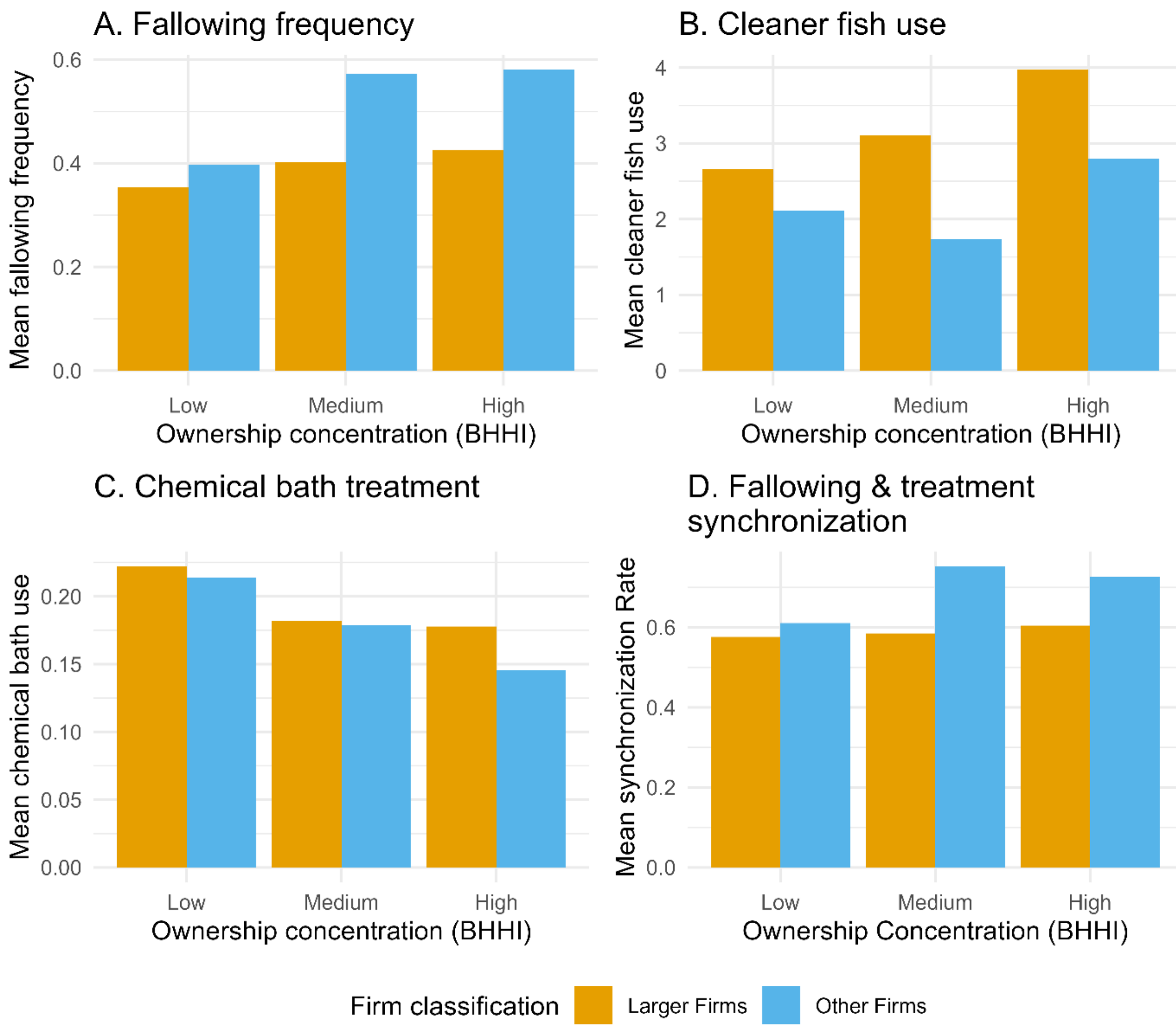

Figure 4: Ownership concentration, Firm classification, and salmon lice management strategies. Panel A shows the mean fallowing frequency across ownership concentration categories (BHHI) for larger and other firms. Panel B presents the average use of cleaner fish. Panel C illustrates chemical bath treatments. Panel D reports the synchronization rate of fallowing and treatments. Major companies are the top 4 with the highest production.

We test this hypothesis in sections Empirical Specification and Results, taking advantage of the fact that the Norwegian aquaculture industry holds robust data collection practices. Licensed farmers must report data on fish stocks, lice infections, treatments, and seawater temperature to the authorities at monthly or bi-weekly frequencies, creating a comprehensive dataset for analyzing production dynamics and biosecurity management.

A summary of key descriptive statistics illustrates the structure of the dataset and industry characteristics over the study period. The dataset includes 30,566 monthly observations spanning 849 farms between 2012 and 2017,[3] covering approximately 90% of total production.[4] Standing biomass averaged 1,289 tons per farm, while salmon lice prevalence averaged 12.86 lice per ten fish, with peak values reaching 881 lice per ten fish in extreme cases. Since we lack observations when a farm is fallow between production cycles, the panel is unbalanced. Chemical treatments were applied in 20% of observations, and feed treatment was used in 9% of cases. The average distance between farms was 4.86 km, and the BHHI averaged 0.21 (see complete summary statistics in the online supplementary appendix, Table A1).

