The Effects of Strategic Firm Behavior on Aquatic Ecosystems: Disease Risk and Market Power in Salmon Aquaculture

Carolyn Fischer, Resources for the Future

Atle G. Guttormsen, Norwegian University of Life Sciences

Martin D. Smith, Duke University

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Abstract

We develop a model of a multinational firm producing commodities for a global market in multiple locations with location-specific risks and different regulatory standards. Salmon aquaculture and disease outbreaks provide an empirically relevant example. In the model, market power and the regulatory environments in multiple countries interact to influence how intensively firms use aquatic ecosystems. The presence of market power can lead to a perverse outcome in which high environmental standards in one country both lower the provision of disease management in the other country and reduce industry-wide output. We extend this model to consider additional locations, types of firms, and within-pool risk spillovers. We find that the risk of outbreak in a given location is decreasing with greater firm concentration within the pool, increasing with the outside production of operators within the pool, and increasing with lower risk (or more regulation) in other pools where the operators produce. We examine details of the infectious salmon anemia outbreak in Chile in the late 2000s and find some indirect evidence in support of the theoretical model. We suggest other applications of multinational risk management.

Keywords: salmon, aquaculture, disease, market power, strategic environmental policy

JEL Codes: Q22

1. Introduction

Aquaculture is an increasingly important use of aquatic ecosystems. In 1970, aquaculture contributed just 3% of global seafood production (4 million metric tons) (FAO, 2014). By 2014 that share had grown to roughly 50% (66.6 million metric tons), and forecasts suggest continued growth (Asche, Roheim, and Smith, 2015; FAO, 2014; World Bank, 2013). Advances in fish farming techniques, improved transportation, logistics, freezing, and storage technologies and the globalization of the seafood trade have contributed to the rise of aquaculture (Anderson, 2002; Asche, 2008; Asche et al., 2015a). Nevertheless, this growth has relied on bringing more aquatic ecosystems under management and, in many cases, greater intensification of these systems.

Aquaculture's encroachment on marine, estuarine, and freshwater ecosystems raises many environmental concerns. These include conversion of aquatic ecosystems that otherwise provide public goods, effects of effluent from fish farming operations on the surrounding aquatic environment, the potential for farmed fish to spread disease to wild populations, genetic contamination of wild populations with selectively bred (or genetically modified) farmed fish, and the sustainability of aquaculture feed that includes fish meal derived from wild-caught fish (Naylor et al., 2000; Smith et al., 2010a; Asche, Roheim, and Smith, 2015; Conrad and Rondeau, 2015).

With explosive growth and the many potential threats to aquatic ecosystems, salmon farming exemplifies broad trends in aquaculture. Atlantic salmon *(Salmo salar)* was first domesticated in the 1960s in Norway. Atlantic salmon are typically bred in fresh water (often closed systems) and, after juvenile stages, raised to market size in net pen enclosures in the natural environment (most favorably in fjords that allow water exchange with the surrounding marine ecosystem but provide protection from storms and waves). With improvements in selective breeding and feeding technologies, production costs decreased dramatically, and Norwegian farmed salmon supply rose from less than 50 metric tons in 1980 to more than 1 million metric tons in 2010 (Asche, 2008; Asche, Roheim, and Smith, 2015). Production also spread to other countries, including Canada, Chile, and the United Kingdom. In the mid-1990s, Chile was the world's second-largest Atlantic salmon producer even though the country is on the Pacific coast and no salmon are native to the Southern Hemisphere.

Environmental concerns about salmon farming provide provocative examples of all of the issues listed above. Nutrient runoff from salmon net pens can pollute the surrounding aquatic environment (both under the pens and in areas nearby). Fish escapes occur, raising concerns about genetic contamination of wild salmon populations when farms are raising native species. As examples, this issue can be salient for Atlantic salmon in Norway or various Pacific salmon species in British Columbia, Canada. Moreover, a genetically modified Atlantic salmon has been raised in the laboratory but is not yet on the market. The sustainability of fish meal sources is a concern because farmed salmon use large amounts of fishmeal and fish oil, and these products are derived from wild-caught forage fish populations. The spread of sea lice and other pathogens to wild populations through escapes or incidental contact with the surrounding ecosystem and the antibiotics and other pharmaceuticals in effluent from salmon farms are additional concerns (Naylor et al., 2000; Smith et al., 2010a; Abolofia, 2014; Asche, Roheim, and Smith, 2015).

Although the list of environmental concerns in salmon aquaculture is long, the industry's environmental record is mixed. On the positive side, the industry has made significant progress internalizing environmental externalities, including dramatically reducing total antibiotic use in Norway while rapidly expanding production (Asche, Guttormsen, and Tveterås, 1999; Asche, Roheim, and Smith, 2015). Some producers differentiate their farmed salmon with organic certification, and organic salmon garners a premium at the retail level (Asche et al., 2015b). Feed conversion ratios (the amount of fishmeal and fish oil needed to grow one kg of salmon) have also declined significantly (Tacon and Metian, 2008). Moreover, there is no empirical evidence connecting expansion of salmon aquaculture to overfishing of reduction fisheries (for fish meal and oil). Nor is there empirical evidence demonstrating genetic contamination of wild salmon populations from farmed salmon. However, lack of evidence for these effects does not imply their nonexistence, and a recent disease outbreak suggests that environmental concerns about salmon aquaculture continue to be salient, despite some improvements in environmental performance.

Here we focus on a 2009 outbreak of infectious salmon anemia (ISA) that collapsed Atlantic salmon production in Chile. At the time, Chile was the world’s second-largest producer of farmed salmon, after Norway. Although Atlantic salmon production in Chile has now recovered to a large extent, understanding of the disease crisis is lacking. Conventional wisdom suggests that the proximate cause of the collapse was overstocking of fish that allowed disease to spread rapidly, and the ultimate cause was a governance failure in Chile (Asche et al., 2010; Smith et al., 2010b). However, multinational firms operating in Chile had prior experience with ISA in other countries. Moreover, a feature that distinguishes aquaculture as a use of the aquatic environment is that compared with a capture fishery, aquaculture producers have a high degree of control over the production process (Anderson, 2002). This control and the prior experience of multinationals with ISA beg the question of why firms allowed the disease crisis to unfold (Asche et al., 2010).

In this paper, we explore an alternative driver of the Chilean salmon disease crisis, namely market power combined with asymmetric environmental regulation. The basic intuition is that firms with market power will receive some price compensation on their remaining production in the event of a major supply disruption. The possibility of price compensation creates incentives to invest less in risk avoidance. When firms operate in multiple countries, strict regulation in one country can further decrease incentives to undertake preventive measures in the others, because the firms are more likely to have countervailing benefits in the event of an outbreak in the other country.

In our setting, Norway can be viewed as the country with strict environmental policy, relative to Chile, for salmon aquaculture. Anecdotally, we know that both production and export prices in Norway rose during the period of production declines in Chile, suggesting at least ex post that some compensation may have occurred. Did heterogeneous environmental policy and market power in salmon aquaculture contribute to these outcomes?

Some literature has analyzed market power in salmon production. In the 1980s, salmon aquaculture had limited ability to price-discriminate by export region but may have been able to discriminate seasonally because of seasonal fluctuations in wild-caught supplies (DeVoretz and Salvanes, 1993). Steen and Salvanes (1999) find that the salmon market is competitive in the long run, but at the country level, Norway has market power in the short run. Researchers have also explored retailer market power in salmon purchasing but have found little evidence of monopsony power (Fofana and Jaffry, 2008). More recently, Xie et al. (2009) find evidence that demand for fresh farmed salmon in world markets has become less price elastic but perhaps not enough to be considered inelastic. Overall, the literature suggests some potential for market power in farmed salmon.

