The Cost of Lice: Quantifying the Impacts of Parasitic Sea Lice on Farmed Salmon

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ABSTRACT

Diseases are an important challenge in aquaculture. However, most of what is known about the effect of diseases comes from laboratory experiments. Using a farm-level data set containing sea lice infestation counts for all Norwegian salmon farms over an 84-month period, we empirically investigate the biological and economic impacts of observed levels of infective lice. Sea lice, a common ectoparasitic copepod of salmonids, have been shown to reduce fish growth and appetite and cause substantial costs to salmon farmers worldwide. Our results suggest that the percent of total biomass growth lost per production cycle due to average infestations varies from 3.62 to 16.55%, despite control, and depends on farm location. Using a discrete harvesting model, we simulate the economic impact on farm profits over typical cycles. An average infestation over a typical central region spring-release cycle generates damages of US$0.46 per kg of harvested biomass, equivalent to 9% of farm revenues. We estimate that lice parasitism produced US$436m in damages to the Norwegian industry in 2011.

Key words: Aquaculture, fisheries, sea lice, fish disease, biomass growth, panel data.
JEL Code: Q22, C23.

INTRODUCTION

Diseases are an integral part of any biological production process, including aquaculture.[1] Salmon aquaculture provides an interesting example, as there are a number of diseases with impacts that range from trivial to catastrophic. Asche (1997) noted how *vibrosis* and *furunkolosis* outbreaks influenced productivity and production costs in the Norwegian industry. From 2009 to 2012, salmon producers in Chile experienced disease outbreaks severe enough to halt growth in the industry (Asche et al. 2009; Fischer, Guttormsen, and Smith 2016).[2] While the damaging effects of diseases are readily observable, there have been few attempts, beyond surveys and laboratory trials, to empirically assess the impact on cost. This article provides an investigation of the impact of salmon lice in Norwegian salmon aquaculture.

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1. Conrad and Rondeau (2015) provide an example of a bioeconomic analysis for shellfish.
2. Fisher, Guttormsen, and Smith (2016) also discuss how market structure and regulatory environments interact to influence how intensively firms use aquatic ecosystems, including where production takes place.

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In all salmon-producing countries, salmon lice are a substantial concern as the parasite limits growth and may cause increased mortality (Torrissen et al. 2011, 2013). Geographic expansion of the salmon farming industry has fundamentally changed the number and spatiotemporal distribution of hosts in local marine environments, resulting in a heightened risk of on-farm epizootics and spillovers to susceptible wild fish populations (Jansen et al. 2012).[3] There has been a considerable amount of research focusing on the spillover effects of increased sea lice populations on wild salmon returns (Krkosek and Hilborn 2011; Costello 2009; Bjørn, Finstad, and Kristoffersen 2001; Finstad et al. 2000). But increased host density also has a potential own-effect on farmed fish that may generate economic losses to aquaculture as intensity increases. The likely mechanism for both problems is common; increases in farmed salmon density increase the host population for lice, which then propagate in larger numbers and disperse to local and distant wild and farmed stocks.

In what follows, we utilize a unique panel data set that measures farm-level input and production data, biophysical variables, lice infestation counts, and lice treatment applications for all producing Norwegian salmon farms over an 84-month period. This data set facilitates an empirical investigation of the biological and private economic impacts of naturally observed levels of infective sea lice. It allows us to estimate the parasite-inflicted growth impacts and productivity of lice control measures on cultured salmon stocks in a quasi-natural experiment setting. In particular, we estimate a bio-econometric model of fish biomass growth that incorporates productive and biophysical inputs (e.g., feed, stocking density, fish size, and water temperature), harmful inputs (e.g., parasites), and damage abatement inputs (e.g., parasiticide applications). Using our model, we estimate the marginal damages imposed by infective sea lice and conduct counterfactual experiments in order to derive measures of the total private economic costs of lice under realistic farm conditions. Specifically, we incorporate lice infection levels into a discrete version of a harvesting model to econometrically simulate the impact of average infestation scenarios on farm profits over typical production cycles.

Our empirical estimations are the first data-based estimates of own-farm damages associated with sea lice populations in salmon aquaculture.[4] We find that impacts on production and profits are both significant statistically and economically, verifying anecdotal claims by industry participants. Our estimates suggest that damages from typical lice infestation patterns in parts of Norway may be as large as 13% of revenues. We also identify important biological and behavioral factors that influence lice damage, including the influence of water temperature, patterns of stocking and removal, pen density, feeding, and treatment.

The outline of the article is as follows. The next section provides a more detailed background on sea lice and salmon before the data is presented. The following section presents a conceptual model of the private costs of lice, providing motivation for our subsequent empirical strategy before our model of fish biomass growth is outlined and empirical results reported. The empirical results are followed by a section investigating the marginal impacts of lice on fish biomass growth and how they vary over key environmental and production factors, as well as empirical sim-

3. For example, the total number of wild hosts along the Norwegian coast was estimated at 2–2.5M fish (Heuch et al. 2005), while the standing stock of farmed salmon and trout was ~202M on January 31, 2005 and ~343M on December 31, 2011. Furthermore, because farmed hosts remain abundant in coastal waters over winter months when wild hosts are typically scarce, adult female lice are able to continue their larval production year-round (although at slower rates over winter), thereby supporting infection pressures above natural levels (Heuch et al. 2005).

4. In contrast, the existing literature uses farm questionnaires and accounting techniques to estimate the costs of lice infestations on particular farms in particular regions of the world (Pike and Wadsworth 1999; Costello 2009; Rae 2002; Sinnott 1998; Mustafa, Rankaduwa, and Campbell 2001).

ulation estimates for the private costs of lice under average infestation and treatment scenarios. In the final section, some concluding remarks are offered.

SEA LICE AND SALMON

Salmon are among the most successful aquaculture species, and production has grown from a few thousand tonnes in 1980 to about 2.5 million tonnes in 2014. This has been possible due to the ability of aquaculture technologies to control the production process, leading to rapid innovation, lower production costs, and increased product diversity and trade (Anderson 2002; Asche 2008; Roll 2013; Asche et al. 2015; Asche, Roll, and Tveteras 2016). However, with increased production, concern about the impact and number of diseases has also increased, with parasitic salmon lice emerging as one of the most important in recent years in all the major salmon-producing countries (Torrissen et al. 2013).

Lepeophtheirus salmonis is the most economically important species of lice because of its prevalence on farmed Atlantic salmon (*Salmo salar*) in the Northern Hemisphere, and for this reason a vast literature exists on their biology, epidemiology, physiology, pathogenicity, and control (Pike and Wadsworth 1999; Boxaspen 2006; Costello 2006; Johnson et al. 2004; Tully and Noland 2002). Sea lice have simple life cycles and are mobile in both pre-adult and adult stages (Boxaspen 2006). Their life cycle consists of ten separate stages: three free-swimming, four parasitic, and three mobile phases. Mature adult females produce 2 egg-strings with approximately 100–1,000 eggs per string, and a single female may survive for up to 7 months producing 6–11 broods (Costello 2006). Female fecundity and development times of all stages depend on water temperature, and the generation time from egg extrusion to mature adult is 40–50 days at 10°C (Costello 2006). After hatching, lice disperse into the water column as planktonic non-feeding larvae and survive on their own energy reserves for 5–15 days (depending on water temperature) before attaching to their host (Costello 2006; Boxaspen 2006). Larvae are thought to behave like inert particles, drifting with the current; thus, their dispersal depends largely on local hydrologic conditions (Boxaspen 2006). In the third (copepodid) life cycle stage, lice make their initial host attachment using a prehensile antennae and maxillipeds followed by a more durable connection via a frontal filament (Pike and Wadsworth 1999).

Parasitic sea lice (beginning with the infectious copepodid stage) are considered "epidermal browsers" that use a rasping apparatus, sometimes called a "mouth tube," to graze and feed on host mucus, skin, and underlying tissue (Pike and Wadsworth 1999). Primary host responses include reduced appetite and growth. The external wounds, increased stress, and reduced vitality due to lice infection are also likely to increase host susceptibility to secondary infections of viral or bacterial disease (Costello 2006; Johnson et al. 2004; Tully and Noland 2002). Although lice are rarely observed to directly induce host mortality (i.e., non-pathogenic mortality), secondary health impacts resulting from infestation may increase mortality (Pike and Wadsworth 1999).