Empirical Specification

To assess the impact of ownership concentration on salmon lice prevalence and intensity, we separately analyze (i) the probability that a farm has salmon lice in any given month (the extensive margin) and (ii) the severity of infestation conditional on salmon lice being present (the intensive margin). The two margins can be of different importance, as they may be impacted by different factors that farmers have varying abilities to control.

The conceptual distinction between the extensive and intensive margins is grounded in the life cycle and transmission dynamics of the salmon lice as well as the firms' ability to impact these dynamics. Initial infestation at a farm (the extensive margin) is primarily driven by external factors, such as the passive dispersal of planktonic larvae via ocean currents and winds (Jevne et al. 2021). Environmental variables, including seawater temperature and proximity to external reservoirs, influence this process (Krkošek, Lewis, and Volpe 2005; Aldrin, Storvik, and Kristoffersen 2013). A higher degree of firm concentration may impact this process to the extent that they control external reservoirs, and it is an empirical question whether this control can be sufficient to limit the spread of lice. Once an infestation is established, its severity (the intensive margin) becomes a function of on-site parasite population growth, which is strongly density-dependent and can be mitigated through coordinated management (Jansen et al. 2012; Aldrin et al. 2013). To identify the effect of ownership on prevention versus control, our empirical strategy explicitly models these two margins separately.

For the extensive margin, we estimate a fixed-effects probit model with a control function approach (Wooldridge 2015), incorporating the first-stage residuals in the second-stage equation to account for endogeneity. To address the incidental parameters problem, we apply the analytical bias correction method of Fernández-Val (2009), which provides consistent estimation of structural parameters and marginal effects in large N, large T settings. For the intensive margin, we use a standard two-stage least squares (2SLS) approach, where the predicted values of BHHI from the first stage serve as an instrumented regressor. Unlike the extensive margin model, which includes all observations, the intensive margin analysis is restricted to the sample where salmon lice are present.

Identification Strategy

The potential simultaneity between salmon lice levels and ownership concentration at the intensive margin is a key identification challenge. While theory suggests that higher concentration facilitates coordinated management that reduces salmon lice levels, it is also possible that salmon lice prevalence indirectly affects the distribution of production biomass across firms. For instance, this could occur if a severe infestation in a specific production cycle leads to biomass reductions. This change in farm-level biomass would be attributed to the owning firm, mechanically altering the zone-wide BHHI without reflecting any true change in corporate ownership structure.

To isolate exogenous variation in ownership concentration, we instrument the BHHI using the log inverse of the number of concurrent active production cycles (which is then also the number of active farms) in all other production zones. The instrument is denoted as:

$$Z_{pt} = \log\left(\frac{1}{\sum_{p' \neq p} C_{p't}}\right) \qquad (3)$$

where $C_{p't}$ is the number of active production cycles in the production zone $p' \neq p$ at time t.

The validity of this instrument rests on two pillars: (1) Its relevance is driven by firms' long-term strategic planning, (2) while the exclusion restriction is credibly maintained by strict regulatory barriers that block the feedback channel from local salmon lice outbreaks to production decisions in other zones.

The instrument's relevance stems from the centralized, long-term planning process inherent in Norwegian salmon farming. The primary operational constraint for any firm is its total Maximum Allowable Biomass (MAB), a legally mandated production cap linked to its portfolio of licenses. To maximize output within this fixed capacity, firms must create a single, companywide optimization plan 18-24 months in advance (Oglend and Soini 2020; Oglend, Asche, and Straume 2024). This plan dictates the stocking schedules and production intensity across all their sites in all zones, and is based on long-term forecasts of market prices, costs, and seasonal factors (Asche, Oglend, and Selland 2017). A firm's strategic decision to alter its production intensity in zone p is therefore part of the same plan that determines the number of concurrent production cycles in other zones (p'). This creates a robust link between the ownership concentration in zone p and production activity in other zones, driven by a common, pre-planned strategic driver rather than a reaction to a mid-cycle biological shock.

Crucially, the exclusion restriction ought to hold because this strategic allocation occurs far in advance in time, and the regulation prevents firms from reactively moving production in response to a local lice outbreak (see Section Salmon Aquaculture, Dynamics of Salmon Lice Spread, and Ownership Concentration). This regulatory barrier effectively severs the reverse-causal pathway, making it impossible for lice levels in zone p to influence the number of active production cycles in other zones (p') within a given production cycle. Thus, lice realizations in zone p at time t cannot causally alter $C_{p't}$ in other zones p'during the same cycle; early harvest in p affects p only. Our identification strategy is akin to approaches used in the industrial organization literature, such as Nevo (2001), which uses prices from neighboring markets as instruments to control for local price endogeneity, and Azar, Marinescu, and Steinbaum (2022), which instruments local labor market concentration with job postings in other states to address potential endogeneity in labor supply.

