Disease Risk and Market Structure in Salmon Aquaculture

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February 12, 2016

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. We specifically examine details of the infectious salmon anemia outbreak in Chile in the late 2000s, the multi-national nature of some firms operating in Chile, and the overall market structure of the salmon farming industry as motivation for our theoretical model. In the model, market structure and the regulatory environments in multiple countries interact to influence how intensively firms use aquatic ecosystems. Downward-sloping market demand 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-location risk spillovers. We find that the risk of outbreak in a given location is decreasing with greater firm concentration within the location, increasing with the outside production of operators within the location, and increasing with lower risk (or more regulation) in other locations where the operators produce. We suggest other applications of multinational risk management.

Keywords: salmon, aquaculture, disease management, market power, strategic behavior,

multinationals, industrial organization, infectious salmon anemia

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). Advances in fish farming techniques, transportation, logistics, freezing, and storage technologies as well as the globalization of the seafood trade have driven 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 greater intensification in many locations.

Aquaculture's encroachment on marine, estuarine, and freshwater ecosystems raises many environmental concerns. These include conversion of aquatic ecosystems that otherwise provide public goods, effluent from fish farming operations flowing into the surrounding aquatic environment, the potential for farmed fish to spread disease or to genetically contaminate wild populations, and the sustainability of aquaculture input use (Naylor et al., 2000; Smith et al., 2010a; Asche, Roheim, and Smith, 2015; Conrad and Rondeau, 2015). Some problems are external to the industry, while others, like disease management, may be largely internal but suffer from collective action failures. Regulatory responses to these problems can differ widely across jurisdictions.

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. 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). As selective breeding and feeding technologies improved, 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.

The salmon aquaculture industry's environmental record is mixed. Environmental concerns include nutrient runoff from net pens into the surrounding aquatic environment (both under the pens and in areas nearby); fish escapes that may genetically contaminate wild salmon populations; the sustainability of fishmeal and fish oil used in feed and derived from wild-caught forage fish populations; the spread of sea lice and other pathogens to wild populations by creating a reservoir to breed pathogens or through escapes or incidental contact with the surrounding ecosystem; and antibiotics and other pharmaceuticals in effluent from salmon farms (Naylor et al., 2000; Smith et al., 2010a; Abolofia, 2014; Asche, Roheim, and Smith, 2015). The industry has made significant progress internalizing some environmental externalities, including dramatically reducing total antibiotic use in Norway while rapidly expanding production (Asche, Guttormsen, and Tveterås, 1999). Some producers also differentiate farmed salmon with organic certification and garner a premium at the retail level (Asche et al., 2015b). Feed conversion ratios (the amount of feed needed to grow one kg of salmon) have 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 clear evidence demonstrating deleterious effects of genetic contamination of wild salmon populations, and wild salmon contamination is not an issue at all for Chile, which lacks native salmon populations. Nevertheless, 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 an outbreak of infectious salmon anemia (ISA) that began in 2007 and collapsed Atlantic salmon production in Chile by 2010. At the time, Chile was the world's second-largest producer of farmed salmon, after Norway. Although salmon production in Chile has recovered, 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, compared with a capture fishery, aquaculture producers have a high degree of control over the production process in their use of the aquatic environment (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 develop a model of multinational risk management, market structure, and asymmetric environmental regulation. The model suggests several mechanisms that lead to suboptimal disease avoidance behavior and that could contribute to disease problems like the ISA outbreak in Chile. The basic intuition is that, in the event of a major supply disruption in one location, multinational firms will receive some price compensation on production in other locations as long as market demand is not perfectly elastic. This possibility creates incentives to invest less in risk avoidance, incentives that are already dampened by the collective action nature of disease avoidance. These incentives are relevant even if the firm does not have market power in the traditional sense of being able to price above marginal cost; a disease outbreak affects the production of all firms in the location in a non-marginal way, which decreases industry supply and results in a higher equilibrium price. In essence, production risks are hedged by having production in multiple, unconnected locations, and the collective action nature of risk can be a source of market power for an otherwise small, price-taking firm. Furthermore, strict regulation in one country can further decrease incentives for a multinational firm to undertake preventive measures in the other country because the firms expect countervailing benefits in the event of an outbreak in the other country. For salmon aquaculture, Norway can be viewed as the country with strict environmental policy, relative to Chile.