Research on the economic impacts of lice on farm profitability has been minimal and predominantly survey based.[5] For example, from "discussions with farmers in Atlantic Canada and on the basis of personal experience," Mustafa, Rankaduwa, and Campbell (2001) found that a typical 200,000-fish Canadian salmon farm lost 336,000 CAD (or approximately US$231,724) per

5. In contrast, there is a large scientific literature on the transmission dynamics of farm-to-wild salmon lice spillover (Krkosek, Lewis, and Volpe 2005; Price et al. 2011) and the subsequent ecological effects on wild salmonids (Krkosek and Hilborn 2011; Costello 2009; Bjørn, Finstad, and Kristoffersen 2001; Finstad et al. 2000).

grow-out cycle from a typical lice infestation without regular treatments. Notably, they found that the greatest financial loss due to sea lice was attributable to reduced fish growth, reported as 200 g per fish per cycle for a total loss of 40,000 kg per farm. Similarly, "from discussions with farmers," Rae (2002) found that the costs of stress on infected fish and losses due to reduced growth were approximately 5% of the annual production value of Atlantic salmon on Scottish farms. Lastly, in an often-cited review paper, Costello (2009) uses farm-level cost estimates from the literature and FAO production statistics to estimate the global cost of sea lice control to be US$480M in 2006 or 6% of the total annual production value of farmed salmon in those countries affected by lice. Notably, he finds that the "most significant costs of sea lice where control is successful in preventing pathogenicity, are treatment costs, reduced fish growth, and reduced food conversion efficiency."

Although such survey-based estimates may "help place the cost of lice in the context of other measures the [salmon] industry may take to improve profitability," they are otherwise incapable of providing a more nuanced understanding of the impacts of lice on farm profits (Costello 2009). For this reason, we believe that the main contribution of the available literature has been to accurately describe and rank the economic importance of the different impacts that lice are likely to have on farm profits, rather than to provide precise quantitative measures accounting for variation in biophysical conditions.[6] By providing the first data-based estimates of such impacts, our results offer a significantly higher degree of specificity than previous estimates.

DATA

Norway is the global leader in salmon aquaculture, producing 1.06 million tonnes of Atlantic salmon and 0.06 million tonnes of rainbow trout (*Oncorhyncus mykiss*) in 2011, with an ex-farm value of over 28.5 billion NOK (approximately US$4.85 billion). Operators must obtain a production license from the Directorate of Fisheries and are required to report monthly statistics on fish stocks, lice infections and treatments, and seawater temperature at a depth of three meters to the authorities by the beginning of the following month. Production licenses grant operators the legal right to farm fish in a specified geographical location for a distinct number of years and often also limit the level of standing biomass that may be in the pens at any time.[7] Because multiple licenses may be utilized simultaneously at the same location, all data was aggregated by farm site.[8] The panel data set covers 84 monthly reports, from January 2005 through December 2011, of all farmed salmon in Norway. In total, the data set consists of 1183 distinct producing farms in 175 municipalities, covering 48,397 non-zero biomass observations.[9] Following epidemiological research by Jansen et al. (2012), we group farms into three distinct geographical regions by latitude when reporting spatial differences in our empirical results.[10] Specifically, the central region comprises all farms between latitudes 67° and 62° 35 minutes.

6. Hermansen and Heen (2012); Tyholdt (2014); and Asche, Oglend, and Zhang (2015) all provide evidence of the importance of biophysical factors.

7. This is referred to as the maximum total allowable biomass (MAB) and is typically set to 780 or 945 tonnes per license depending on the region.

8. The data do not report the number of net pens per license or farm site; and thus, we do not have a precise understanding of the scale of each farm site beyond the number of fish. However, farms are reported to have an average of 6–8 pens per site (Asche and Bjørndal 2011).

9. All zero biomass observations occur when the farm is inactive (i.e., holding zero fish). After harvesting, a period of fallowing is required by the regulatory system (Asche and Bjørndal 2011).

10. Jansen et al. (2012) provides the three main regions based on one of the main biophysical variables; temperature (Hermansen and Heen 2012; Tyholdt 2014; and Asche, Oglend, and Zhang 2015).

Sea lice infection on salmon farms has been regulated since 1997 to reduce the harmful effects of lice on farmed and wild fish (Heuch et al. 2005). Regulations set thresholds for the maximum mean number of sea lice per fish (i.e., lice counts) and a compulsory reporting system for all mobile stages of infective lice. From 2000 to 2013 the legal lice infection thresholds, enforced by the Norwegian Food Safety Authority (NFSA), were set to 0.5 adult female lice per fish or 3 lice per fish of other mobile stages (i.e., adult males or pre-adult mobiles) in the period Jan 1–Aug 31, and 1 adult female or 5 other mobiles per fish in the period Sep 1–Dec 31. If thresholds are exceeded, it is mandatory for the farmer to medically treat or slaughter their fish within two weeks. To enforce the stated threshold levels, the NFSA requires farmers to regularly count sea lice in their pens and report the highest mean count during a month. Prior to August 2009, farmers were mandated to report the highest mean counts of sea lice from a 20 fish sample from a single net pen. After this date, farmers were required to report the mean of means from samples of 10 fish from 50% of all active pens; whereby all pens are to be counted for every two rounds of sampling in order to improve control.

Farm-level summary statistics for our data set are shown in table 1. Data include water temperature and geographic coordinates for each farm. Data on fish stocks include species type, fish numbers, average fish weight, and standing biomass. Data on farm production activities include quantity of feed use, number of chemical delousing treatments, fish stocking and harvesting numbers, average harvested fish weight, and harvested biomass. Data on lice prevalence include counts of adult females, and all other mobile stages (i.e., infective lice capable of grazing and relocating), including pre-adult mobiles and adult males. Values for the total number of actively producing farms and licensed companies were generated by the authors, along with the number of months a given fish stock has been at sea (i.e., number of sea months since initial stocking).[11] Graphical inspection of the overall mean values of key time series highlights the seasonality and regional heterogeneity of farm and company operations, standing farm biomass levels, water temperatures, lice counts, and the use of chemical delousing treatments (see figure A1). Graphs [A-C] illustrate that the recent growth in salmon production in Norway has been driven by a steady growth in farm-level production across regions rather than an increase in the total number of farm sites or companies in operation. As is also apparent from figure A1, southern region farms are, on average, the smallest yet most numerous and densely sited, while central region farms are, on average, the largest. Graphs [D–F] illustrate: (1) the importance of water temperature on lice counts across regions; (2) that chemical delousing treatments are used primarily as a method of post-infestation control, and (3) the recent increase in peak lice infections in the warmer central and southern regions.[12]

Although required by law, some companies failed to report data such as biomass levels, water temperature, lice treatments and/or lice counts for every month. Additionally, some data were identified as erroneous by the authors—likely due to inaccurate company bookkeeping or processing errors by the government agency. These randomly missing and erroneous values are

11. Due to the transfer of fish between farms and the simultaneous grow-out of multiple cohorts by several companies on a single farm site, this variable is an imperfect proxy for fish age.

12. The apparent relative increase in peak lice infections post-2009 may be slightly muted, in part, by the change in lice reporting standards; where lice counts prior to August 2009 may have been slightly overestimated (Jansen et al. 2012). Stratification of our data set pre- and post-August 2009 yields no significant qualitative changes to our empirical results. However, some care needs to be taken in interpreting the results relative to the current management regime, where only mature females are counted.