A possible concern is that a lice outbreak in zone p might prompt firms to initiate new cohorts elsewhere, thereby increasing $\sum_{p' \neq p} C_{p't}$. However, this is largely prevented by the MAB regulations that link MAB to specific production zones (see Section Salmon Aquaculture, Dynamics of Salmon Lice Spread, and Ownership Concentration). Furthermore, observed behavioral margins under lice pressure are intra-cycle, meaning treatments and modest harvest acceleration with smaller harvest sizes result in associated economic losses, as there is very limited scope for initiating new cohorts elsewhere (Zhang, Sogn-Grundvåg, and Tveterås 2023). Accordingly, contemporaneous salmon lice in p have little scope to raise $C_{p't}$ for $p' \neq p$ within the same cycle.

Nonetheless, we acknowledge that the instrument may not perfectly satisfy the exclusion restriction. If salmon lice outbreaks in one zone indirectly influence industry-wide production decisions, such as through coordinated regulatory responses or shifts in consumer demand, Z_{pt} could be correlated with the error term. To our knowledge, no regulatory coordination has occurred at the industry level or for larger regions, and there is no evidence that salmon lice issues have impacted consumer demand. Still, to assess the validity of the instrument, we test for departures from the exclusion restriction in Section Sensitivity Analysis.

To mitigate omitted variable concerns and capture unobserved heterogeneity, we include a set of fixed effects denoted by α_{iqy}, which accounts for both year-by-quarter (qy) and firm-by-production-cycle[5] (i) fixed effects. This structure controls for seasonality, firm-level management strategies, and localized biosecurity conditions, ensuring that geographic characteristics such as hydrography and biophysical factors are accounted for. Additionally, we estimate an alternative specification where α_{iqy} includes quarter (q), year (y), firm (i), and cycle fixed effects, controlling for broader time trends and firm-specific cycle effects. This specification minimizes any biases arising from interactions between seasonality and industry-wide dynamics.

Extensive Margin

Our extensive margin specification is given by:

$$\Pr\left(\text{lice}_{jt} = 1\right) = \Phi\left(\text{BHHI}_{pt}^{T}\eta + \hat{u}_{pt}\rho + \mathbf{X}_{jt}^{T}\boldsymbol{\theta} + \boldsymbol{\alpha}_{iqy}\right), \qquad (4)$$

where Φ is the standard normal cumulative distribution function (CDF), $\text{lice}_{jt} = 1$ if the farm j reports any lice in period t, $\hat{u}_{pt} = \text{BHHI}_{pt} - \widehat{\text{BHHI}}_{pt}$, where $\widehat{\text{BHHI}}_{pt}$ is obtained from the first-stage regression of BHHI on the instrument and control variables. The coefficient ρ captures the extent of endogeneity bias in BHHI, and the coefficient η on $\widehat{\text{BHHI}}_{pt}$ is the estimated causal effect of an exogenous shift in BHHI on the outcome.

To model the likelihood of an initial infestation, the vector X_{jt} includes control variables representing exogenous exposure risk: water temperature, time at sea, and the minimum distance to the nearest active farm (Aldrin et al. 2013; Jansen et al. 2012; Kristoffersen et al. 2018). In many biological control problems (especially those where propagule pressure is continuous or reinvasion is certain), preventing the first infestation is infeasible; optimal management therefore targets the intensive margin, i.e., reducing parasite load once infestation has occurred (Epanchin-Niell and Hastings 2010; Epanchin-Niell and Wilen 2012).

Intensive Margin

For the intensive margin, we estimate the effect of BHHI on log salmon lice count using 2SLS:

$$s_{jt} = \widehat{\text{BHHI}}_{pt}^{T}\beta + \mathbf{X}_{jt}^{T}\boldsymbol{\theta} + \boldsymbol{\alpha}_{iqy} + \varepsilon_{jt} \qquad (5)$$

where s_{jt} is the log transformation of the dependent variable, i.e., salmon lice average per ten fish at farm j at time t. The difference from the extensive-margin model is that this specification is estimated only on the subset of production cycles where $s_{jt} > 0$. ε_{jt} is the error term.

For the intensive margin, the vector of controls X_{jt} is now augmented to include farm-level management, i.e., local biomass density, the use of chemical treatments, and time at sea. α_{iqy} are the same as previously described in Equation 4.

Results

The Extensive Margin

Table 2 presents estimates from our fixed-effects probit specification, which uses a control-function approach to address the endogeneity of the BHHI. This specification evaluates the effect of the BHHI on the probability that a farm experiences its first occurrence of salmon lice within a given month (the extensive margin). Before turning to our primary variable, we note that the control variables perform as expected: the probability of a salmon lice outbreak is significantly higher with greater local biomass density and warmer sea temperatures in the preceding quarter. At the same time, it is significantly lower as the distance to the nearest active farm increases (see the online supplementary appendix, Table A3, for full results).