In the next section, we briefly describe the Chilean disease crisis and characterize the market structure for salmon aquaculture. In Section 3, we develop a model of a multinational firm with production in two locations. We model the firm's behavior, taking country-level regulation as given. 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. Finally, Section 5 discusses the policy implications and other possible cases to which our model applies.

2. The disease crisis in Chile and salmon market conditions

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 performance, 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 pharmaceuticals 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.

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 1984. The disease 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 appeared that 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). Perhaps the most compelling 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. There is little evidence that salmon producers had market power in the traditional sense of being able to price above marginal cost consistently and globally, but there are some indications of market power that was regional and/or transitory. 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) found that the salmon market was competitive in the long run, but at the country level, Norway had market power in the short run. Jaffry, Fofana, and Murray (2003) found that the UK retail market for salmon was competitive in the short and long 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) found evidence that demand for fresh farmed salmon in world markets has become less price elastic but perhaps not enough to be considered inelastic. Another recent paper found a trend in salmon aquaculture toward larger companies but not enough market concentration for concerns about anti-competitive behavior (Asche et al. 2013). Overall, the literature suggests some potential for market power in farmed salmon, a potential concern over future market power as the industry grows larger and more concentrated, and, importantly, a market demand that is not perfectly elastic. Some downward slope to demand is consistent with the anecdotal export price increase in Norway during the period of production declines in Chile (Figure 3), suggesting at least ex post that some compensation may have occurred.

We analyze market concentration and find that, at the onset of the disease crisis, the industry was unconcentrated at the firm level despite trending toward more concentration. However, the industry is highly concentrated when viewed from the perspective of country of ownership or production. Table 1 summarizes salmon production (in whole fish equivalents) and market shares for the 30 largest firms in 2008, the year after the onset of the disease crisis. 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.

We calculate Herfindahl-Hirschman indices (HHIs) of market concentration, where $HHI = \sum_{i=1}^{n} (s_i)^2$, *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. Although the standard practice in mergers and acquisitions is to use the firm-level HHIs, the strategic environmental policy literature suggests that countries may set regulations to encourage or discourage own country output (Barrett 1994), implying that country-level measures may be more appropriate. Our theoretical model developed below assumes exogenous environmental policy at the country level, but 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. Unfortunately, we lack production data delineated by country and firm.

We also compute HHIs over time. Because we do not have a complete time series of country of ownership or country of production, we only compute the firm-level HHI. Figure 4 plots the result. The industry was never close to being concentrated or highly concentrated by this measure. However, the market concentration was trending upward prior to the disease crisis. This trend suggests the potential for market power in the future. To the extent that our theoretical model below highlights incentives for underprovision of risk avoidance, these incentives may become more pronounced in the future. Nevertheless, it appears that the disease crisis at least temporarily interrupted this trend toward greater concentration, as some of the largest firms experienced the most significant production declines.

The industry response to the disease crisis in Chile is also important information. When production declined in Chile during the disease crisis, production in the rest of the world stayed relatively flat, but production in Norway expanded (Figure 1). 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) estimated a residual demand model for the US salmon market and found 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 summarized 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."

3. Simple model of a multinational producer

Much of the basic problem can be understood by analyzing 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). Following our motivating example, we use country to distinguish places with heterogeneous regulations, but the model and incentives apply generally to regulations that vary across jurisdictions. In each location *l*, the firm faces a risk with probability ρ_l that its stock will be decimated by a disease outbreak, but it can undertake measures to lessen this risk by share γ_l , relative to an externally determined baseline probability, ρ_l^0; i.e., $\rho_l(\gamma_l) = \rho_l^0(1-\gamma_l)$. Total costs of planned production are convex in both the quantity of production (in this case of fish / biomass) q_l , and the degree of risk reduction: $C(q_l, \gamma_l)$, where $C_q(q_l, \gamma_l) > 0, C_\gamma(q_l, \gamma_l) > 0, C_{qq}(q_l, \gamma_l) > 0,$ and $C_{\gamma\gamma}(q_l, \gamma_l) > 0.$ We do not impose an assumption as to how production scale affects the marginal cost of care.