Table 1. Summary Statistics (2005–2011)

Monthly Fish Stock, Production, Lice Infection, and Water Temperature Data						
Variable	Observations	Farms	Mean	Std. Dev.	P5*	P95*
Total number of producing farms[a]	48,397	1,183	548.71	32.85	491	598
Total number of operating companies[b]	48,397	1,183	158.96	20.88	133	190
Months at sea	48,397	1,183	10.63	8.18	1	24
Water temperature (°C)	48,397	1,183	8.90	3.58	3.8	15.30
Number of fish released[f]	5,245	1,018	350,490.80	302,632.40	19,160	943,800
Number of fish	48,396	1,183	502,502.70	388,883.40	0	1,189,654
Average fish weight (kg)	45,943	1,169	2.31	2.05	0.13	5.77
Fish biomass (kg)	48,397	1,183	870,963.90	891,542.90	0	2,716,128
Feed use (tonnes)	46,996	1,177	163.17	171.89	4.68	517.10
Number of fish mortalities[f]	47,199	1,166	5,308.76	16,865.45	83	21,419
Number of fish removals[f]	8,099	839	2,125.95	10,644.26	34	7,585
Number of fish escapes[f]	81	58	23,914.80	40,868.33	12	108,579
Number of miscellaneous fish losses[f]	1,950	364	34,51.47	49,688.17	1	10,000
Number of fish harvested[f]	13,384	1,061	110,648.00	132,365.40	7,489	313,775
Average harvested fish weight (kg)[f]	13,378	1,061	4.49	1.76	1.51	6.57
Harvested fish biomass (kg)[f]	13,378	1,061	431,423.80	391,944.80	30,819	1,204,832
Mobile lice (dummy)	47,954	1,183	0.67	0.47	0	1
Adult female lice (avg. number/fish)	47,889	1,183	0.25	0.69	0	1.23
Other mobile lice (avg. number/fish)[c]	47,815	1,183	0.76	1.80	0	3.5
Total mobile lice (avg. number/fish)[d]	47,954	1,183	1.01	2.28	0	4.6
Chemical lice treatment (dummy)[e]	47,985	1,181	0.15	0.36	0	1
Number of chemical lice treatments	47,983	1,181	0.20	0.63	0	1
Atlantic salmon (dummy)	48,397	1,183	0.93	0.26	0	1
Rainbow trout (dummy)	48,397	1,183	0.12	0.32	0	1
Latitude (decimal degrees)	48,309	1,167	63.71	3.62	59.29	70.05
Longitude (decimal degrees)	48,309	1,167	10.01	5.40	5.03	21.90
Northern region (dummy)	48,309	1,167	0.24	0.43	0	1
Central region (dummy)	48,309	1,167	0.31	0.46	0	1
Southern region (dummy)	48,309	1,167	0.45	0.50	0	1

* P5 and P95 are the 5th and 95th percentiles of the data.
[a] Farms reporting non-zero fish numbers and biomass.
[b] Licensed and actively producing companies.
[c] Pre-adult mobiles and adult male lice.
[d] Adult females plus other mobile lice.
[e] Chemical delousing (in-feed or bath) treatments.
[f] Non-zero observations only.
Source: Norwegian Directorate of Fisheries (2012).

imputed following a similar process as outlined in the electronic supplemental material for Jansen et al. (2012).

CONCEPTUAL MODEL OF THE PRIVATE COSTS OF LICE

In what follows, we utilize a harvesting model, adapting the models of Bjørndal (1988), Arnason (1992), and Guttormsen (2008) to conceptualize the economic impact of a particular lice infestation on farm profits. In doing so, we motivate both our empirical strategy of estimating the impact of lice on farm biomass growth and clarify both the biological and economic assumptions necessary to obtain our cost estimates.

A salmon farmer will typically stock a single year class of juvenile fish at some initial time and batch harvest the residual stock, T, months later (Bjørndal 1988).[13] In what follows, we consider harvest time, T, to be strictly exogenous in order to focus our attention on the economic impacts of lice over typical production cycles of fixed duration. Given that the largest portion of variable costs during grow-out is due to the feeding of fish, our subsequent analysis focuses on feeding as the primary variable cost of production (Guttormsen 2002; Asche and Oglend 2016). Moreover, as fish farmers generally feed using tables from the feed companies (Asche and Bjørndal 2011), it is reasonable to treat feeding quantities as exogenous. The biological literature informs us that fish growth, and therefore biomass growth, is a function not only of time (i.e., fish age), but also of things such as water temperature, photoperiod, fish size, stocking density, and the prevalence of parasites and disease (Pike and Wadsworth 1999). Fish are also likely to experience a reduction in their appetite due to lice parasitism, which will affect the quantity of feed use during a farmer's grow-out cycle (Costello 2006). To incorporate these potential lice impacts into a farmer's discounted net revenues from a single production cycle, we allow for farm biomass growth, $\dot{B}$, to be a function of a time-varying level of lice per fish, $L(t)$. In other words, $L(t)$ is an exogenous trajectory (or scenario) of lice per fish over a single production cycle.[14] If we further incorporate a farmer's ability to employ periodic costly chemical delousing treatments to their fish stock, the farmer's discounted profits are:

$$\begin{aligned}\Pi(T) = P(T) \cdot \left(B_0 + \int_0^T \dot{B}(t, L(t)) \cdot dt\right) \cdot e^{-rT} \\ - C_f \int_0^T FCR \cdot \dot{B}(t, L(t)) \cdot e^{-rt} \cdot dt - C_r \sum_{n=1}^{N} e^{-rT_n},\end{aligned} \tag{1}$$

where T is harvest time, $P(T)$ is the per kg price of fish, B_0 is the initial lice-free stock of biomass, and $\dot{B}(\cdot)$ is fish biomass growth. Further, C_f is the unit price of feed, FCR is the feed conversion rate (i.e., the per-period quantity of feed use per kg of biomass growth), r is the farmer's discount rate, C_r is the unit treatment cost, N is the total number of treatments, and T_n is the time at which treatment $n \in [1, N]$ occurs.[15] In this formulation, we have assumed that the per-kg price of fish and the feed conversion rate are both independent of the level of lice. In other

13. Alternatively, as is observed in our data, some farms will release and harvest their fish over multiple months.

14. There is discussion with respect to what extent lice infections are due to biomass at a specific farm or whether they are regional. In general, lice are regarded as a regional phenomenon with limited impact of the biomass of a specific farm (Torrissen et al. 2013); hence, we treat lice growth as exogenous.

15. Because biomass growth depends both on time and on the time-varying level of lice per fish, biomass growth is integrated over the standard arc-length of *L(t)* (written as *dt* in equation 1).

words, the price of fish does not depend on size—thereby not depending on the degree to which lice impact such factors—and feeding efficiency is not negatively impact by lice (Asche and Guttormsen 2001; Costello 2009). A sensitivity analysis shows that such an assumption has minimal impact on our results.[16]

By incorporating lice in this fashion we use equation (1) to devise the economic impact of a particular lice infestation scenario (as defined by *L(t)* and the associated treatment schedule) on discounted farm profits over a single production cycle of fixed duration. Hence, the economic impact of a particular lice infestation is simply the difference in discounted net revenues between two otherwise identical production cycles—one with the lice infestation and one without.[17] If, for example, we consider a production cycle of length T with N total lice treatments,[18] and assume that *L(t)* is a non-negative step function with I total intervals each of arbitrary length,[19] then the private economic cost of a particular lice infestation and corresponding treatment regime is:

$$\begin{aligned}\Pi(T)^{nolice} - \Pi(T)^{lice} = & \underbrace{e^{-rT} \cdot P(T) \sum_{i=1}^{I} \int_{t_{i-1}}^{t_i} \left(\dot{B}(t,0) - \dot{B}(t,L(t))\right) dt}_{Revenue\ loss} \\ & \underbrace{- C_f \cdot FCR \sum_{i=1}^{I} \int_{t_{i-1}}^{t_i} \left(\dot{B}(t,0) - \dot{B}(t,L(t))\right) e^{-rt} \cdot dt}_{Feed\ cost\ savings} + \underbrace{C_r \sum_{n=1}^{N} e^{-rT_n}}_{Treatment\ cost} .\end{aligned} \tag{2}$$

Equation 2 tells us that the magnitude of the private cost is composed of three distinct parts: revenue loss, feed cost savings, and treatment cost. The revenue loss captures the lost revenue from harvesting a lower level of biomass due to the negative impacts of lice on fish growth, the feed cost savings captures the farmer's lower expenditure on feed from the reduced appetite of their fish, and the treatment cost captures the total cost of undertaking N total chemical treatments. Additionally, equation 2 indicates that in order to estimate this impact for a particular infestation and treatment scenario we must build an empirical model of fish biomass growth that depends on the level of lice and all other exogenous factors influencing the current period's level of fish growth. In the next section, we use our farm-level panel data to build such a model in order to later simulate a discrete and parameterized version of equation 2.

EMPIRICAL MODEL OF FISH BIOMASS GROWTH

In our data set, farm biomass levels are reported as standing levels in live weight on the last day of every month, and therefore account for all changes in biomass within months, including stocking, harvesting, and other losses such as mortalities, escapes, and miscellaneous losses—all of which are reported as cumulative monthly values. Because we are interested in measuring the impacts of lice solely on the biological growth of farm biomass, our model structurally ac-

16. This is not surprising due to the high correlation of the prices, which makes the size classes aggregatable (Asche and Guttormsen 2001).

17. We use zero lice as our counterfactual because any positive level of lice will generate losses to farm biomass growth that may (at least partially) be averted by the use of chemical treatments or other methods.

18. Each of which occurs at some interior, but not necessarily unique, time T_n where $0 < T_1 \leq T_2 \leq \cdots \leq T_N < T$.