The table reports point estimates alongside cluster-bootstrapped standard errors, which account for both the two-stage estimation process and the panel structure of the data. The coefficient on BHHI is negative (0.089) but not statistically significant, as indicated by both the analytical and bootstrapped standard errors. Furthermore, we formally test for endogeneity by including the first-stage residuals directly in the second-stage estimation. The resulting coefficient on the BHHI residuals is not statistically significant, suggesting we cannot reject the null hypothesis of exogeneity (Wooldridge 2010). Thus, no robust evidence suggests that higher ownership concentration reduces the likelihood of a farm encountering salmon lice for the first time. In other words, concentrated ownership does not appear to alter the initial infestation probability.

Table 2: Impact of Ownership Concentration on the Probability of Initial Salmon Lice Occurrence (Extensive Margin).

Variable	Estimate	Std. Error	Boot. Std. Error	L. Boot. CI	U. Boot. CI
BHHI	0.089	3.456	78.269	-9.149	33.560
BHHI residuals	-3.009	3.518	78.260	-33.296	6.238

Note: Estimates are asymptotically bias-corrected for binary choice models with fixed effects, as derived by Fernández-Val (2009). Bootstrapped standard errors at production zone level (500 repetitions) are used to account for the two-stage estimation process. L and U denote the lower and upper confidence interval bounds. Bootstrapped 95% confidence intervals are reported. Residual deviance = 21807.74, Null deviance = 27748.24, n = 27802 (2323 observations deleted due to perfect classification).

The Intensive Margin

Table 3 (with the full table in the online supplementary appendix, Table A5) presents the second-stage results for our 2SLS estimation. First-stage estimates are presented in the online supplementary appendix, Table A4. We report results for two distinct sets of models: Models 1 and 3 include only those covariates that we consider strictly exogenous (namely, log sea temperature and its lag, local biomass density, and minimum distance to an active farm), while the other set includes an extended set of controls by additionally incorporating variables such as time at sea and chemical feed (Models 2 and 4). The rationale for presenting these two groups of specifications lies in the argument of Frölich (2008) that including potentially endogenous controls might introduce inconsistency in the parameter of interest if these controls are correlated with the instrument. On the other hand, omitting them risks omitted variable bias when the instrument and the excluded explanatory variables are correlated.

Table 3: Two-stage Least Squares (2SLS) Estimates of the Effect of Firm-Level Ownership Concentration (BHHI) on Log Salmon Lice Levels (Intensive Margin) at the Farm-Month Level.

Dependent Variable:	*log(y)*			
Model:	(1)	(2)	(3)	(4)
Variables				
BHHI	-16.6***	-18.0***	-11.8**	-12.9**
	(3.77)	(3.81)	(5.05)	(5.11)
Fixed-effects				
Year-by-quarter	Yes	Yes		
Cycle-by-firm	Yes	Yes		
Year			Yes	Yes
Quarter			Yes	Yes
Cycle			Yes	Yes
Fit statistics				
Observations	24,580	24,580	24,580	24,580
Wu-Hausman	52.123	63.406	13.909	17.319
Wald (IV only)	19.340	22.419	5.4254	6.4071
F-test (IV only)	58.841	70.440	16.314	19.878
Kleibergen-Paap	155.70	155.47	75.008	74.920

Note: The instrument, Z_{pt}, is the log inverse of the number of production cycles in other production zones. All models include controls for sea temperature, lagged sea temperature, local biomass density, and minimum distance to an active farm. Models 2 and 4 additionally control for time at sea and chemical feed. Tables A6 and A7 in the online supplementary material report the first- and second-stage estimates for the full sample in levels (includes zero outcomes). For comparability with log-linear models, the 2SLS coefficient on BHHI is expressed as a partial elasticity by dividing by the sample mean of sea lice. Driscoll-Kraay (L=6) standard errors in parentheses. Signif. Codes: ***: 0.01, **: 0.05, *: 0.1

The coefficient on ownership concentration in the extensive-margin specification is statistically indistinguishable from zero, indicating no association between concentration and the probability of initial lice infestation. This result aligns with our descriptive data; as shown in the online supplementary appendix, Table A2, a high proportion of farms (78% on average) report at least one occurrence of salmon lice per month, suggesting that initial infestation is a nearly ubiquitous event.

The first-stage regression results strongly support the relevance of our instrument, Z_{pt}. Across all specifications (see the online supplementary appendix, Table A4), the coefficient on Z_{pt} is negative and statistically significant. A one-unit increase in Z_{pt} is associated with a decrease in BHHI ranging from 1.228 to 2.149, depending on the model specification. The F-statistics for the instrument in the first stage are consistently high (ranging from 431.19 to 807.90), substantially exceeding the conventional thresholds for weak instruments (50 suggested by Keane and Neal (2024)). The Kleibergen-Paap statistic, which is robust to heteroskedasticity and clustering, further corroborates the instrument's strength by rejecting the null hypothesis of weak identification.

The second-stage results reveal that increased ownership concentration of production sites leads to improved salmon lice control. Specifically, higher BHHI values are associated with lower salmon lice levels, conditional on the presence of salmon lice. The coefficient on BHHI is negative and statistically significant across all specifications (see Table 3). However, the significance levels vary with different covariate combinations and fixed effects structures. The magnitude of the effect is economically meaningful: in Model 2, a 0.01 increase in BHHI (equivalent to moving from 0.20 to 0.21 on the 0-1 scale or a 100-point increase on the traditional 0-10,000 HHI scale) is associated with approximately a 16.5% reduction in average salmon lice levels per ten fish. Given that the sample mean of salmon lice is 12.86 per ten fish, this represents a reduction of about two salmon lice per ten fish.