The vast literature on trade and environment provides important backdrop to our problem. Much of this literature focuses on whether production concentrates in places with lax environmental standards and whether trade liberalization ends up reducing environmental quality in low-income countries (Antweiler, Copeland, and Taylor, 2001). For resource extraction, the trade-off is between rent dissipation and overexploitation in the long run versus benefits from trade in the short run (Taylor and Brander, 1997). Our setting has features of both cases. Like issues surrounding pollution havens, there are questions about whether trade liberalization and standard setting facilitate concentration of production in countries with lax environmental standards. But similar to the resource extraction case, the driver of disease problems may be a collective action failure that resembles open access in a fishery.

When trade itself is the vehicle for externalities, the situation is even more complicated. Invasive species, for example, are often spread through international trade. Tariffs to control the spread of invasives and provide the associated public goods can be difficult to distinguish from protection of domestic industry (Margolis, Shogren, and Fischer, 2005).

Another strand of the literature offers competing ideas: weak environmental policy is a subsidy to domestic industry, but strong environmental policy could benefit domestic industry if the Porter hypothesis were to hold and firms discover ways of reducing costs in response to regulation (Greaker, 2003). This tension is echoed in the political science literature on trade and environment. The concern that lax environmental standards attract business is thought of as a race to the bottom, but some evidence suggests firms may have incentives to adopt stricter environmental standards than local authorities require or may find it beneficial to export environmentalism (Garcia-Johnson, 2000; Prakash and Potoski, 2006). A reasonable question to pose about our setting is whether multinational firms behave the same way in different countries, and if not, why incentives to export environmentalism (as seemed present in the chemical industry, for example, according to Garcia-Johnson, 2000) were not present in aquaculture.

The theoretical literature on strategic environmental policy generates a range of insights about problems similar to the one we analyze but none that perfectly match the setting. A natural starting place is the classic result that market power can actually mediate an environmental externality (Buchanan, 1969). The result is predicated on the externality's being positively correlated with output. The mechanism is relevant to our setting but different. In our case, if a disease outbreak hits, production is low but compensated partially through higher prices. If there is no disease outbreak, production is high with corresponding low prices. In the model below, we find that disease risk coupled with market power lowers production on average. Because a disease outbreak is a risk, market power reinforces rather than offsets the externality.

Market power in the output market can create incentives for governments to set stricter or more lax standards than would be optimal under perfect competition (Barrett, 1994). The logic of strict environmental policy follows similarly from Buchanan's insight: setting strict standards can reinforce a firm's market power. However, the nature of imperfect competition affects the best responses of governments. With Cournot competition, there are incentives for weak environmental policy to attract a larger share of the imperfectly competitive market, whereas with Bertrand competition, incentives cut in the other direction to set policy too stringent to raise prices (Barrett, 1994; Greaker, 2013).

What is missing from all of this literature that appears central in our setting is the implications of large multinational firms with production facilities in multiple countries with heterogeneous standards. The economics literature largely ignores market power or the multinational nature of firms, whereas the political science literature seeks motivations for firms' behavior on the cost side but does not address imperfect competition. In the next section, we briefly describe the Chilean disease crisis. In Section 3, we develop a model of a multinational firm with market power and production in two locations. We model the firm's behavior, but unlike the strategic environmental policy literature, we take country-level regulation as given, and thus we derive theoretical implications of the firm's decisions to control disease spread under exogenous environmental standards that differ across locations. Next, Section 4 extends the model to consider risk spillovers as well as multiple types of firms with different operational scales; from this analysis we derive predictions for firms' behavior and for the risk of disease outbreaks in different locations. Section 5 provides some analysis of the salmon aquaculture market conditions to explore the plausibility of our theoretical insights. Finally, Section 6 discusses the policy implications and other possible cases to which our model applies.

2. The Disease Crisis in Chile

In 2005, Chile had the fastest-growing salmonid production industry worldwide. Chile became the world's largest producer of rainbow trout and coho salmon and, after Norway, the second-largest producer of Atlantic salmon. Figure 1 illustrates this dramatic growth. However, after two decades of rapid growth and strong financial results, the industry started to experience problems. The symptoms were rising mortalities in the freshwater and marine production phases, increased need for, and use of, pharmaceuticals (antibiotic, antifungal, and antiparasitic treatments), and reduced growth of juvenile fish. Farmed salmon are generally transferred from fresh water to the marine environment at the smolt stage, when their wild counterparts would migrate through brackish water to the ocean. From 2004 to 2007 the average harvest weight per transferred smolt decreased from 3.0 kg to 1.8 kg, and the average harvested fish weight decreased from 4.5 kg to 2.7 kg (Vike, 2014).

Although Chilean producers attempted to address disease problems with pharmaceuticals, it turned out that production problems were primarily due to an outbreak of the viral disease infectious salmon anemia, for which these treatments were ineffective. ISA causes lethargy, appetite loss, and damage to internal organs. At the time of the outbreak, there were no effective treatments for the virus, and its spread could be limited only through careful management and biosecurity efforts (http://www.fao.org/fishery/culturedspecies/Salmo_salar/en).

The world's largest salmon-producing company, Marine Harvest, was the first company to report problems. In 2007, Marine Harvest reported that it had discovered ISA at a farm producing Atlantic salmon in Chile. From 2008 to 2010 the production of Atlantic salmon in Chile suffered a more than 60% decrease due to the devastating viral outbreak. The production stagnated for five years, and 2011 was the first year after the crisis with production levels similar to those of 2005–2006. These trends are apparent from the overall salmonid production in Chile (Figure 1) and can be seen in global Atlantic salmon production as well (Figure 2). Vike (2014) provides a more detailed explanation of how the virus arrived in Chile and spread within the industry and discusses possible measures to control the spread of such diseases.

3. Model of a Multinational Producer

Much of the basic problem can be understood by looking at the incentives of a single, multinational firm. We have a large firm with commodity production (e.g., salmon farming) in two countries (in our example, Chile (*c*) and Norway (*n*)); the firm is in competition with a fringe (*f*) of other producers (e.g., wild-caught and other farmed salmon). In each country *i*, the firm faces a risk ρ_i that its stock will be decimated by a disease outbreak, but it can undertake measures to lessen this risk by share γ_i. Total costs of production are convex in both the quantity of production (in this case of fish / biomass) q_i, and the degree of risk reduction: $C(q_i, \gamma_i)$, where $C_q(q_i, \gamma_i) > 0, C_\gamma(q_i, \gamma_i) > 0, C_{qq}(q_i, \gamma_i) > 0,$ and $C_{\gamma\gamma}(q_i, \gamma_i) > 0.$ We do not impose an assumption as to how production scale affects the marginal cost of care.

The following table defines the four possible outcomes and their probabilities:

Outcome (notation)	*Harvest*	*Probability*
(b) both sources are harvested successfully	$q_c + q_n$	$(1-\rho_c(1-\gamma_c))(1-\rho_n(1-\gamma_n))$
(c) only the Chilean stock survives	q_c	$(1-\rho_c(1-\gamma_c))\rho_n(1-\gamma_n)$
(n) only the Norwegian stock survives	q_n	$\rho_c(1-\gamma_c)(1-\rho_n(1-\gamma_n))$
(f) both stocks fail; fringe harvest supplies the market	0	$\rho_c(1-\gamma_c)\rho_n(1-\gamma_n)$

The expected farmed salmon production is

$$E\{Q\} = (1-\rho_c(1-\gamma_c))q_c + (1-\rho_n(1-\gamma_n))q_n$$

The firm is large enough to influence global prices, and we assume it faces a linear demand curve, $P = y - mQ$, representing the residual function of global demand after the fringe supply is taken into account (see Appendix for more detail). Based on the four harvest outcomes, the corresponding price outcomes are

$$P_b = y - m(q_c + q_n); \quad P_c = y - mq_c; \quad P_n = y - mq_n; \quad P_f = y$$

Firms compete in terms of quantity, as in Cournot competition. This assumption seems realistic for salmon production, where quantity decisions are made two years in advance of the harvest.