The following list defines the four possible outcomes and their probabilities, where *h* indexes the possible outcomes $(h = \{b, c, n, f\})$, z_i gives the probability of that outcome, and Q_h indicates the total successfully farmed harvest:

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

We assume the firm faces a downward-sloping linear inverse 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). The terms *y* and *m* are the intercept and slope respectively of this inverse residual demand curve. Based on the four harvest outcomes, the corresponding price outcomes are $P_h = y - mQ_h$, or

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

Firms compete by committing to a given quantity, as in Cournot competition. This assumption seems realistic for salmon production, where quantity decisions are made two to three years in advance of the harvest, creating a capacity commitment for any subsequent price competition (Tirole 1988, p. 217). Thus, Cournot-style quantity competition unfolds at the time that stocking decisions are made.

The expected value of a unit of planned farmed salmon production from a given location (V_l) is

$$\begin{aligned} E\{V_c\} &= z_b P_b + z_c P_c \\ E\{V_n\} &= z_b P_b + z_n P_n \end{aligned}$$

These expected values are prices associated with possible market outcomes weighted by probabilities of these outcomes.

3.1 Incentives with market power

A large firm with market power recognizes that its behavior can influence market prices as well as a given stock's survival probability. Note that, in this context, existence of a downward-sloping market demand and the potential for a firm-level quantity shock to be large enough to influence the market price are sufficient for a firm to have market power. The large firm has expected profits of

$$\pi = E\{V_C\}q_c + E\{V_N\}q_n - C_c(\gamma_c, q_c) - C_n(\gamma_n, q_n)$$

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

$$\begin{aligned}\frac{\partial \pi}{\partial \gamma_c} &= \frac{\partial E\{V_c\}}{\partial \gamma_c} q_c + \frac{\partial E\{V_n\}}{\partial \gamma_c} q_n - \partial C_c / \partial \gamma_c \\ &= \frac{\rho_c^0}{1-\rho_c} E\{V_c\} q_c + \rho_c^0 (1-\rho_n)(P_{all} - P_n) q_n - \partial C_c / \partial \gamma_c = 0;\end{aligned}$$

and

$$\begin{aligned}\frac{\partial \pi}{\partial q_c} &= E\{V_c\} + \frac{\partial E\{V_c\}}{\partial q_c} q_c + \frac{\partial E\{V_n\}}{\partial q_c} q_n - \partial C_c / \partial q_c \\ &= E\{V_c\} - \partial C_c / \partial q_c - m(z_b + z_c) q_c - m z_b q_n = 0.\end{aligned}$$

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

Substituting and rearranging, we get

$$\frac{\partial C_c / \partial \gamma_c |_{MP}}{\rho_c^0 q_c} = \frac{E\{V_c\}}{1-\rho_c} - (1-\rho_n) m q_n; \qquad (1)$$

$$\partial C_c / \partial q_c |_{MP} = E\{V_c\} - m(1-\rho_c)(q_c + (1-\rho_n) q_n). \qquad (2)$$

The decision in (1) is to equalize the marginal cost of risk avoidance in Chile (per unit of expected output loss) with the increase in the expected value of the Chilean stock, conditional on survival, less the decrease in expected revenues in Norway. Similarly, the quantity decision in (2) weighs the marginal cost of additional planned production in Chile against the additional expected value of that production less the expected decrease in revenues for both locations due to lower prices. Note that the latter two effects would not be present for a price-taker, as we see next.