Several checks support the robustness of these findings. First, additional control variables (including biomass density, water temperature, and salinity) affect the BHHI coefficient's magnitude but do not alter its sign or statistical significance. Second, results remain consistent when varying the fixed effects from combined year-by-quarter and production cycle-by-firm effects (Models 1 and 2) to separate year, quarter, and cycle effects (Models 3 and 4), indicating that specific temporal or firm-level interactions do not drive our findings. Third, we employ Driscoll-Kraay standard errors with six lags to account for spatial and temporal dependence, which is particularly important given the geographic proximity of farming sites and the potential for salmon lice to be driven by spatially correlated shocks.

We assess the sensitivity of our inference to alternative variance estimators in the online supplementary appendix, Table A8. Results remain statistically significant when we compute (Conley 1999) standard errors using a biologically motivated 30 km distance cutoff (Krkošek, Lewis, and Volpe 2005; Aldrin, Storvik, Kristoffersen 2013). When we instead apply a wild-cluster bootstrap with the 11 production zones as clusters (Cameron, Gelbach, and Miller 2008; Fischer and Roodman 2021; Webb 2023), the p-value rises (0.121), reflecting the conservative nature of bootstrap inference with few clusters. These variance estimators differ only in how they accommodate cross-zone correlation in the disturbance process; the instrumental-variables identifying moment conditions are unaffected. Given that broad ecological and regulatory shocks can generate dependence across zones, we report Driscoll-Kraay and Conley standard errors in the main results and provide the wild-cluster bootstrap in the online supplementary appendix, Table A8, for completeness.

Finally, we estimate the Anderson-Rubin (AR) statistic for model (2), which is robust to weak instruments. The AR yields an F-statistic of 11.2295 ($p = 0.0008$), with a 95% confidence interval for the BHHI coefficient of [-31.5547, -7.2989].

Figure 5 compares the ordinary least squares (OLS) estimates of the BHHI coefficient with 2SLS estimates, each with 95% confidence intervals. OLS estimates are close to zero and statistically insignificant. In contrast, 2SLS estimates are substantially negative and strongly significant, confirming the importance of accounting for endogeneity. The Anderson–Rubin confidence interval also rejects the null of no effect, allaying concerns about weak-instrument bias.