3.1 Incentives with market power

The imperfectly competitive firm has expected profits of

$$
\begin{aligned}
\pi = {} & (1-\rho_c(1-\gamma_c))(1-\rho_n(1-\gamma_n))(q_c+q_n)\left(y-m(q_c+q_n)\right) \\
& +(1-\rho_c(1-\gamma_c))\rho_n(1-\gamma_n)q_c\left(y-mq_c\right) \\
& +\rho_c(1-\gamma_c)(1-\rho_n(1-\gamma_n))q_n\left(y-mq_n\right) \\
& -C_c(\gamma_c,q_c)-C_n(\gamma_n,q_n)
\end{aligned}
$$

Maximizing with respect to production levels and risk reduction, the first-order conditions for the choice variables in country *c* are

$$
\frac{\partial\pi}{\partial q_c} = (1-\rho_c(1-\gamma_c))\left((1-\rho_n(1-\gamma_n))\left(y-2m(q_c+q_n)\right)+\rho_n(1-\gamma_n)\left(y-2mq_c\right)\right)-\partial C_c/\partial q_c = 0;
$$

$$
\frac{\partial\pi}{\partial\gamma_c} = \rho_c\left((1-\rho_n(1-\gamma_n))(q_c+q_n)P_b+\rho_n(1-\gamma_n)q_cP_c-(1-\rho_n(1-\gamma_n))q_nP_n\right)-\partial C_c/\partial\gamma_c = 0.
$$

We do not derive first-order conditions for country *n,* as they are symmetric.

Substituting and rearranging, we get

$$
\partial C_c/\partial q_c\,|_{IC} = (1-\rho_c(1-\gamma_c))\left(y-2m\left(q_c+(1-\rho_n(1-\gamma_n))q_n\right)\right); \tag{1}
$$

$$
\frac{\partial C_c/\partial\gamma_c\,|_{IC}}{\rho_c q_c} = y-m\left((1-\rho_n(1-\gamma_n))2q_n+q_c\right). \tag{2}
$$

3.2 Incentives for a price taker

Suppose instead that this firm were a price taker. In this case, it does not expect to influence world prices, but it has expectations about the price it would receive for its harvests. The perfectly competitive (*PC*) firm has the following expected profits function:

$$
\pi = E\{P\}\left((1-\rho_c(1-\gamma_c))q_c+(1-\rho_n(1-\gamma_n))q_n\right)-C_c(\gamma_c,q_c)-C_n(\gamma_n,q_n)
$$

In this case, the first-order conditions are simply

$$\frac{\partial \pi}{\partial q_c} = E\{P\}(1-\rho_c(1-\gamma_c)) - \partial C_c / \partial q_c = 0;$$
$$\frac{\partial \pi}{\partial \gamma_c} = E\{P\}\rho_c q_c - \partial C_c / \partial \gamma_c = 0.$$

Substituting and rearranging, we have

$$\partial C_c / \partial q_c |_{PC} = E\{P\}(1-\rho_c(1-\gamma_c)); \tag{3}$$

$$\frac{\partial C_c / \partial \gamma_c |_{PC}}{\rho_c q_c} = E\{P\} \tag{4}$$

In other words, the marginal cost of production equals the expected price times the survival probability. The marginal cost of increasing the survival probability per unit of production equals the expected price.[1]

3.3 Comparing incentives

We can thus compare the two behaviors by comparing the right-hand sides of the first-order conditions. With respect to risk reduction, the difference between the two right hand sides of Equations (2) and (4), all else equal, is (after simplifying)

$$\frac{(\partial C_c / \partial \gamma_c)|_{IC} - (\partial C_c / \partial \gamma_c)|_{PC}}{\rho_c q_c} = -m\left(\rho_c(1-\gamma_c)q_c + (1-\rho_n(1-\gamma_n))q_n\right) < 0$$

---

[1] The expected price in equilibrium is affected by the risks and farming intensity, but the price-taking firm does not take these changes into account in its decision-making. The expected price is the average of the possible prices, weighted by their probabilities:

$$\begin{aligned} E\{P\} &= (1-\rho_c(1-\gamma_c))(1-\rho_n(1-\gamma_n))P_b + (1-\rho_c(1-\gamma_c))\rho_n(1-\gamma_n)P_c \\ &\quad + \rho_c(1-\gamma_c)(1-\rho_n(1-\gamma_n))P_n + \rho_c(1-\gamma_c))\rho_n(1-\gamma_n)P_f \\ &= y - mE\{Q\} \end{aligned}$$

In other words, the expected price equals the residual demand intercept minus the slope times the expected total harvest across both countries.

Thus, given its levels of production, the firm with market power uses less care than it would if it were a price taker. This distortion is increasing with the slope of demand and with the levels of output. It is also increasing with the disease risk levels in that country's operations; however, it is decreasing with the risk levels in the other country, since that increases the probability that this country's harvest will generate large rents.

Consider now the effects of imposing stringent regulation in Norway, such as requiring a minimum above what the firm would provide on its own. This latter result implies that the Norwegian regulation actually exacerbates the distortion. *By reducing the probability of big rents for the Chilean harvest and by increasing the expected Norwegian rents in the event of a crash in the Chilean stock, the Norwegian regulation tends to reduce the level of care taken in Chile.*

Comparing the first-order conditions for output, Equations (1) and (3), we have

$$\partial C_c / \partial q_c |_{IC} - \partial C_c / \partial q_c |_{PC} = -m(1-\rho_c(1-\gamma_c))\left(\left(q_c(1+\rho_c(1-\gamma_c)) + q_n(1-\rho_n(1-\gamma_n))\right)\right) < 0$$

Thus, given the same levels of care, the firm with market power prefers to restrict production in order to raise prices. This distortion also grows larger as demand gets steeper. Larger risk in either country tends to mitigate the distortion. Since $(1-\rho_c(1-\gamma_c))(1+\rho_c(1-\gamma_c)) = 1-\rho_c^2(1-\gamma_c)^2$, the net effect of an increase in ρ_c is to shrink the distortion. Consequently, *more stringent regulation in Norway will tend to decrease production in both countries.* In essence, our problem involves two market failures that interact: underproduction and underprovision of risk reduction.

4. Multipool operators and spillovers from risk prevention

Now we generalize the model to include important characteristics of the risk management problem for international markets. We consider multiple firms that may be engaged in different combinations of production locations. For example, the Norwegian firm Marine Harvest is the largest Atlantic salmon producer, with production in Norway and Chile, plus other countries we assume are part of the fringe. AquaChile, the second-largest salmon firm, has production in Chile but not in Norway. Small producers also operate in these locations. We will consider that risk reduction occurs through collective efforts of risk reduction within a given farming location.

Although one could generalize to any number of locations, the three are sufficient for the intuition in this case. Of these three locations, one is in Norway (*n*), which has stringent regulation, and two are in Chile without regulation, distant enough that their risks are uncorrelated. Let us assume that one (*cH*) has weakly higher baseline risk than the other (*cL*), such as due to different geographical circumstances. For example, salmon lice create a production risk that varies across location. These parasites attach to exterior surfaces of the fish and typically cause slower growth and other sublethal health effects. The occurrence of salmon lice varies from fjord to fjord, and thus the risk for a large lice problem varies from location to location.