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 in each location, $E\{P_l\}$. The price-taking (*PT*) firm has the following expected profits function:

$$\pi = E\{P_c\}(1-\rho_c^0(1-\gamma_c))q_c + E\{P_n\}(1-\rho_n^0(1-\gamma_n))q_n - C_c(\gamma_c, q_c) - C_n(\gamma_n, q_n)$$

In this case, the first-order conditions are simply

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

Assuming the firm has rational expectations, the expected equilibrium price will equal the expected value of output from the location, conditional on that location's stock surviving: $E\{P_l\} = E\{V_l\}/(1-\rho_c)$.[1] Substituting and rearranging, we have

$$\frac{\partial C_c / \partial \gamma_c |_{PT}}{\rho_c^0 q_c} = E\{P_c\} = \frac{E\{V_c\}}{(1-\rho_c)}; \quad (3)$$

$$\partial C_c / \partial q_c |_{PT} = E\{P_c\}(1-\rho_c^0(1-\gamma_c)) = E\{V_c\}. \quad (4)$$

The marginal cost of increasing the survival probability per unit of production equals the expected price. The marginal cost of production equals the expected value (the price times the survival probability). In essence, the competitive firm is a price-taker in the output market and does not expect that it can influence the survival probability of the production of other firms in

[1] In the next section, we will derive this result from the optimal policy problem.

its location. However, it can influence the survival probability of its own production, and it does incorporate production survival probabilities of other firms in computing its expected price.

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 (1) and (3), all else equal, is (after simplifying)

$$\frac{(\partial C_c / \partial \gamma_c)|_{MP} - (\partial C_c / \partial \gamma_c)|_{PT}}{\rho_c q_c} = -m(1-\rho_n^0(1-\gamma_n))q_n < 0.$$

The firm with market power has a lower equilibrium marginal cost of care. Because marginal cost is increasing and convex in the amount of care a firm exerts, 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 outbreak likelihood in that country's operations; however, it is decreasing with the outbreak likelihood 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 (2) and (4), we have

$$\partial C_c / \partial q_c |_{MP} - \partial C_c / \partial q_c |_{PT} = -m(1-\rho_c^0(1-\gamma_c))(q_c + (1-\rho_n^0(1-\gamma_n))q_n) < 0$$

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. A higher probability of outbreak in either country tends to mitigate the distortion. Consequently, *more stringent regulation in Norway will tend to decrease planned production in both countries.* In other words, part of the expected increase in output from lower risk in Norway will be tempered by lower stocking levels in both countries. In essence, our problem involves two market failures that interact: underproduction and underprovision of risk reduction.

4. Multi-region operators and spillovers from risk prevention

Now we generalize the model to include important characteristics of the risk management problem for international markets. First, 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, one of the next three largest salmon firms (depending on the year), has production in multiple locations in Chile but not in Norway. Small producers also operate in individual locations. Second, we consider that the likelihood of disease outbreak reflects collective efforts of risk reduction within a given farming location. Third, we consider that baseline risk may be influenced by the total production in a given location, as higher stocking densities increase the likelihood of disease transmission. With many firms competing, the collective action nature of risk management, coupled with the collective nature of the risky outcome of stock failure, means that small firms still exert a kind of market power. Although the loss of an individual firm's production may not have a large effect on market prices, the loss of the entire stock at a given location can move global prices, and all firms have an influence on that risk.

Although one could generalize to any number of locations, 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 with less stringent regulation, distant enough that their risks are assumed uncorrelated.[2] Let us assume that one has weakly higher baseline risk than the other, such as due to different geographical circumstances. So, *cH* represents the Chilean location with higher baseline risk, while *cL* represents the Chilean location with lower baseline risk.

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 location; furthermore, to the extent that one company raises or lowers the likelihood of an outbreak, it does so for all firms. Collective baseline probabilities for disease outbreaks are also assumed to be a nondecreasing function of total production in each location: i.e., $\rho_l^0(Q_l)$, where $Q_l = \sum_{i=1}^{x_M} q_{M,l}^i + \sum_{i=1}^{x_D} q_{D,l}^i + \sum_{i=1}^{x_{O,cH}} q_{O,l}^i$ for Chilean locations and $Q_n = \sum_{i=1}^{x_M} q_{M,n}^i + \sum_{i=1}^{x_{O,n}} q_{O,n}^i$ in Norway. The net disease risks are the following product of all risk-reduction efforts and the baseline collective likelihood:

[2] 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.