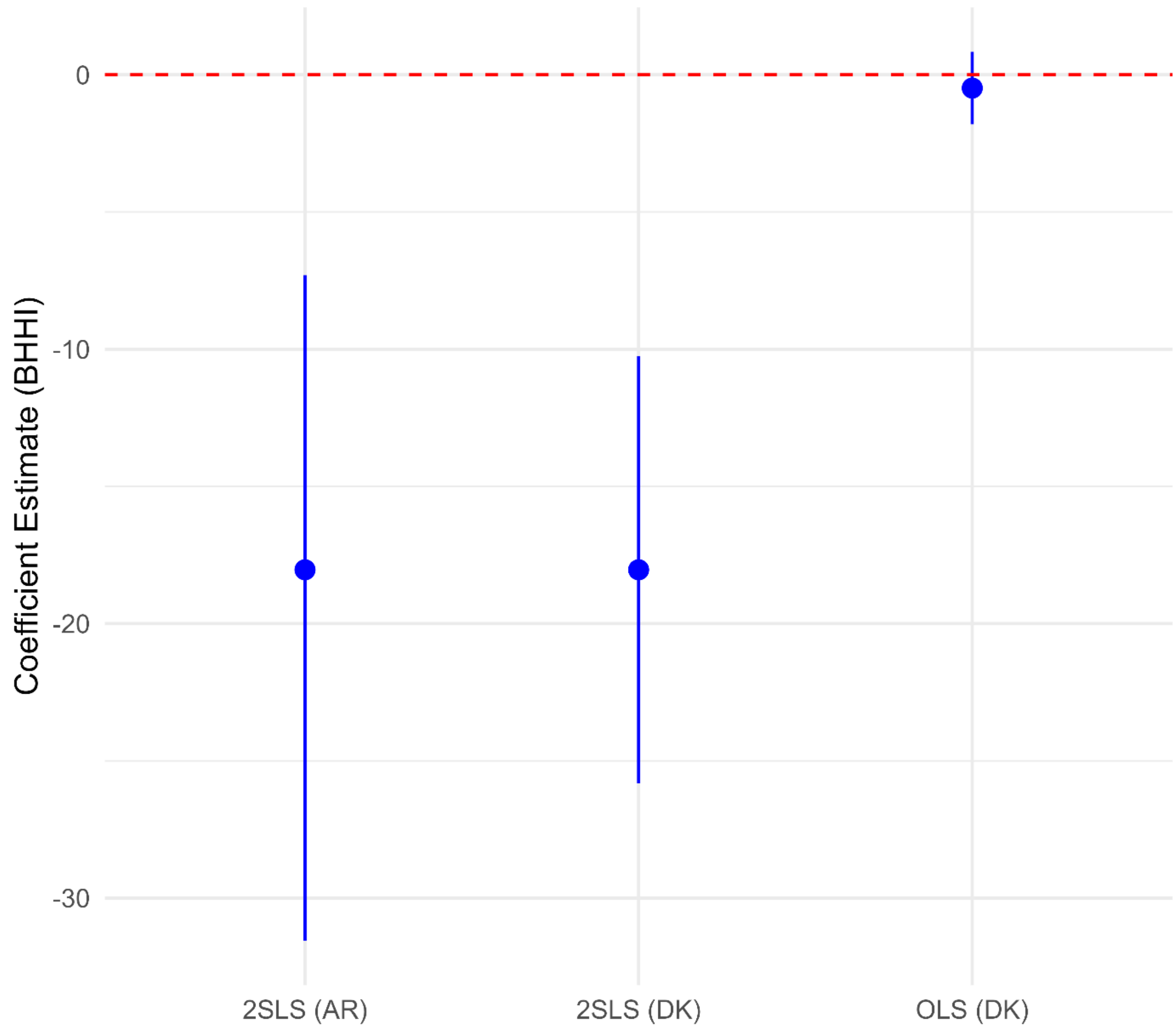

Figure 5: Comparison of OLS and 2SLS estimates of the BHHI coefficient using Driscoll-Kraay (DK) and Anderson-Rubin (AR) statistic.

Sensitivity Analysis

Standard IV estimation relies on the exclusion restriction, which requires that the instrument Z_{pt} affect the outcome s_{ct} only through the endogenous regressor $BHHI_{pt}$, i.e., this assumption sets $\gamma = 0$ in

$$s_{jt} = \beta BHHI_{pt} + \mathbf{X}_{jt}^{T}\boldsymbol{\theta} + \boldsymbol{\alpha}_{iqy} + \gamma Z_{pt} + \varepsilon_{jt} \quad (6)$$

where γ captures any direct effect of the instrument on salmon lice levels. In the full sample, γ cannot be estimated without bias; if $BHHI_{pt}$ is endogenous and is an outcome of Z_{pt}, the estimate of γ will be contaminated by "collider bias" (Cunningham 2021). But suppose we can identify a subpopulation for which $BHHI_{pt}$ is not an outcome of Z_{pt}, i.e., a subpopulation for which the first stage coefficient on Z_{pt} is zero. Then we could estimate the above equation and test the null hypothesis that $\gamma = 0$. Rejecting the null would suggest a violation of the exclusion restriction in the "zero first stage" (ZFS) subpopulation; since there is no first-stage relationship between the instrument and the endogenous explanatory variable of interest in the given subpopulation, any correlation between the instrument and the outcome in that subpopulation represents a violation of the exclusion restriction.

We construct a zero first-stage subsample by exploiting the unique characteristics of production zone 13. This zone is typically operated by only one or two firms on a non-continuous basis, causing its ownership concentration (BHHI) to be consistently at or near its maximum. Consequently, our instrument, which is driven by industry-wide strategic planning, has little to no capacity to induce variation in concentration within this specific production zone. Further, production zone 13 is usually operated by only one or two firms on a non-continuous basis, resulting in high ownership concentration by default. Taken together, the above suggests that the instrument has little room to shift concentration in production 13, i.e., the coefficient on the instrument in the first-stage regression ought to be zero when only using production 13 in estimation.

We test for a zero first-stage relationship in production zone 13 and are unable to reject the null. We then estimate the above equation and are unable to reject the null hypothesis that $\gamma = 0$. We further check robustness by using the local-to-zero approach of (Conley, Hansen, and Rossi 2012) and (van Kippersluis and Rietveld 2018); see (Hossain, Mullally, and Onel 2024) for an application. Local-to-zero treats γ as a small but nonzero parameter governed by a prior distribution, often $\gamma \sim N\left(\mu_\gamma, \Omega_\gamma\right)$. Here, we take $\mu_\gamma = \hat{\gamma}$ from the production zone 13 subsample. Uncertainty is captured by the variance Ω_γ, which can be widened or narrowed to reflect how strongly one trusts the ZFS estimate.

Figure 6 shows how the local-to-zero approach changes our coefficient of interest. The adjusted estimate of β (the effect of ownership concentration on salmon lice) is -35.43 with a standard error of 12.00 (95% CI: $[-58.95, -11.90]$, $p = 0.0032$). In contrast, our original 2SLS estimate obtained by assuming the exclusion restriction holds perfectly was -15.13 (SE 5.49), 95% CI $[-25.89, -4.36]$, $p = 0.0059$. Although the effect of concentration on salmon lice becomes stronger when allowing for deviations from the exclusion restriction, the sign and magnitude of the effect remain the same. We conclude that our results are robust to violations of the exclusion restriction.