19. By assuming L_t is a step function we partially discretize our problem, helping to motivate our subsequent empirical analysis.

counts for all such ancillary changes in biomass unrelated to fish growth. If we define the net growth in ancillary biomass on farm i at time t as $AB_{it} = (Stocking_{it} - Harvesting_{it} - Moralities_{it} - Removals_{it} - Escapes_{it} - Misc.Losses_{it})$, where each variable is measured in units of biomass,[20] we express the biological growth rate of farm biomass as:

$$r_{it} = \frac{(Biomass_{it} - AB_{it}) - Biomass_{it-1}}{Biomass_{it-1}}, \tag{3}$$

where i denotes the i^{th} farm, and t denotes the t^{th} of T months during a specific production cycle on farm i.

To estimate the impact of lice on the biological growth rate of farm biomass, we express r_{it} as a non-linear function of a vector of time dependent explanatory variables, including the level of lice per fish. Specifically, we let $ln(1 + r_{it}) = x'_{it}\beta$, where x'_{it} is a vector of explanatory variables that influence growth rates as discussed in relation to equation (1), and β is the associated vector of parameters to be estimated. Allowing for the presence of additive time-invariant, farm-specific effects α_i; month-specific effects γ_{it} (which capture seasonality); and an unobservable error term, ϵ_{it}, our model for farm i at time t is:[21,22]

$$ln\left(\frac{Biomass_{it} - AB_{it}}{Biomass_{it-1}}\right) = x'_{it}\beta + \alpha_i + \gamma_{it} + \epsilon_{it}. \tag{4}$$

Because fish growth is likely to be a lagged production process, whereby the impacts of certain explanatory variables are distributed over time, we allow for x'_{it} to include lagged values of certain explanatory variables. In this form, our model is a finite distributed lag linear panel model. Referring to equation 4, our choice of panel estimator relies upon our assumptions of α_i. When conducting an F-test for the presence of farm-specific effects, we reject that all farm-specific effects, α_i, are jointly equal to zero for all model specifications (see table 2). Furthermore, a Hausman test rejects the consistency of random effects, implying that our model parameters for all model specifications may be consistently estimated using the fixed-effects *within* estimator. Graphical and statistical examinations of the residuals from our estimation of equation 4 provide a signal that the errors exhibit heteroskedasticity, autocorrelation, and cross-sectional (i.e., cross-farm or *spatial*) correlation; thus, we utilize standard errors (SEs) that correct for these issues.

Table 2 reports estimation results for equation 4 using the *within* estimator for progressively more complex model specifications. Given the micro-nature of the data, the model´s fit is reasonably good, as the overall R^2 increases from 0.23 to 0.31.[23] Moreover, all parameters, including the models with interaction effects, are statistically significant. Because the additional regressors in

20. Because only harvests are reported in units of biomass, we construct the remainder of AB_{it} using the product of reported fish numbers and average fish sizes. For non-harvest losses we multiply fish numbers by the average of fish sizes from current and previous months, while for stocking we use fish sizes from the current month of stocking because our data does not report the average size of stocked fish.

21. Equation 4 assumes that all ancillary changes in biomass occur at the end of each month. Further analysis, assuming that all or some portion of the changes instead occur at the beginning of each month, confirms that such an assumption has little to no effect on model results.

22. This setup explicitly disallows for the possibility of lice-induced mortality by directly accounting for the level of reported mortalities in AB_{it}. For comparison, when we remove mortalities from AB_{it} (i.e., allowing for the possibility of lice-induced mortality) we discover no qualitative changes to our results.

23. The R^2 of 0.31 also suggests that there are a number of factors that are not accounted for, most likely farm-specific factors not captured by the farm fixed effects.

Table 2. Biological Growth Model Results

Dependent variable $= ln((Biomass_{it} - AB_{it}) / (Biomass_{it-1}))$				
Variable	Pooled OLS	FE (Model A)	FE (Model B)	FE (Model C)
Time[a]	0.0005** (0.0002)	0.0005** (0.0002)	0.0006** (0.0002)	0.0005** (0.0001)
Months at sea$_t$[d]	–0.0034** (0.0004)	–0.0023** (0.0007)	–0.0022** (0.0007)	–0.0021** (0.0006)
Feed use$_t$ ('00s of tonnes)[c]	0.0134** (0.0016)	0.0142** (0.0020)	0.0383** (0.0059)	0.0315** (0.0063)
× feed use$_t$	–	–	–0.0029** (0.0006)	–0.0028** (0.0006)
Average fish size$_{t-1}$ (kg)	–0.0453** (0.0026)	–0.0522** (0.0042)	–0.0572** (0.0047)	–0.0530** (0.0043)
Number of fish$_{t-1}$ ('00,000s)	–0.0029** (0.0007)	–0.0037** (0.0014)	–0.0068** (0.0015)	–0.0049** (0.0015)
Average water temp$_{t-1}$ (°C)	0.0131** (0.0009)	0.0139** (0.0014)	0.0332** (0.0037)	0.0251** (0.0031)
× avg. water temp$_{t-1}$	–	–	–0.0010** (0.0002)	–0.0010** (0.0001)
Lice$_{t-1}$ (avg. number/fish)[d]	–0.0049** (0.0006)	–0.0043** (0.0007)	–0.0060** (0.0020)	–0.0033* (0.0014)
× lice$_{t-1}$	–	–	0.0002** (0.0001)	0.0002** (0.0000)
× avg. fish size$_{t-2}$[e]	–	–	0.0022** (0.0004)	0.0019** (0.0004)
× avg. water temp$_{t-1}$	–	–	–0.0009** (0.0002)	–0.0008** (0.0001)
× num. of treatments$_t$[f]	–	–	0.0009** (0.0003)	0.0007* (0.0003)
Farm fixed effects	NO	YES (F = 1.81**)	YES (F = 1.73**)	YES (F = 1.62**)
Month fixed effects[g]	NO	NO	NO	YES (F = 79.95**)
Marginal Effects				
Feed use$_t$	0.0134** (0.0016)	0.0142** (0.0020)	0.0274** (0.0039)	0.0209** (0.0042)
Average water temp$_{t-1}$	0.0131** (0.0009)	0.0139** (0.0014)	0.0133** (0.0010)	0.0059** (0.0015)
Lice$_{t-1}$	–0.0049** (0.0006)	–0.0043** (0.0007)	–0.0092** (0.0012)	–0.0064** (0.0009)
Observations	41,487	41,487	37,884	37,884
Number of farms	1111	1111	1089	1089
Average observations per farm	37.3	37.3	34.8	34.8
R^2 (within/overall)	(– /0.23)	(0.23/0.26)	(0.26/0.30)	(0.28/0.31)
Hausman test	–	$\chi^2(7) = 92.06$**	$\chi^2(13) = 114.73$**	$\chi^2(24) = 131.30$**
AIC	–13,454	–15,469	–21,230	–22,103

Cameron, Gelbach, and Miller (2011) (CGM) standard errors in parentheses; * p–value < 0.05; ** p–value < 0.01.

[a] Time trend captures linear effect of technological change.

[b] Months at sea is the number of months since initial stocking and is a proxy for fish age.

[c] Feed use enters contemporaneously, as it is a cumulative measure of the quantity of feed used in month *t*.

[d] Total number of mobile lice per fish.

[e] We use a two-month lag instead of a one-month lag because fish size is reported at the end of each month.

[f] Chemical delousing treatments undertaken in the current month are expected to instantaneously reduce adult lice counts, thus mitigating damages from an infestation in the previous month.

[g] Month fixed effects capture (non-temperature related) month-specific effects on biological growth (e.g., photoperiod).

Models B and *C* enter non-linearly, the marginal effects for the associated variables are reported separately along with their standard errors.[24] All parameter estimates are reported with Cameron, Gelbach, and Miller (2011) two-way cluster robust standard errors, which correct for heteroskedasticity and general forms of within-farm autocorrelation and between-farm spatial correlation (i.e., errors are clustered simultaneously over farms and time).