Since we want to consider the role of the production portfolio of different types of firms, let there be x_M multinationals operating in all three locations, x_D domestic companies operating in both Chilean locations, and $x_{O,l}$ small companies for each location *l* that operate only within its boundaries.

Managing disease risk is a collective action problem in each location. If an outbreak occurs, it destroys the stocks of all players in the pool; furthermore, to the extent that one company lowers the risk, it lowers that risk for all firms. The net disease risks are the following product of all risk-reduction efforts:

$$\rho_n = \rho_n^0 \prod_{i=1}^{x_M} (1-\gamma_{M,n}^i) \prod_{i=1}^{x_{O,n}} (1-\gamma_{O,n}^i)$$

$$\rho_{cH} = \rho_{cH}^0 \prod_{i=1}^{x_M} (1-\gamma_{M,cH}^i) \prod_{i=1}^{x_D} (1-\gamma_{D,cH}^i) \prod_{i=1}^{x_{O,cH}} (1-\gamma_{O,cH}^i)$$

$$\rho_{cL} = \rho_{cL}^0 \prod_{i=1}^{x_M} (1-\gamma_{M,cL}^i) \prod_{i=1}^{x_D} (1-\gamma_{D,cL}^i) \prod_{i=1}^{x_{O,cL}} (1-\gamma_{O,cL}^i)$$

Total output in each region (if the stocks survive) is

$$Q_n = \sum_{i=1}^{x_M} q_{M,n}^i + \sum_{i=1}^{x_{O,n}} q_{O,n}^i$$

$$Q_{cH} = \sum_{i=1}^{x_M} q_{M,cH}^i + \sum_{i=1}^{x_D} q_{D,cH}^i + \sum_{i=1}^{x_{O,cH}} q_{O,cH}^i$$

$$Q_{cL} = \sum_{i=1}^{x_M} q_{M,cL}^i + \sum_{i=1}^{x_D} q_{D,cL}^i + \sum_{i=1}^{x_{O,cH}} q_{O,cL}^i$$

We define the following outcomes and their probabilities:

Outcome *(notation)*	*Harvest*	*Probability*
(all) All sources are harvested successfully	$Q_n + Q_{cH} + Q_{cL}$	$z_{all} = (1-\rho_n)(1-\rho_{cH})(1-\rho_{cL})$
(noN) Norwegian stock fails	$Q_{cH} + Q_{cL}$	$z_{noN} = \rho_n(1-\rho_{cH})(1-\rho_{cL})$
(noC) Chilean stock fails	Q_n	$z_{noC} = (1-\rho_n)\rho_{cH}\rho_{cL}$
(noL) Low-risk Chilean stock fails	$Q_n + Q_{cH}$	$z_{noL} = (1-\rho_n)(1-\rho_{cH})\rho_{cL}$
(noL) High-risk Chilean stock fails	$Q_n + Q_{cL}$	$z_{noH} = (1-\rho_n)\rho_{cH}(1-\rho_{cL})$
(Honly) Only high-risk Chilean stock survives	Q_{cH}	$z_{Honly} = \rho_n(1-\rho_{cH})\rho_{cL}$
(Lonly) Only low-risk Chilean stock survives	Q_{cL}	$z_{Lonly} = \rho_n\rho_{cH}(1-\rho_{cL})$
(f) All farmed stocks fail, fringe remains	0	$z_f = \rho_n\rho_{cH}\rho_{cL}$

We can also write the expected values for output from each resource pool as

$$\begin{aligned} E\{P_L\} &= z_{all}P_{all} + z_{noN}P_{noN} + z_{noH}P_{noH} + z_{Lonly}P_{Lonly} \\ E\{P_H\} &= z_{all}P_{all} + z_{noN}P_{noN} + z_{noL}P_{noL} + z_{Honly}P_{Honly} \\ E\{P_N\} &= z_{all}P_{all} + z_{noL}P_{noL} + z_{noH}P_{noH} + z_{Nonly}P_{Nonly} \end{aligned}$$

These expected prices include the possible zero-price outcomes in the case of disease outbreaks.

Let us focus on incentives in pool *cL*. An increase in effort by firm *i* of type *j* decreases disease risk in that pool by a certain percentage: $\frac{\partial \rho_{cL}}{\partial \gamma^i_{j,cL}} = -\frac{\rho_{cL}}{1-\gamma^i_{j,cL}}$. A unit decrease in the risk of an outbreak in pool *cL* increases total expected fish output by the baseline expected loss, or $\frac{\partial E\{Q\}}{\partial \gamma^i_{j,cL}} = \frac{\rho_{cL}}{1-\gamma^i_{j,cL}} Q_{cL}$. As a consequence the overall expected price decreases in proportion to that increase in output: $\frac{\partial E\{P\}}{\partial \gamma^i_{j,cL}} = -m\frac{\rho_{cL}}{1-\gamma^i_{j,cL}} Q_{cL}$. However, the expected prices for a given pool react differently:

$$\begin{aligned} \frac{\partial E\{P_L\}}{\partial \gamma^i_{j,cL}} &= \frac{\rho_{cL}}{(1-\gamma^i_{j,cL})(1-\rho_{cL})} E\{P_L\} > 0; \\ \frac{\partial E\{P_H\}}{\partial \gamma^i_{j,cL}} &= -m\frac{\rho_{cL}}{1-\gamma^i_{j,cL}} Q_{cL}(1-\rho_{cH}) < 0; \\ \frac{\partial E\{P_N\}}{\partial \gamma^i_{j,cL}} &= -m\frac{\rho_{cL}}{1-\gamma^i_{j,cL}} Q_{cL}(1-\rho_{n}) < 0. \end{aligned}$$

Expected prices in the pool receiving more care go up (since the risk of a 0 price with an outbreak falls), while expected prices in other pools go down.

With respect to quantity adjustment in the low-risk Chilean pool, total expected global output goes up in proportion to the survival rate: $\frac{\partial E\{Q\}}{\partial q^{i}_{j,cL}} = (1-\rho_{cL})$. In turn, the expected global price falls in proportion: $\frac{\partial E\{P\}}{\partial q^{i}_{j,cL}} = -m(1-\rho_{cL})$. The expected prices for any given pool with respect to a firm's output increase in pool *cL* are all negative, but also depend on that pool's survival rate:

$$\begin{aligned}
\frac{\partial E\{P_L\}}{\partial q^{i}_{j,cL}} &= -m(1-\rho_{cL});\\
\frac{\partial E\{P_H\}}{\partial q^{i}_{j,cL}} &= -m(1-\rho_{cL})(1-\rho_{cH});\\
\frac{\partial E\{P_N\}}{\partial q^{i}_{j,cL}} &= -m(1-\rho_{cL})(1-\rho_{n}).
\end{aligned}$$

4.1 Firm Incentives

Firm *i* has expected profits of

$$\begin{aligned}
\pi^{i}_{j} = {} & E\{P_L\}q^{i}_{j,cL} + E\{P_H\}q^{i}_{j,cH} + E\{P_N\}q^{i}_{j,n}\\
& - C^{i}_{j,cL}(\gamma^{i}_{j,cL}, q^{i}_{j,cL}) - C^{i}_{j,cH}(\gamma^{i}_{j,cH}, q^{i}_{j,cH}) - C^{i}_{j,n}(\gamma^{i}_{j,n}, q^{i}_{j,n})
\end{aligned}$$