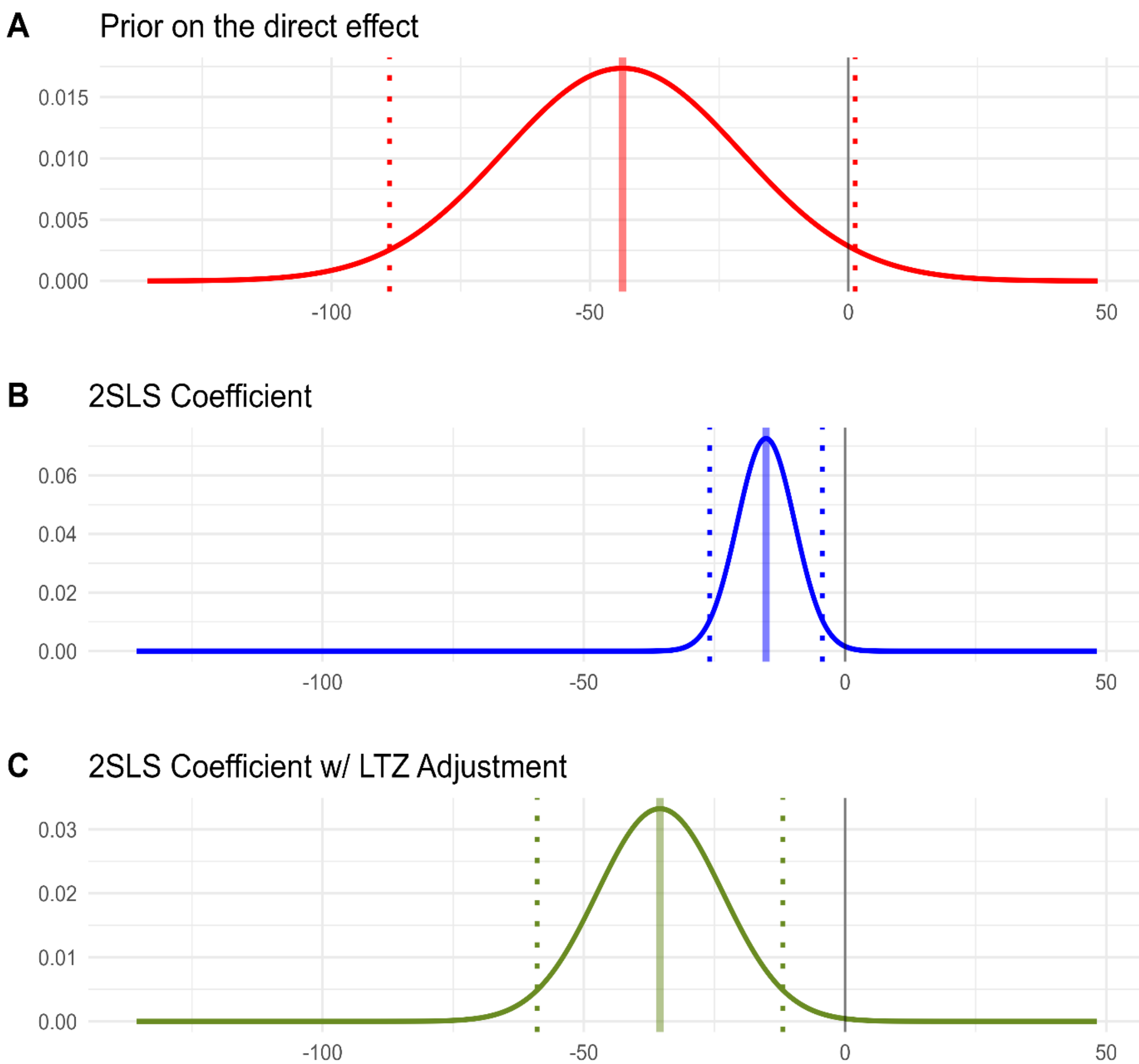

Figure 6: Distributions of (A) the prior on the direct effect, (B) the 2SLS coefficient estimate, and (C) the 2SLS coefficient with LTZ adjustment. The solid vertical lines indicate point estimates, and dotted lines represent the corresponding 95% confidence intervals.

Conclusions

Effective management of transboundary ecological processes requires aligning the spatial scale of these processes with property rights. This study examines the role of ownership concentration at production sites in achieving such alignment, using the Norwegian salmon industry as a case study, with a focus on the endemic parasite salmon lice. We distinguish between the effects of ownership concentration on the extensive margin (the probability of any salmon lice being present) and the intensive margin (the severity of the infestation, conditional on presence). Using data from Norwegian salmon farms between 2012 and 2017, we quantify ownership concentration through the Biomass Herfindahl-Hirschman Index (BHHI) and assess its effect on salmon lice prevalence.

Our findings show (i) no statistically significant effect on the extensive margin and (ii) a large negative effect on the intensive margin. A 100-point increase in BHHI is associated with a substantial reduction in salmon lice loads (between 11.1% and 16.5%), conditional on an infestation being present. However, we find no statistically significant effect of ownership concentration on the extensive margin. These results remain robust to spatial dependence and serial autocorrelation, and our sensitivity analysis reinforces these findings for the intensive margin.