$$
\begin{aligned}
\rho_n &= \rho_n^0(Q_n)\prod_{i=1}^{x_M}(1-\gamma^i_{M,n})\prod_{i=1}^{x_{O,n}}(1-\gamma^i_{O,n}) \\
\rho_{cH} &= \rho_{cH}^0(Q_{cH})\prod_{i=1}^{x_M}(1-\gamma^i_{M,cH})\prod_{i=1}^{x_D}(1-\gamma^i_{D,cH})\prod_{i=1}^{x_{O,cH}}(1-\gamma^i_{O,cH}) \\
\rho_{cL} &= \rho_{cL}^0(Q_{cL})\prod_{i=1}^{x_M}(1-\gamma^i_{M,cL})\prod_{i=1}^{x_D}(1-\gamma^i_{D,cL})\prod_{i=1}^{x_{O,cL}}(1-\gamma^i_{O,cL})
\end{aligned}
$$

We define the following outcomes and their probabilities (z's):

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	$Q_n + Q_{cH}$	$z_{noL} = (1-\rho_n)(1-\rho_{cH})\rho_{cL}$
(noH) 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	0	$z_f = \rho_n\rho_{cH}\rho_{cL}$

We can also write the values that can be expected to be earned from production in each resource location as

$$
\begin{aligned}
E\{V_L\} &= z_{all}P_{all} + z_{noN}P_{noN} + z_{noH}P_{noH} + z_{Lonly}P_{Lonly} \\
E\{V_H\} &= z_{all}P_{all} + z_{noN}P_{noN} + z_{noL}P_{noL} + z_{Honly}P_{Honly} \\
E\{V_N\} &= z_{all}P_{all} + z_{noL}P_{noL} + z_{noH}P_{noH} + z_{Nonly}P_{Nonly}
\end{aligned}
$$

These location-specific values incorporate the possible price outcomes—including zero-quantity outcomes in the case of disease outbreaks—as well as the probability of survival. As such, they differ from the expected price for surviving stocks, as described earlier.

Let us focus on incentives in location *cL*. A unit increase in the likelihood of an outbreak in location *cL* decreases total expected fish output; as a consequence the expected value of surviving harvests increases in proportion to that decrease in output. A change in the probability of survival in location *cL* changes the expected value of stocks in each location in the following manner:

$$
\begin{aligned}
\frac{\partial E\{V_L\}}{\partial \rho_{cL}} &= -(1-\rho_n)(1-\rho_{cH})P_{all} - \rho_n(1-\rho_{cH})P_{noN} - (1-\rho_n)\rho_{cH}P_{noH} - \rho_n\rho_{cH}P_{Lonly} \\
&= -\frac{E\{V_L\}}{(1-\rho_{cL})} < 0 \\
\frac{\partial E\{V_H\}}{\partial \rho_{cL}} &= (1-\rho_n)(1-\rho_{cH})(P_{noL} - P_{all}) + \rho_n(1-\rho_{cH})(P_{Honly} - P_{noN}) \\
&= (1-\rho_{cH})mQ_{cL} > 0 \\
\frac{\partial E\{V_N\}}{\partial \rho_{cL}} &= (1-\rho_n)(1-\rho_{cH})(P_{noL} - P_{all}) - \rho_{cH}(1-\rho_n)(P_{Nonly} - P_{noH}) \\
&= (1-\rho_n)mQ_{cL} > 0
\end{aligned}
$$

Thus, a higher outbreak probability in *cL* lowers the expected value of production in that location but raises the expected values of production in the other locations. These effects are unambiguous, since prices for the remaining locations are always higher in the absence of surviving output in *cL* (and the marginal effects on the probabilities are equal, given the combination of other surviving locations, but of opposite sign depending on whether output in the *cL* location survives). These results do not hinge on firm-level market power; they only require the collective action nature of risk reduction and a downward-sloping market demand.