For each of the model specifications in table 2, the marginal effect of lice on fish biomass growth is negative and significant at greater than the 1% level. Thus, our results suggest that after accounting for all other factors that impact fish biomass growth, farms with higher monthly average lice counts have lower levels of biomass growth in the following month. Furthermore, accounting for farm fixed effects, the use of chemical treatments and other biologically relevant interaction terms, including monthly fixed effects, improves the overall statistical fit of the model. Lastly, the lice interaction terms suggest that the damaging marginal effect of lice on fish biomass growth will decay at higher levels of lice, fish sizes, and chemical delousing treatments. Moreover, damages intensify at higher water temperatures, suggesting that an additional louse will generate the greatest damages when water temperatures are high and fish are small, as well as lice- and treatment-free. Before using our empirical results to estimate the total private economic costs of sea lice infestations, it is valuable to first explore the marginal impacts of lice more closely; i.e., the loss of biomass growth due to a marginal increase in the level of the current infestation (or number of lice per fish).

VARIATION IN MARGINAL LICE EFFECT

In what follows, we refer to the marginal effect of lice on fish biomass growth as the marginal lice effect (MLE). We model the rate of farm biomass growth as opposed to its level, and therefore must transform our parameter estimates to produce marginal effects measured in units of biomass directly. In what follows, we report the MLE in units of live weight of lost biomass growth and by the percent change in the rate of biomass growth. Importantly, we account for the effectiveness of chemical delousing treatments at reducing effects of lice by allowing the number of treatments on a farm in the month following infestation to reduce the MLE. In other words, a given infestation level will result in less damage to biomass growth if a farm has undertaken an additional treatment in the month following the infestation.[25] By incorporating a farm's chosen treatment regime in this fashion, we are able to later account for such behavior in our total cost estimates for different lice and treatment scenarios over typical production cycles.

Table 3 presents the MLE at the means of all covariates (MLEM) by geographical region.[26] The first and third columns report the total loss in farm biomass growth and percent loss in the rate of farm biomass growth from an instantaneous unit increase in lice per fish on a farm the previous month when all model covariates are fixed at their respective region-specific means. For example, in the colder northern region, where farms are large yet relatively sparse and commonly

24. Because our model is linear in parameters, the marginal effects are the same if calculated as an average or at the means of all covariates.

25. We assume that the treatment efficiency is 100%, so that after a treatment, a farm is assumed to have no lice. As treatments are regarded as highly effective, this is not unreasonable even if it is an over estimate. The main challenge for a farm is the infection pressure from the lice pool in the water column around the farm following a treatment.

26. The MLEM for a particular region is the MLE evaluated at the region-specific means of all covariates, including the estimated fixed effects and number of chemical treatments. Alternatively, one may calculate the MLEM while fixing the number of chemical treatments to 0, 1, or 2 in order to investigate the marginal impact with and without treatment (see [D] of figure 1 for a graphical representation).

Table 3. Marginal Lice Effect at Means (MLEM) by Region

Region	MLEM (Δ kg)[1]	MLEM (Δ %)[2]
North	–6,755.3** (1,121.0)	–3.13** (0.52)
Central	–8,164.5** (1,203.6)	–3.43** (0.51)
South	–7.839.9** (1,015.6)	–3.93 (0.52)

Model C with CGM SEs in parentheses; ** p–value < 0.01.
[1] Change in kg of biomass growth.
[2] Percent change in rate of biomass growth.

free of lice, an additional louse per fish on a farm (i.e., an increase in total lice $L(t-1)$ from 0.41 to 1.41 holding all else constant) will reduce biomass growth the following month by 6,755 kg and reduce the biomass growth rate by 3.13%. In the warmer southern region, where farms are small yet abundant and lice are relatively prevalent, an additional louse per fish on a farm (i.e., an increase in total lice $L(t-1)$ rom 1.32 to 2.32 holding all else constant) will reduce growth the following month by 7,840 kg and reduce the growth rate by 3.93%. Thus, there appears to be a reasonable amount of inter-region heterogeneity when it comes to the impact of lice on farm biomass growth. Consequently, such biological losses will generate revenue losses at the time of harvest upwards of US$34,532 in the northern region, US$41,736 in the central region, and US$40,077 in the southern region.[27]

The spatial (i.e., inter-regional) heterogeneity of the MLEM is driven by variation in model covariates. Differences in farm-level water temperatures, ambient levels of lice, average fish sizes, and lice treatment regimes generate a considerable amount of variability in the MLEM. Graphs [A–D] of figure 1 depict the variability of the MLEM, as measured in kg of lost farm biomass, over different values of water temperature, average lice per fish, average fish sizes, and numbers of chemical lice treatments by region. These results confirm biological research suggesting that larger, more mature lice are likely to generate greater negative impacts on their hosts due to the size of host skin lesions, and that the negative growth impacts of lice infection are inversely related to fish size. Thus, smaller salmon is more vulnerable to lice infections (Boxaspen 2006; Pike and Wadsworth 1999). Graphs [A–B] of figure 1 highlight the strong sensitivity of the MLEM to relevant changes in temperature and fish size, while graph [C] highlights its relative insensitivity to relevant changes in ambient levels of lice. The shape of graph [C] suggests that only at lice levels near the 85th percentile (or approximately 2 lice per fish) does the MLEM begin to diminish substantially, suggesting that the incentive for farmers to marginally reduce lice levels is (for the most part) independent of the current level of lice pressure. Similarly, graph [D] highlights the relative insensitivity of the MLEM to relevant changes in the number of chemical delousing treatments, suggesting that although post-infestation treatments mitigate the marginal damage of lice, they are by no means capable of reducing such damages to zero. Because our data reports the number of treatments that occur, rather than (for example) the quantity of chemicals used, graph [D] is a step function where the step size is equivalent to the biomass savings from undertaking an additional treatment. Lastly, graph [D] of figure 1 illustrates that 84% of the time, in any given month, farms will administer no treatments, 13% of the time they will administer 1, and 3% of the time they will administer 2 or more.

27. This assumes a price of 30.07 NOK/kg-the average weekly spot price of 3–5 kg superior grade fish from 2005–2011 and an exchange rate of 0.17 US$/NOK.