These findings contribute to the broader literature on environmental externalities and resource management by providing empirical validation for theories on spatial-dynamic externalities and cooperative management. Our goal, however, is not to claim that ownership concentration is the only path to effective coordination. Ownership concentration is notable for its inherent ability to align incentives within firms, thereby lowering the transaction costs of synchronisation. Yet, regulatory mandates, formal producer cooperatives, or result-based payments can, in principle, achieve comparable ecological gains, provided they embed credible incentives and enforcement. The most suitable mechanism will depend on context-specific factors, such as transaction costs, administrative capacity, competition policy, and antitrust constraints. We focus on ownership simply because Norway's licensing and reporting framework provides unusually precise, farm-level, time-varying data on ownership shares.

Our empirical approach draws heavily on the theoretical framework proposed by Epanchin-Niell and Wilen (2015). Although salmon aquaculture operates in an aquatic environment, the underlying principles governing its production processes do not differ fundamentally from other forms of food production. By showing that higher ownership concentration is associated with lower salmon lice severity, our results are consistent with the hypothesis that coordination in the form of ownership concentration facilitates collective biosecurity actions. This also aligns with the empirical evidence reported by Singerman, Lence, and Useche (2017) for citrus greening control. Consequently, we anticipate that the mechanism we document will be relevant in other contexts where coordinated action can mitigate pest impacts. However, as our empirical setting employs ownership as the coordination instrument, we cannot determine how strong an alternative coordination mechanism must be to achieve comparable outcomes.

Our empirical results establish a robust relationship between ownership concentration and a lower prevalence of salmon lice; however, the specific mechanisms driving this effect remain untested. Patterns observed in the data suggest that firms operating in more concentrated production zones may implement more effective management strategies, such as synchronized fallowing, coordinated treatment applications, and increased use of preventive measures like cleaner fish. In particular, firms with higher ownership concentration appear to exhibit greater synchronization in biosecurity practices, which could reduce reinfection risks and improve treatment efficacy. These mechanisms align with theoretical predictions that ownership concentration facilitates coordinated responses to transboundary externalities. Future research with detailed operational data on treatment timing, fallowing practices, and farm-level decision-making could provide more direct evidence of how ownership concentration improves salmon lice management.

The policy implications of these findings are threefold. First, regulatory frameworks that influence ownership structures, such as antitrust policies and licensing regimes, should consider the trade-off between market competition and environmental coordination. While excessive consolidation may raise concerns about market power and monopsonistic behavior in input markets, moderate ownership concentration appears to enhance biosecurity and sustainability outcomes by aligning production incentives with ecological dynamics. Second, policymakers could explore alternative mechanisms to achieve similar coordination effects in fragmented production systems, such as incentive-based cooperative frameworks or regulatory mandates for synchronized management. Third, establishing clear biosecurity and disease load regulations with well-defined penalties for exceeding thresholds could incentivize ownership concentration or cooperative management without requiring direct intervention.

Contextualizing these findings within subsequent policy developments is also instructive. Our analysis, based on data from 2012-2017, predates the introduction of Norway's Traffic Light System (TLS), a regulatory shift that altered the industry's incentive structure (Jensen, Tveterås, and Nielsen 2024). The TLS framework, by treating each production zone as a single entity with collective consequences, strongly reinforces our paper's central conclusion: mitigating the salmon lice externality requires coordination at a scale beyond the individual farm. While a full evaluation of the TLS is beyond the scope of this paper, our findings suggest that production zones with higher pre-existing ownership concentration may be better positioned to meet these collective targets. This interaction between ownership structure and new regulatory frameworks presents a compelling avenue for future research.

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[1] The Norwegian salmon aquaculture industry is currently regulated using a traffic light system (TLS), initiated on October 30, 2017. This system links production growth to salmon lice pressure, using the environmental conditions within each production zone to determine whether production should increase, remain constant, or decrease (Olaussen 2018). It is important to note that the TLS uses the definition of production zones promulgated on January 25, 2017, to serve this new regulatory framework. In this research, we use the production zones, but it is worth noting that the production zones did not exist before 2017.

[2] These thresholds align with concentration categories used in antitrust analysis (Pandey, et al. 2023)

[3] A significant regulatory change occurred in 2017 with the introduction of the so-called Traffic Light System (TLS), which provide a link between lice levels and production growth (Jensen, Tveterås, and Nielsen 2024). Since this change in regulatory framework could influence production decisions and salmon lice management strategies, we restrict our analysis to 2012–2017 to ensure that our results are not confounded by these structural changes.

[4] The data set cover the production from all commercial licenses. However, a number of other types of licenses such as research and educational license also exist, and the fish produced at these licenses are also harvested (Hersoug et al. 2021).

[5] It is critical to distinguish a production cycle from the farm site itself. A farm site ('lokalitet') is a fixed physical location, whereas a production cycle is a discrete, time-bound event that takes place at that site. For example, a single farm site may host 'Cycle 1' in year one and 'Cycle 2' in year two; each of these cycles is a separate observation in our model and inherently contains the characteristics of the geographical location.