First, consider the firm *i*'s incentive for risk prevention in pool *cL*:

$$\begin{aligned}
& \frac{\partial \pi^{i}_{j,cL}}{\partial \gamma^{i}_{j,cL}} = \frac{\partial E\{P_L\}}{\partial \gamma^{i}_{j,cL}} q^{i}_{j,cL} + \frac{\partial E\{P_H\}}{\partial \gamma^{i}_{j,cL}} q_{i,cH} + \frac{\partial E\{P_N\}}{\partial \gamma^{i}_{j,cL}} q_{i,n} - \frac{\partial C^{i}_{j,cL}}{\partial \gamma^{i}_{j,cL}} = 0\\
& \quad \rightarrow \frac{\partial C^{i}_{j,cL}}{\partial \gamma^{i}_{j,cL}} = \frac{\rho_{cL} Q_{cL}}{1-\gamma^{i}_{j,cL}} \left(\frac{E\{P_L\}}{(1-\rho_{cL})} \frac{q^{i}_{j,cL}}{Q_{cL}} - m\Big((1-\rho_{cH})q^{i}_{j,cH} + (1-\rho_{n})q^{i}_{j,n}\Big)\right).
\end{aligned} \tag{5}$$

This equation reveals several aspects of the multi-firm, multi-pool care problem. First, we see that the smaller is the firm's market share within the pool, $q^i_{j,cL} / Q_{cL}$, the less incentive it has to contribute to risk reduction in the pool. In the Appendix, we show that the cumulative effects of this free-riding lead to higher disease risk as production in the pool becomes more disperse. A potential exception is if there are large production scale effects that increase the marginal cost of care.

Second, we see that for a given level of production in pool *cL*, the single-location firm (i.e., $j = O,$ with $q^i_{O,cL} > 0,$ and $q^i_{O,cH} = q^i_{O,n} = 0$) has the greatest incentive to take care. The domestic producer with multiple locations in Chile ($q^i_{D,cL} > 0$ and $q^i_{D,cH} > 0,$ but $q^i_{D,n} = 0$) has less incentive for care than the single-pool firm, since a crash in pool *cL* raises prices for pool *cH*. Similarly, the large multinational firm (with $q^i_{M,l} > 0,$ for all *l*) will consider the price effects on its Norwegian production as well, further lowering its willingness to tackle risk reduction. Of course, these cross-pool price effects can be offset in part to the extent that the multi-location firm is a bigger producer in *cL* than the single-pool firm, and that it perceives downward-sloping demand.

Furthermore, we see clearly here that regulation in the foreign country (Norway) directly affects the incentives of the multinational firm only. To the extent that Norway lowers its disease risk, the multinational firm with market power has even less incentive to provide care in this Chilean pool.

Higher baseline risks among the Chilean pools both tend to increase risk-reduction effort. Within a pool, higher risk raises the return to care. Higher risk of an outbreak in the other domestic pool (*cH*) lessen the expected gain from price compensation in the event of the loss of production in the first pool (*cL*).

With respect to output in location *cL*, the first-order conditions for firm of type *j* are

$$\begin{aligned}\frac{\partial \pi^{i}_{j,cL}}{\partial q^{i}_{j,cL}} &= E\{P_L\} + \frac{\partial E\{P_L\}}{\partial q^{i}_{j,cL}} q^{i}_{j,cL} + \frac{\partial E\{P_H\}}{\partial q^{i}_{j,cL}} q_{i,cH} + \frac{\partial E\{P_N\}}{\partial q^{i}_{j,cL}} q^{i}_{j,n} - \frac{\partial C^{i}_{j,cL}}{\partial q^{i}_{j,cL}} \\ &= E\{P_L\} - m(1-\rho_{cL})\left(q^{i}_{j,cL} + (1-\rho_{cH})q^{i}_{j,cH} + (1-\rho_n)q^{i}_{j,n}\right) - \frac{\partial C^{i}_{j,cL}}{\partial q^{i}_{j,cL}} = 0\end{aligned} \tag{6}$$

Since incremental output in any location decreases expected prices for all locations, firms with larger production have more incentive to withhold production. This is especially true for the large multinational firm, given that the price-depressing effects are felt across its global production portfolio. However, the location of production does matter: the expected price effects are strongest for the pool where output is expanding; the expected price effects for other pools are tempered by the risk of outbreaks there. Thus, for a given total output, a firm with a diverse production portfolio has somewhat less incentive to hold back in pool *cL* than a firm with all of its production in *cL*. However, lowering the risk of outbreaks in other pools increases the large firm's incentives to maintain higher prices with less production. Greater regulatory stringency in Norway thus increases the exercise of market power in Chile by multinational firms.

4.2 Optimal Policy

As a benchmark, it is useful to derive the optimal policy outcome. Global welfare is the sum of the expected total surplus across all scenarios *h*, minus the total costs of production and care across each firm *i* of type *j* operating in pool *l*:

$$
\begin{aligned}
W &= E\{U(Q)\} - \sum_{l=\{n,cL,cH\}} \sum_{j=\{M,D,O\}} \sum_{i=1}^{x_j} C^i_{j,l}(q^i_{j,l}, \gamma^i_{j,l}) \\
&= \sum_h z_h U(Q_h) - \sum_{l=\{n,cL,cH\}} \sum_{j=\{M,D,O\}} \sum_{i=1}^{x_j} C^i_{j,l}(q^i_{j,l}, \gamma^i_{j,l})
\end{aligned}
$$

where $U(Q_h) = (y + P_h)Q_h / 2 = (y - mQ_h / 2)Q_h$ is the area under the demand curve.

Maximizing welfare with respect to care (assuming that quantities are optimized as well), we have

$$
\begin{aligned}
\frac{\partial W}{\partial \gamma^i_{j,cL}} &= \sum_h \frac{\partial z_h}{\partial \gamma^i_{j,cL}} U(Q_h) - \frac{\partial C^i_{j,cL}}{\partial \gamma^i_{j,cL}} \\
&= \left(\frac{\partial E\{P_L\}}{\partial \rho_{cL}} - \frac{m}{2} Q_L \right) Q_L \frac{\partial \rho_{cL}}{\partial \gamma^i_{j,cL}} - \frac{\partial C^i_{j,cL}}{\partial \gamma^i_{j,cL}}
\end{aligned}
$$

This implies that

$$
\frac{\partial C^i_{j,cL}}{\partial \gamma^i_{j,cL}} = \frac{\rho_{cL}}{1 - \gamma^i_{j,cL}} \left(\frac{E\{P_L\}}{1 - \rho_{cL}} + \frac{m}{2} Q_{cL} \right) Q_{cL}. \tag{7}
$$

Note that optimal prevention recognizes the spillover benefits to all firms producing in pool *cL*. If the salmon price were fixed (as is assumed in many common property pool models), the optimal level of care would simply equalize marginal costs with the expected change in revenue for all production from pool *cL*. However, with downward-sloping demand (and thus concave utility), there is an added benefit from reducing the probability of low-output outcomes; hence, the welfare-maximizing contributions are more precautionary.

In other words, even in the absence of market power among cross-pool producers, and even without risk spillovers within a pool, welfare-maximizing prevention still exceeds private provision in a multipool market.

4.4 Predictions

From this model, we can generate several predictions regarding firms' behavior and market outcomes, based on equation (5):

1) The firm's expenditures on care within a pool are
    a. increasing with its production in that pool;
    b. decreasing with its production outside that pool;
    c. increasing with the baseline risk of the pool; and
    d. decreasing with lower risk (or more regulation) in other pools where the firm produces.
2) The risk of outbreaks within a given location are
    a. decreasing with greater concentration of firms within the pool;
    b. increasing with the outside production of operators within the pool; and
    c. increasing with lower risk (or more regulation) in other pools where the operators produce.