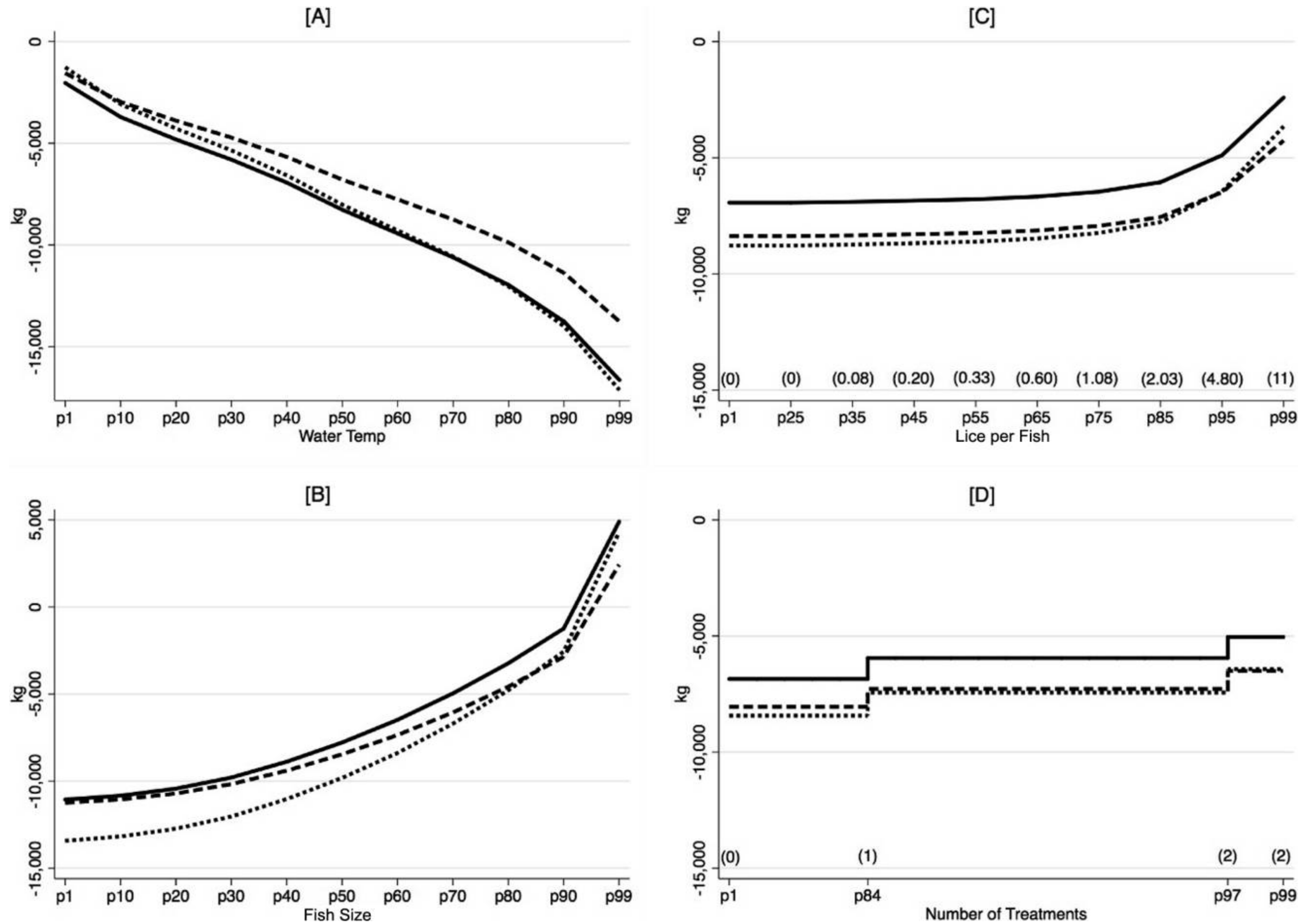

Figure 1. Variation in MLEM by: [A] ***avg. water temp***$_{t-1}$, [B] ***avg. fish size***$_{t-2}$, [C] ***avg. lice per fish***$_{t-1}$, and [D] ***number of treatments***$_{t}$.

Note: P1 indicates overall 1st percentile, and value in parentheses indicates actual numerical value. All other covariates, including fixed effects, are fixed at region-specific means. North (solid); central (dotted); south (dashed)).

ESTIMATING THE PRIVATE COSTS OF LICE

Our model provides an estimate ($\hat{g}_{it}$) of the level of biomass growth on farm i in month t as a function of the level of lice on farm i in month $t-1$ and other important control factors.[28] By employing our model to estimate the monthly level of growth on a farm with and without lice, ceteris paribus, we generate an estimate of the monthly biomass growth loss due to lice that may then be embedded in a discrete and parameterized version of equation 2 to obtain an estimate of the total private costs of lice.

Using a fully discretized version of equation 2, where each subinterval I of the grow-out cycle corresponds to a single sea month, t, our estimate becomes:

$$\frac{P}{(1+r)^T}\sum_{t=1}^{T}(\Delta\hat{g}_{t+1})-\sum_{t=1}^{T}\frac{C_f\cdot FCR}{(1+r)^{t+1}}(\Delta\hat{g}_{t+1})+\sum_{t=1}^{T}\frac{C_r\cdot N_{t+1}}{(1+r)^{t+1}}, \tag{5}$$

where N_t is the number of treatments in sea month t and $\Delta\hat{g}_{t+1} = (\hat{g}_{t+1}^{nolice} - \hat{g}_{t+1}^{lice})$, where $\hat{g}_{t+1}$ is our prediction of the conditional biomass growth in sea month $t+1$, and $\Delta\hat{g}_{t+1}$ is the estimated monthly loss of biomass growth in month $t+1$ from an infestation of L_t lice per fish in sea month t, having subsequently undertaken N_{t+1} treatments.[29] Therefore, $\Sigma_{t=1}^{T}(\Delta\hat{g}_{t+1})$ is the total loss of biomass growth during the cycle, and $FCR\cdot(\Delta\hat{g}_{t+1})$ is the monthly reduction in feed use due to the loss of appetite from lice parasitism.

In the analysis that follows, we utilize equation 5 to estimate the cost for an average lice infestation scenario and treatment regime over typical fall- and spring-release production cycles for each region of Norway. In commercial salmon farming in Norway, fish are typically born in hatcheries in January and stocked as smolts in net pens that fall (approximately 9–11 months old) or the following spring (approximately 15–17 months old).[30] This creates two distinct production cycles with unique durations, temperature profiles, growth patterns, harvesting weights, lice infection levels, and treatment regimes (see figure 2). In our analysis, we thus exploit the fact that spring-release cycles last 20 months, on average, while fall-release cycles last 16 months, on average.[31]

Figure 2 illustrates the typical grow-out cycles and their corresponding average lice infestation scenarios and treatment regimes. Specifically, figure 2 plots the sea-month-, region-, and season-of-release-specific mean values of key model covariates as well as the levels of lice per fish and number of chemical treatments. Importantly, by conditioning our estimates of $\hat{g}_{t+1}^{lice}$ and $\hat{g}_{t+1}^{nolice}$ on sea-month-specific mean values of model covariates we characterize "typical" production cycles with and without average lice infestations and treatment scenarios. Figure 3 illustrates the pre-

28. To obtain estimates reported in kg of biomass growth ($\hat{g}_{it}$), we transform the predicted values of our original model ($\hat{y}_{it}$) as follows: $\hat{g}_{it} = [\exp(\hat{y}_{it})-1]\cdot Biomass_{it-1}$. Such predictions remain consistent in the face of the well-known log-transformation bias, and corrections using the so-called "smear estimator" provide no significant improvements. In what follows, we present only the untransformed predictions.

29. In other words, $\hat{g}_{t+1}^{lice}$ and $\hat{g}_{t+1}^{nolice}$ are the predicted levels of biomass growth in sea month $t+1$ when the level of lice per fish in sea month t is L_t or zero, respectively; the number of treatments in sea month $t+1$ is N_{t+1} or zero, respectively; and all other model covariates are fixed at their sea month specific mean values. An alternative approach that dynamically adjusts the levels of fish size and biomass in the "no lice" scenario requires stronger assumptions and has little impact on results.

30. Approximately 44% of all cycles in our data are spring-release, and 28% are fall-release. Fall-releases have become more prevalent over time as hatchery technology has reduced the time to smoltification; e.g., fish were released in the fall 42% of the time versus just 40% in the spring on southern farms in 2011.

31. We reject the null hypothesis that fall- and spring-release cycles of 1–2 years are, on average, of equal duration (p-value = 0.00) and fail to reject that such cycles are equal across regions (spring-release p-value = 0.97; fall-release p-value = 0.16).

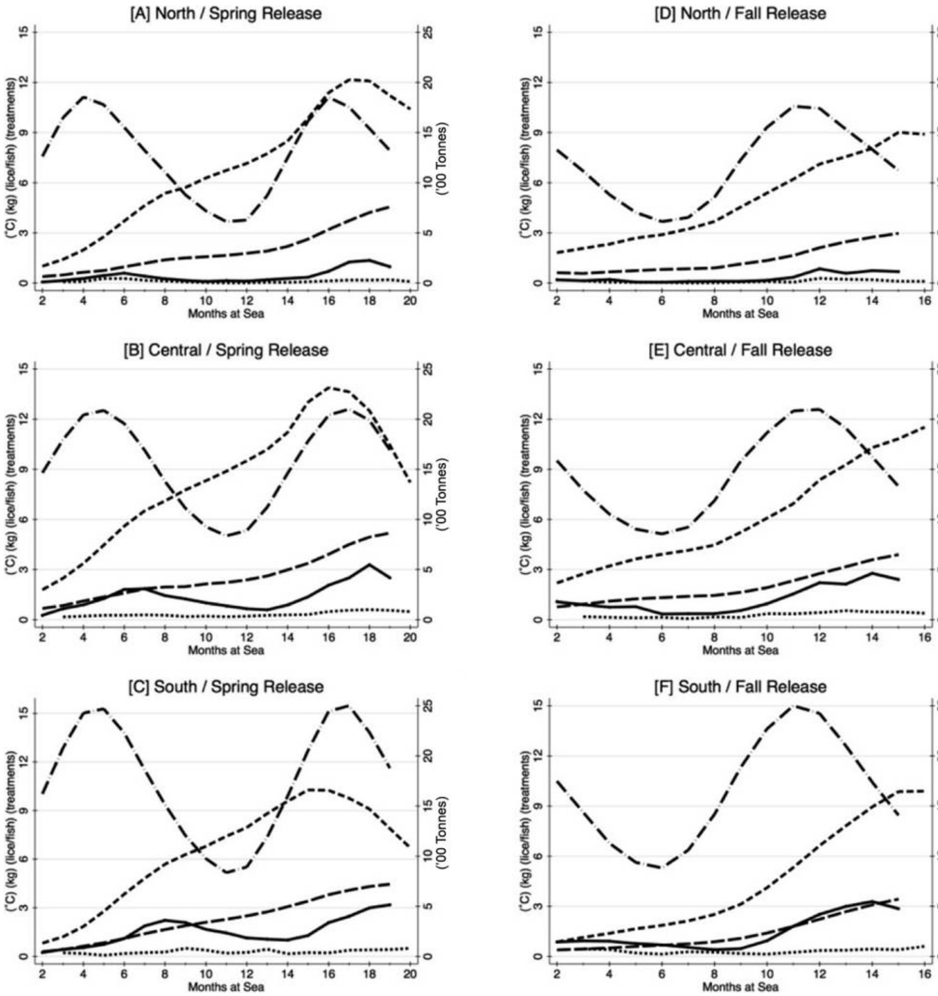

Figure 2. Typical Spring-release [A–C] and Fall-release [D–F] Productions Cycles Represented by Region and Season-of-Release

Note: The lines are sea-month-specific mean values of water temperature in °C (long dash-dot), fish size in kg (long dash), and biomass in hundreds of tonnes (dash). Average lice infestation and treatment scenarios represent region-, season-of-release-, and sea-month-specific mean values of lice per fish (solid) and number of chemical treatments (short dash). The graphs highlight the higher mean temperatures in the south compared to the north and that fish grow faster and are harvested earlier in the south. The graphs also show lower lice levels in the northern region and how those levels are correlated with temperature, but with a lag.

dicted monthly loss of biomass growth ($\Delta\hat{g}_t$) and its 95% confidence interval (CI) for each unique production cycle, as well as corresponding average infestation and treatment scenario. These graphs highlight that the lice-inflicted monthly loss of biomass growth during a typical production cycle is greatly impacted by both within- and between-region variations in water temperature. Point estimates for the percent of total biomass growth lost to average lice infestations despite control over spring (fall) release production cycles are 3.62% (2.65%) for northern-region farms, 11.82% (11.39%) for central-region farms, and 16.55% (15.82%) for southern-region farms.

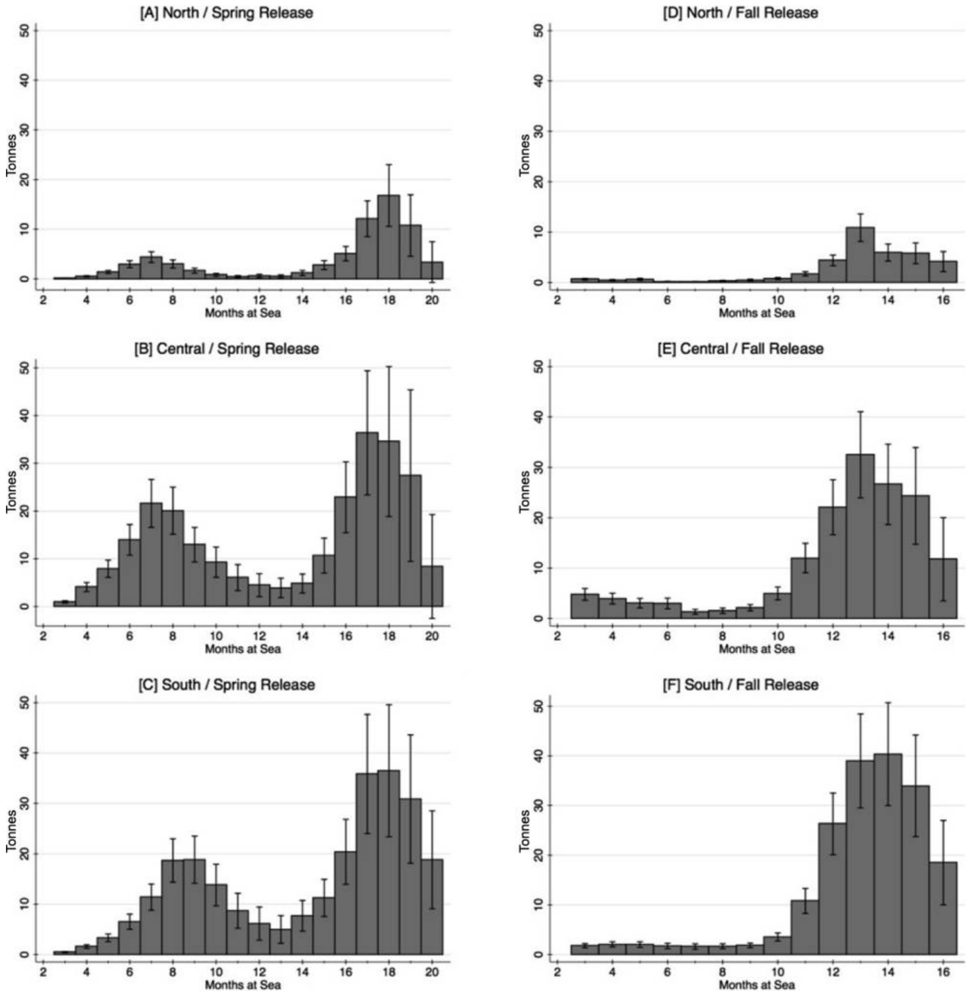

Figure 3. Predicted Monthly Loss of Biomass Growth ($\Delta \hat{gt}$) from Average Lice Infestation and Treatment Scenarios with 95% CIs

Note: Predictions are conditional on average number of monthly treatments and, therefore, incorporate the contemporaneous biomass savings from treatment each month.

Results for the private economic costs of average lice infestation and treatment scenarios (assuming zero discounting) are reported in column 3 of table 4 by region and season-of-release.[32] When divided by the total quantity of harvested biomass, these cost estimates may be interpreted as the cost of lice (see column 4). For example, a typical spring-release production cycle in the northern region will experience an economic loss of US$321,635, equivalent to US$0.15 per kg of harvested biomass or 3.02% of total revenues. A typical spring-release cycle in the southern region will experience a much greater loss of US$1,115,091, equivalent to US$0.67 per kg or 13.10% of total revenues. These numbers are striking—suggesting that typical infestations and treatment regimes are from 3 to 4.5 times more costly per kg on central and southern region

32. The discount rate is set to zero since with the relatively short production time, typically between 11 and 17 months, it will not have a large impact.

Table 4. Cost of Average Infestation and Treatment Scenarios ($r = 0$)[a]

Region	Release	Total Cost of Lice (US$)	Cost/kg of Lice (US$)[b]	Percentage of Revenue
North	Spring	321,635 [222,366, 420,905]	0.15 [0.11, 0.20]	3.02 [2.09, 3.95]
Central	Spring	1,117,839 [756,777, 1,478,901]	0.46 [0.31, 0.61]	9.01 [6.10, 11.92]
South	Spring	1,115,091 [797,995, 1,432,187]	0.67 [0.48, 0.86]	13.10 [16.82, 9.37]
North	Fall	182,315 [142,684, 221,946]	0.12 [0.09, 0.14]	2.27 [1.78, 2.76]
Central	Fall	702,059 [523,213, 880,906]	0.42 [0.31, 0.53]	8.19 [6.10, 10.28]
South	Fall	833,277 [648,126, 1,018,429]	0.65 [0.51, 0.79]	12.71 [9.89, 15.54]

Model C with CGM standard errors; exchange rate of 0.17 NOK/US$.
Bracketed variation generated by setting monthly biomass losses equal to the low or high end of 95% CI.
[a] All cases include the cost of treatments at 225,000 NOK (US$38,250) each.
[b] Cost divided by region- and season-of-release-specific mean of total harvested biomass.

farms than on northern region farms. Not only are there differences across regions but also across season-of-release. Warmer water temperatures and longer grow-out cycles in the spring typically lead to higher average levels of lice, treatments, and biomass growth, thereby generating slightly larger economic impacts in all regions for the spring- versus fall-release stocks. For example, typical infestation and treatment scenarios are anywhere from 1 to 1.25 times more costly for spring-release stocks.[33]

For comparison, a survey of salmon farmers in eastern Canada by Mustafa, Rankaduwa, and Campbell (2001) reported that farms with "sea lice problems" that did not treat for lice experienced an economic loss of US$0.45 per kg from the negative impacts of lice on fish growth. Although it is unclear exactly what they mean by "sea lice problems" in terms of the specifics of the infestation, this value sits in the mid-range of price estimates reported in column 4 of table 4 for spring-release production cycles in the central region. Furthermore, a review article on the global costs of sea lice to the salmon farming industry by Costello (2009) reported that Norwegian farms experienced an average economic loss of US$0.24 per kg (equivalent to 6.22% of production value) in 2006 from the negative impacts of lice including the costs of parasiticides. Although, as in the Mustafa, Rankaduwa, and Campbell (2001) study, it is unclear exactly what is meant by the "costs of sea lice" and "sea lice control"; these values sit between the impacts reported for northern and central region farms. Lastly, the Norwegian Research Council estimated in 2011 that lice infestations cost Norwegian salmon farmers US$0.34 per kg of harvested biomass. Importantly, all of these studies employed surveys to elicit typical biological impacts of lice that were then translated to dollar values using simple accounting techniques. In contrast, the results reported in table 4 are data-based estimates obtained by analyzing self-reported and government audited lice counts on individual farms over extended periods of time.