In our Norway-Chile case, then, we would expect that Chilean locations with greater Norwegian intensity have less prevention and higher risk, unless production is highly concentrated. Locations with lots of little producers can have higher risk if spillovers are a big problem, even if the portfolio factor of multipool production is not an issue. Finally, more stringent regulation in Norway exacerbates disease risk in Chilean pools where large multinational firms are significant players.

5. Market Conditions and Indirect Evidence

We do not have access to firm-specific data to formulate a direct test of our conceptual model. The main contribution of our paper is to offer the theoretical model as a contributing explanation for the Chilean disease crisis in particular, and as a new approach to the strategic behavior of multinational firms facing environmental risks and regulatory environments that vary across countries. In this section, we examine market conditions in salmon aquaculture and explore empirical anecdotes and data that indirectly support the plausibility of our theoretical model.

One interesting piece of indirect evidence for lack of care in disease prevention is based on antibiotic use. Chilean salmon farmers used 350 times more antibiotics per kilogram of salmon than Norwegian salmon farmers (Asche et al., 2010). The explanation for low antibiotic use in Norway is the use of vaccination (Asche et al., 2010). However, this can only serve as an illustration of how Chilean aquaculture in general focused more on medication than on prevention. The illness that was the main reason for the crisis, infectious salmon anemia, could at that time neither be prevented with vaccination nor be treated with antibiotics (ISA is a virus, not a bacterial disease).

Anecdotal evidence indicates that global salmon farming companies did not use their experience from Norway in the Chilean operations. Norwegian farmers had a long experience with prevention of ISA. The virus was discovered in Norwegian fish farms as early as in 1984. The disease quickly spread to several sites by the end of the 1980s and led to significant losses. The worst outbreak was in 1990, when 80 plants were affected (Asche, Guttormsen and Tveterås, 1999). Researchers immediately started to conduct epidemiological studies to identify risk factors and take measures against the continued spread. The measures included restrictions on the transport of fish, requirements for health facilities on site, the introduction of fences between cohorts, disinfection of wastewater from slaughterhouses, slaughter of sick fish, and establishment of safety zones around infected farms. The measures were effective, and in 1994 there were only two new cases of ISA-infected plants (Thorud and Håstein 2003). In Chile it seemed like most of these measures were ignored, and large concentrations of salmon smolt in inland lakes provided perfect conditions for growth of the disease (Asche et al. 2009). Indeed, perhaps the most compelling piece of evidence for lack of care on the part of multinational aquaculture companies is that the virus that infected Chile was most likely introduced via salmon embryos shipped from Norway to Chile (Vike et al., 2009).

A difficult question to answer is whether salmon aquaculture firms had sufficient market power to anticipate benefits from restricting expected supply through careless disease management in Chile. Table 1 summarizes Atlantic salmon production (in whole fish equivalents) and market shares for the 30 largest firms in 2008, the year before the disease crisis collapsed production. We report markets shares of the top 30 as well as market shares overall, assuming that 20 additional firms comparable to the 30th-largest round out the industry. In both cases, one firm stands out as having a large market share: Marine Harvest, with just over 20% of production.

To explore this question further, we next calculate Herfindahl-Hirschman indices (HHIs) of market concentration. Specifically, $HHI = \sum_{i=1}^{n} (s_i)^2$, where *n* is the number of firms, and *s* is the market share of each firm. We report HHIs calculated three ways: one at the firm level, another at the country of ownership level, and a third at the country of production level. The latter two replace firms and corresponding market shares with countries as the unit of analysis. The standard approach in the literature is to use the firm-level HHIs, whereas the strategic environmental policy literature, with a focus on setting regulations to encourage or discourage own country output, suggests that country-level measures may be more appropriate. Although our theoretical model assumes exogenous environmental policy at the country level, total production at the country level is important for understanding strategic behavior and suggests that country-level HHIs have some relevance for our setting. Table 2 reports the results. At the firm level, the industry is unconcentrated according to standard cutoffs for HHIs. It does not meet the standard for highly competitive, but the unconcentrated rating does not indicate significant concern about market power. Rather, it might indicate more concern about risk spillover effects and free riding. However, the country of ownership and country of production measures tell a very different story; both lead to an HHI that is considered high concentration. This indicates that actions taken by the Norwegian (or Chilean) governments would be expected to impact global prices and production quantities.

The industry response to the disease crisis in Chile is also important information. Figure 1 illustrates production in Norway, Chile, and the rest of the world. When production declined in Chile during the disease crisis, production in the rest of the world stayed relatively flat, but production in Norway expanded. Of course, Norwegian production was already trending up before the crisis, so the counterfactual production path may not be so different. Anecdotally, fresh salmon fillet exports from Norway to the United States (the main importer of Chilean salmon) increased 473.5% for the period of January–May 2009 relative to January–May 2008. Prices of Norwegian exports increased overall but not monotonically during the disease period (Figure 2). Also, Xie and Zhang (2014) estimate a residual demand model for the US salmon market and find that profit margins increased for whole Canadian salmon after the Chilean ISA outbreak but did not find similar evidence for Canadian salmon fillets. The Intrafish (2009) industry report summarizes the implications succinctly: “2009 will go down in the history books as one of the best financial years ever for salmon producers who managed to avoid disease and other problems.”

6. Discussion

Our conceptual model adds to the strategic environmental policy literature by introducing a simple model of a multinational firm with market power and production distributed across multiple regions. Two market failures can interact in ways that would differ if the firms were not multinational (or if the market were perfectly competitive).

The empirical evidence that we examine for the salmon aquaculture case is mixed and, at best, indirectly supportive of our theoretical model. It appears likely that firms with salmon production exclusively outside Chile benefited from the crisis through price compensation. However, overall production for Marine Harvest—the largest firm in the industry and with production in Chile, Norway, and several other countries—declined by 9% in 2009 (Intrafish 2009). The fact that the ISA virus was traced to Norway has generated conspiracy theories about deliberate introduction; we find this argument unlikely. Marine Harvest was such a large producer in Chile, it would not have incentive to induce a crash in the fish stock deliberately, even though it might have lacked sufficient incentives to take care. Moreover, Marine Harvest was the first company to report ISA problems in Chile. The companies with the greatest incentive to introduce a disease would be major competitors with little or no production in the Chilean locations subject to the outbreak. However, temporary high prices also create long-term risks, such as potential damage to the industry’s image or the possibility that consumers switch to alternative products. Industrial sabotage seems relatively rare, and there is no reason to believe it more likely in the salmon industry. More compelling are the complications of this market that tend to lead to the underprovision of care.

Whether or not Norwegian strict standards played a role in the Chilean disease crisis, there is no evidence of intent on the part of policymakers. Indeed, the primary regulations related to the management, control, and development of fish farming—the Aquaculture Act of 1985 and Act No. 54, "Act relating to measures to counteract diseases in fish and other aquatic animals," of 1997—were passed before Chile became a major market player. Those acts were amended or superseded in 2003, when the Food Production and Food Safety Act was passed; this additional stringency may have influenced the behavior of multinational players, but nothing indicates that the growing Chilean industry was a factor in the regulation. Much of the strategic environmental policy literature models standard setting with the intent of capturing rents for the home country. In our model, environmental policy is exogenous. It could be the outcome of an international strategy that we do not model, or it could be well-intentioned policy aimed only at protecting domestic environmental quality. Underlying intent has no bearing on the potential to influence outcomes in other countries.