CONCLUSIONS

High-density food production environments are particularly susceptible to the spread of pests and diseases that are likely to generate both private and external economic damages via production and quality loss, in addition to the direct costs of damage control measures. The limited availability of accurate quantitative terrestrial farm-level data on input choices together with pest levels

33. As shown in equation (2), the model also allows us to decompose the different cost components of lice cost. This shows that the largest component of the cost is the forgone growth. For the scenarios in table 4, feed cost reduction is negligible, less than US$0.01, and the share of treatment cost of the total cost varies from zero in the northern region to 10.91% in the central region for a spring release.

has severely restricted the ability of researchers to precisely measure their effects on crop production, as well as the impacts of management and treatment. In this article, a unique data set that measures farm-level input and production data, biophysical variables, sea lice infestation counts, and chemical treatment applications for all producing Norwegian aquaculture salmon farms over an 84-month period allows us to specify a bioeconometric model of fish biomass growth that accounts for infections and treatments.[34] Using our model, we conduct a number of counterfactual experiments in order to derive measures of the private economic damages of naturally observed levels of infective sea lice despite control under real-time farm conditions.

Our results provide the first rigorous empirical analysis to quantify the impacts of sea lice on the biological growth of farmed salmon and the profitability of individual farms. Our total cost estimates represent the value of completely avoiding an average lice infestation scenario or, in other words, of maintaining a farm entirely free of lice or the willingness-to-pay for a hypothetical vaccine for lice. Furthermore, our estimates of the marginal impacts of lice on fish biomass growth provide essential information to farmers on the marginal cost of infective lice, which they may use to improve their decision making on when to employ chemical treatments or other related lice control efforts. Lastly, the magnitude of our estimates for the price of lice confirm the anecdotal and survey-based claims of farmers, policymakers, and researchers that sea lice can be costly, and provides ample motivation for conducting a more detailed bioeconomic analysis of sea lice in the future.

The inclusion of a farm's chosen treatment regime in our analysis provides an estimate of the productivity or marginal returns to treatment. Although a full bioeconomic approach—one that identifies the delousing efficacy of treatments over an entire production cycle—would be necessary to conduct a comprehensive cost-benefit analysis of chemical treatments, our results provide an initial estimate of the contemporaneous biomass savings from chemical treatments.[35] Moreover, we can identify the break-even point where the cost per treatment of US$38,250 exactly equals the value of the contemporaneous biomass saved.[36] For example, the break-even point for conducting a treatment occurs when the contemporaneous biomass savings reach 7,485 kg, which occurs when lice levels are between approximately 7–10 lice per fish, depending on the region of infestation. Given that farms often conduct treatments when lice are well below such levels (see figure 2), these results suggest that the much of the economic benefit from these treatments may likely accrue over the remainder of the production cycle (i.e., removing lice today will mitigate future growth of the lice population tomorrow and therefore generate benefits over time) and/or that farmers are treating primarily because of government mandates.

Although we focus on the economic impact of lice for typical region- and season-of-release specific grow-out cycles, the internal validity of our model allows us to estimate the total cost of lice for other grow-out cycles, including specific cycles on specific farms. Furthermore, our estimates may be used to estimate the industry-wide economic impacts of lice. For example, when using our estimates from table 4 and distinguishing by region and season-of-release, we find that the total economic impact of lice on the Norwegian salmonid farming industry in 2006 is estimated to be US$301 million, which is equivalent to 8.81% of the industry's total production value. These estimates suggest that previous industry-wide estimates by Costello (2009) of US$165M and 6.22%

34. See Smith (2008) for an extended discussion on bioeconometrics.

35. Unfortunately, our data does not distinguish between oral and topical chemical treatments and thus are estimates representing a weighted average of the two.

36. This assumes a price of 30.06 NOK/kg, which is the average weekly spot price from 2005–2011 for 3–5 kg "superior" grade fish and an exchange rate of 0.17 NOK/US$.

are likely too low. Using the same methodology, estimates for 2011 are US$436M and 8.70%, suggesting that the estimate of US$334M by the Research Council of Norway may also be slightly low. Finally, this is the first study of lice using a very rich data set, and there are a number of potentially important extensions. Among the most intriguing is the extent to which there are strategic interactions between farmers both in terms of collective action and free riding externalities. The fisheries literature empirically demonstrates that such interactions can be important (Huang and Smith 2014).

APPENDIX

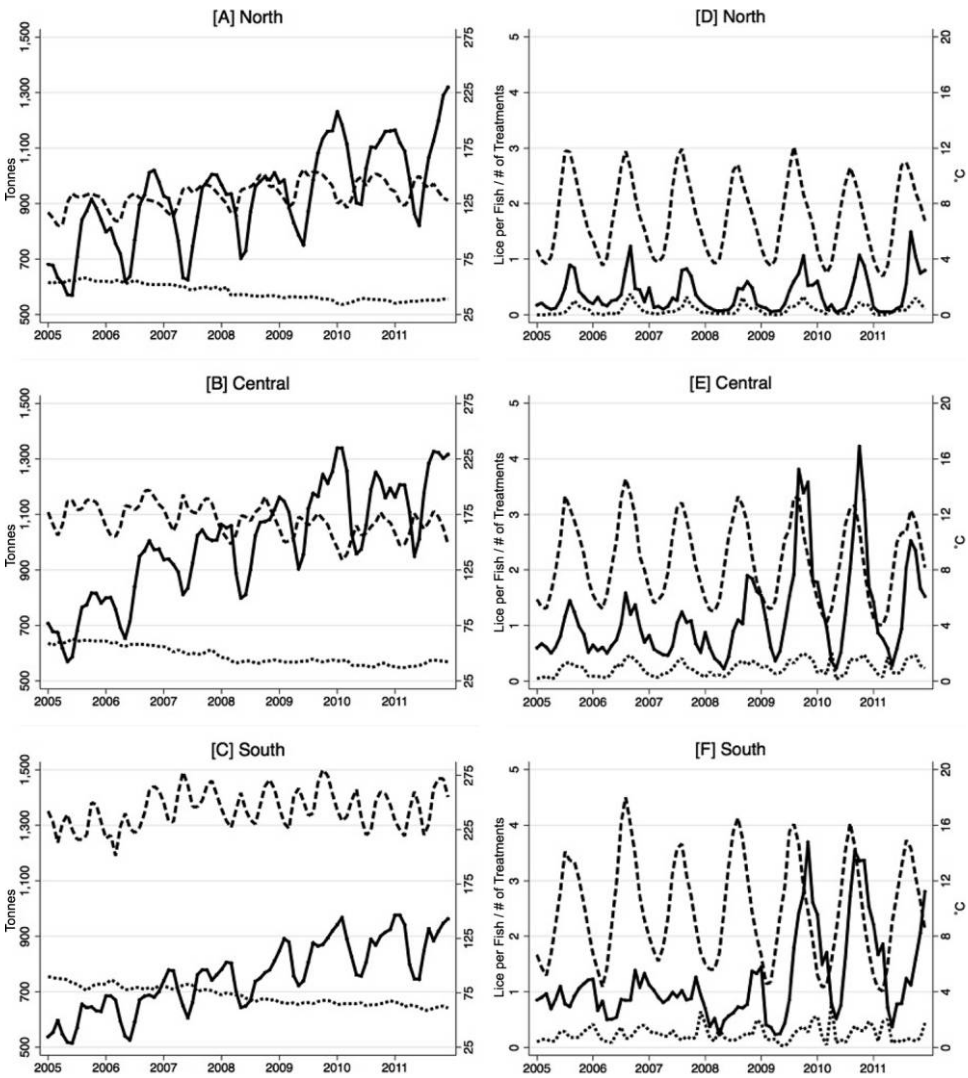

Figure A1. [A–C] Monthly Total Number of Active Producing Farms (dashed) and Companies (dotted), and Average Standing Farm Biomass in Tonnes of Live Weight (solid) by Region. [D-F] Monthly Average Water Temperature (dashed), Average Total Mobile Lice per Fish (solid), and Average Number of Chemical Treatments (dotted) by Region.

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