Could the disease crisis have been avoided? Our analysis does not speak directly to this binary question. The conventional explanation for the crisis is a collective action failure precipitated by relatively weak governance in Chile, and the UN Food and Agriculture Organization (2014) continues to emphasize governance as the key to avoiding disease outbreaks in aquaculture. Even if this explanation correctly identifies the main driver of the crisis, market power and firms' behavior in response to environmental standard setting could have contributed to the problem. Our model is clear that in the absence of market power, we would see more provision of disease avoidance on the part of multinational players; it does not indicate that with perfectly competitive markets disease outbreaks would not occur. Indeed, having many competing players operating within a location can exacerbate the risk of outbreaks. Our theoretical model nests the conventional explanation for the Chilean disease outbreak—weak governance combined with the common-pool nature of disease control—but goes further to illustrate the influences of market power and multinational production. For policymakers, these are the crucial lessons of our analysis. If there is some potential upside for multinational firms of a major supply disruption (or significant price compensation), regulation must be that much stricter in the country with weaker standards. And the country with stricter standards potentially faces a trade-off in global environmental quality when it sets its own standards.

7. Other applications

These results can be considered more broadly applicable than to fish farming and seafood supplies. The necessary market conditions are (1) multinational (or multijurisdictional) producers; (2) a fair degree of market concentration; (3) world product price consequences of major risky events in a given location (which may require spillover effects across firms within a given location to have a big enough output effect); and (4) meaningful differences in regulation across jurisdictions. For managed aquatic ecosystems, the fourth criterion will nearly always be satisfied, with many possible cases satisfying the others.

Within aquaculture, the global shrimp industry has experienced sharp production declines due to outbreaks of early mortality syndrome, a disease caused by a strain of a microorganism native to estuarine ecosystems throughout the world (FAO, 2014). Regulation and enforcement certainly varies across major shrimp-producing countries. However, whether the mechanisms in our model apply to this case is unclear. Unlike salmon, shrimp farming is distributed across more countries, with many more small farms that own production. There appears to be no potential for market power at the producer (farm) level, but there may be significant concentration at the processor or wholesaler level. In this sense, the shrimp case mirrors commodity food grains, for which there are many producers but a highly concentrated processing sector.

Another example at the intersection of food production, disease, and aquatic ecosystems may be the recent disease outbreaks of listeria, cyclospora, and salmonella tied to packaged salads. These outbreaks seem to involve regional water quality issues and environmental health practices, where rules (or levels of enforcement) differ across states, counties, and regions within the United States. The packagers have substantial market shares (Fresh Express has 30% market share, Dole, 21%, and Earthbound, 6%) (Cook 2014). In this case, the contamination has a direct link to human health but otherwise has no effect on production (the opposite of the salmon case, in which production was affected with no direct effects on human health). A microbial outbreak that leads to a big recall could put substantial upward pressure on prices because of the supply disruptions. Of course, the opposite could occur as well, namely downward pressure on prices from consumer reactions.

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Table 1. Market Shares in Farmed Atlantic Salmon, 2008

Company	*Country*	*Whole fish equivalent*	*Share of top 30*	*Share assuming 20 additional size-30 firms*
Marine Harvest	Norway	398,300	0.253	0.212
Mainstream	Norway	113,700	0.072	0.060
AquaChile	Chile	113,500	0.072	0.060
Leroy	Norway	103,000	0.065	0.055
Cook Aquaculture	Canada	78,000	0.050	0.041
Salmar	Norway	59,700	0.038	0.032
Grieg Seafood	Norway	57,500	0.037	0.031
Norway Royal Salmon	Norway	54,000	0.034	0.029
Pesquera Camanchaca	Chile	48,300	0.031	0.026
Pesquera Los Fiordos	Chile	46,900	0.030	0.025
Multiexport Foods	Chile	46,800	0.030	0.025
Salmones Antarctica	Japan	33,300	0.021	0.018
Sjotroll	Norway	31,100	0.020	0.017
Cultivos Marinos Chiloe	Chile	30,000	0.019	0.016
Nordlaks	Norway	30,000	0.019	0.016
Trusal	Chile	28,100	0.018	0.015
Cultivos Yadran	Chile	27,600	0.018	0.015
Scottish Sea Farms/Norkott Havbruk	Norway	25,300	0.016	0.013
Nova Sea	Norway	24,800	0.016	0.013
Lighhouse Caledonia	Scotland	23,600	0.015	0.013
Invertec Pesuera Mar del Chiloe	Chile	22,600	0.014	0.012
Acuinova Chile/Pesca Chile	Spain	22,400	0.014	0.012
Salmones Friosur	Chile	18,800	0.012	0.010
Tassal Group	Australia	18,300	0.012	0.010
Bremnes Seashore	Norway	18,100	0.012	0.010
Salmones Pacific Star	Chile	17,600	0.011	0.009
Pesquerqa El Golfo	Chile	17,300	0.011	0.009
Alasaker Fjordbruk	Norway	17,200	0.011	0.009
Firda Management	Norway	16,000	0.010	0.008
Ventisqueros	Chile	15,500	0.010	0.008
Faroe Salmon (Brakkafrost)	Faroe Islands	15,500	0.010	0.008
Total		1,572,800		1,882,800

Source: Intrafish (2009)

Table 2. Hirfandahl-Hirschman Indices for Farmed Atlantic Salmon, 2008

Firm level		0.092		Unconcentrated
Country of ownership		0.443		High concentration
Country of production		0.335		High concentration

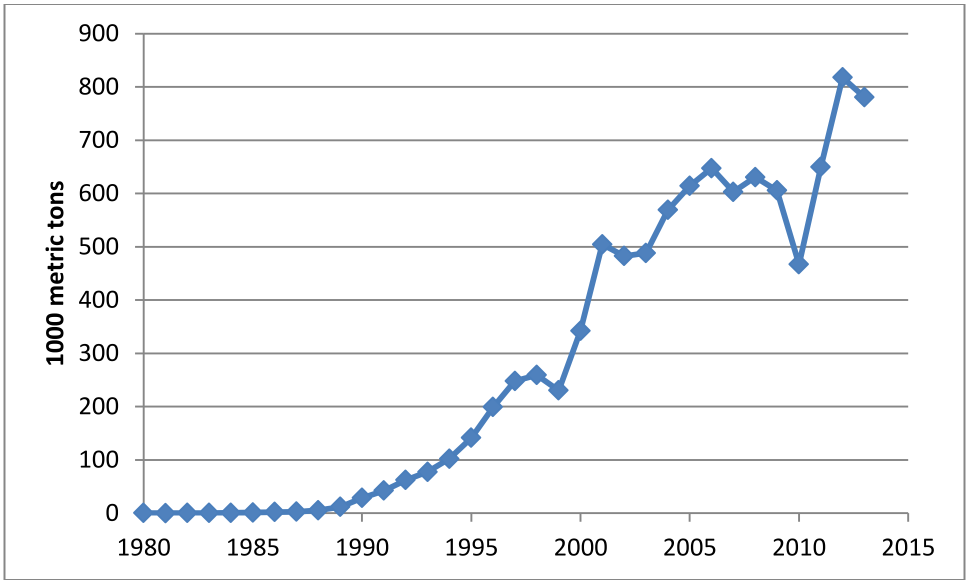

Figure 1. Chilean Production of Farmed Salmonids
Data source: FAO Fisheries and Aquaculture Department, online query
http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en

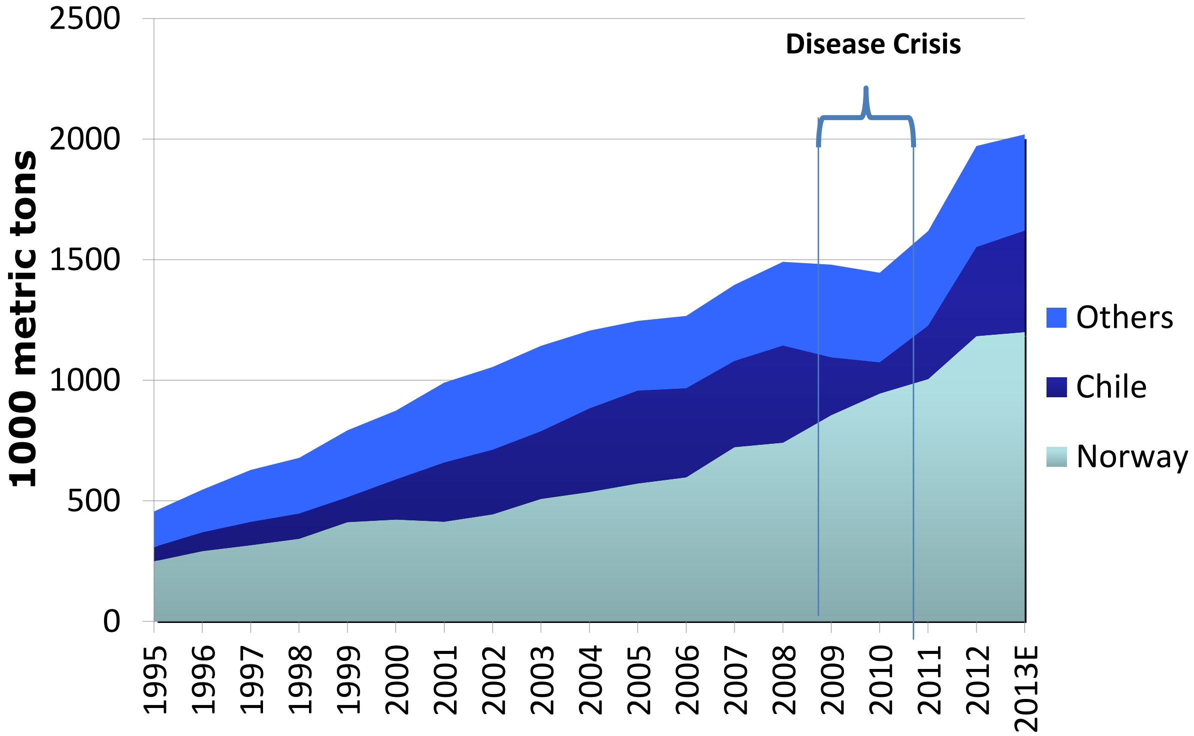

Figure 2. Atlantic Salmon *(Salmo salar)* Production, by Country

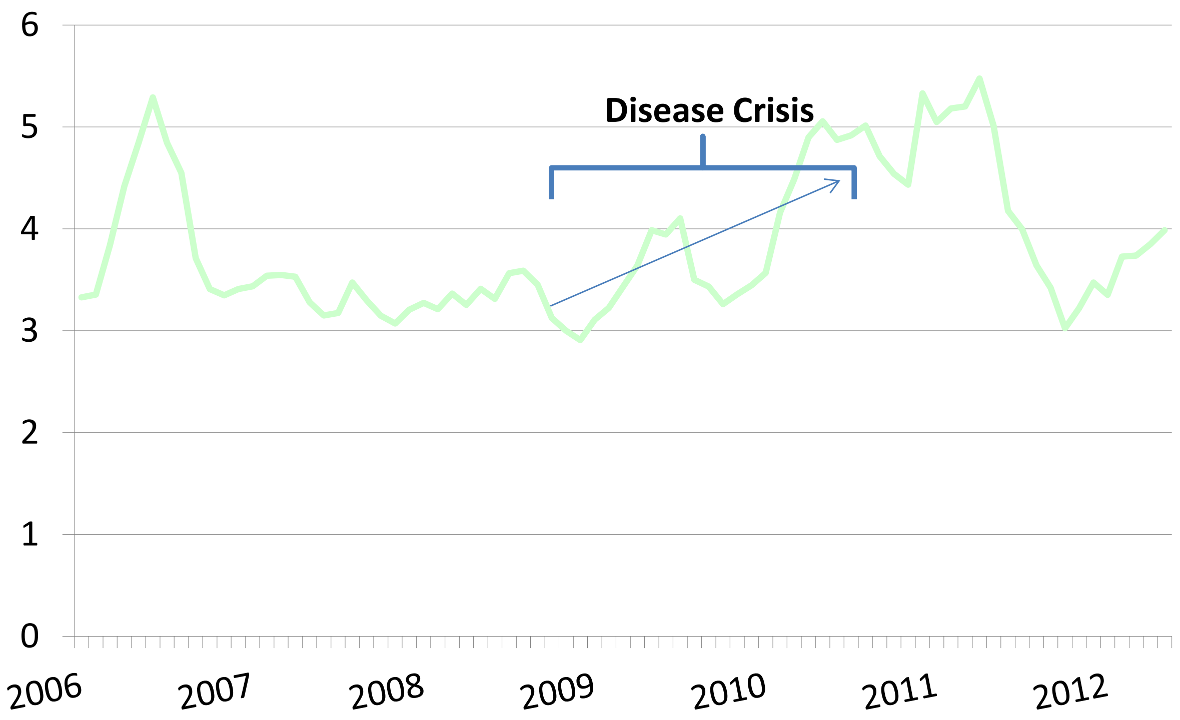

Figure 3. Norwegian Farmed Atlantic Salmon Export Prices (euros per kilogram)

Appendix

Demand function

Let $P = y_D - m_D(q_c + q_n + q_f)$ represent the total global inverse demand function. If the fringe supply is fixed (e.g., if total allowable catches are used to regulate wild-caught salmon supplies), then $y = y_D - mq_f$ and $m = m_D$. On the other hand, recent evidence indicates that the fringe supply may actually be upward sloping because industry-wide quota does not always bind (Valderamma and Anderson, 2010). In this case, let $P = y_f + m_f q_f$ be the fringe (inverse) supply function, leading to $q_f = (P - y_f)/m_f$. Consequently, we get a residual demand curve where $y = (y_D - m_D y_f)/(1 + m_D m_f)$ and $m = m_D/(1 + m_D m_f)$. Thus, the details of the fringe market would influence how we parameterize the residual demand function, but the function retains its linear properties for use in our qualitative analysis.

Concentration and disease risk

To focus on the free-rider effect, consider the case of a single pool with identical firms (so we can drop subscripts and assume that $\gamma_i = \gamma$ and $q_i / Q = 1/x$). Simplifying equation (5), we then have

$$\frac{\partial C(Q/x,\gamma)}{\partial \gamma} = \frac{\rho Q}{1-\gamma}\left(\frac{E\{P\}}{(1-\rho)}\frac{1}{x}\right).$$

Since $\rho = \rho^0(1-\gamma)^x$, we can rearrange this condition as

$$(1-\rho) = \frac{\rho^0 Q}{\frac{\partial C(Q/x,\gamma)}{\partial \gamma}} E\{P\} \frac{(1-\gamma)^{x-1}}{x}$$

Since $1-\gamma<1$, $\frac{(1-\gamma)^{x-1}}{x}$ is decreasing in *x*. Therefore, all else equal, the equilibrium survival probability is decreasing in *x*. A tempering factor is the extent to which the marginal cost of care is increasing in *q*; if large firms have higher *marginal* costs of care, they may contribute less than the cumulative contribution of multiple small firms with lower marginal costs, although that effect would have to be strong to outweigh the free-rider incentive.