An increase in effort by firm *i* of type *j* decreases the likelihood of a disease outbreak in that location by a certain percentage: $\partial \rho_{cL} / \partial \gamma^i_{j,cL} = -\rho^0_{cL}$. Thus, the changes in expected values due to incremental effort in location *cL* are

$$\frac{\partial E\{V_L\}}{\partial \gamma^i_{j,cL}} = \frac{\rho^0_{cL}}{(1-\rho_{cL})} E\{V_L\} > 0;$$
$$\frac{\partial E\{V_H\}}{\partial \gamma^i_{j,cL}} = -m\rho^0_{cL} Q_{cL}(1-\rho_{cH}) < 0;$$
$$\frac{\partial E\{V_N\}}{\partial \gamma^i_{j,cL}} = -m\rho^0_{cL} Q_{cL}(1-\rho_n) < 0.$$

Expected values for the location receiving more care go up (since the odds of a zero return with an outbreak falls), while expected values of other locations go down (since a larger expected production lowers expected prices).

With respect to quantity adjustment in the low-risk Chilean location, as long as demand is downward sloping, additional output will decrease prices in all states in which that stock survives. An increase in a firm's production in *cL* raises expected global output; in turn, expected global prices fall in proportion. Not only do production decisions affect price outcomes directly, but they also influence risk, as $\frac{\partial \rho_{cL}}{\partial Q_{cL}} = \frac{\partial \rho^0_{cL}}{\partial Q_{cL}} \frac{\rho_{cL}}{\rho^0_{cL}}$. Let Ω_l be the set of situations in which stock *l* survives. The changes in expected values for output in each location with respect to a firm's output increase in location *cL* are thus the sum of the price-related changes and the risk-related changes:

$$\frac{\partial E\{V_l\}}{\partial q^i_{j,cL}} = \sum_{h\in\Omega_l} z_h \frac{\partial P_h}{\partial Q_{cL}} + \frac{\partial E\{V_l\}}{\partial \rho_{cL}} \frac{\partial \rho_{cL}}{\partial Q_{cL}}$$

Substituting and simplifying, we see that

$$\frac{\partial E\{V_L\}}{\partial q^i_{j,cL}} = -m(1-\rho_{cL}) - \eta_{cL}\frac{\rho_{cL}}{Q_{cL}}\frac{E\{V_L\}}{(1-\rho_{cL})} < 0;$$
$$\frac{\partial E\{V_H\}}{\partial q^i_{j,cL}} = -m(1-\rho_{cH})(1-\rho_{cL}(1+\eta_{cL}));$$
$$\frac{\partial E\{V_N\}}{\partial q^i_{j,cL}} = -m(1-\rho_n)(1-\rho_{cL}(1+\eta_{cL})).$$

where $\eta_{cL} = \dfrac{\partial\rho^0_{cL} / \rho^0_{cL}}{\partial Q_{cL} / Q_{cL}}$ is the elasticity of the baseline outbreak probability with respect to total output, and $(1-\rho^0_{cL}(1+\eta_{cL}))$ is the change in expected surviving quantity from an incremental change in total stocking ($\partial\{(1-\rho^0_{cL})Q_{cL}\}/\partial Q_{cL}$).

The price-related changes in expected values for any given location with respect to a firm's output increase in location *cL* are all negative (but also depend on that location's survival rate). That is, an increase in planned production for *cL* will lower the price for all the locations to the extent that it increases expected quantity. But an increase in planned production in *cL* also increases the risk of an outbreak in *cL*, and that effect lowers the expected output from *cL* and raises the expected price for all other locations. Thus, the risk-related changes in values are positive for the other locations. The net effects for the other locations are thus ambiguous; they will be negative as long as the outbreak risk elasticity—or the overall probability of failure—is not so large as to imply that further stocking decreases expected output in that location.

4.1 Firm incentives

Firm *i* has expected profits of

$$\pi^i_j = E\{V_L\}q^i_{j,cL} + E\{V_H\}q^i_{j,cH} + E\{V_N\}q^i_{j,n} - C^i_{j,cL}(\gamma^i_{j,cL}, q^i_{j,cL}) - C^i_{j,cH}(\gamma^i_{j,cH}, q^i_{j,cH}) - C^i_{j,n}(\gamma^i_{j,n}, q^i_{j,n})$$

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

$$\frac{\partial \pi^{i}_{j,cL}}{\partial \gamma^{i}_{j,cL}} = \frac{\partial E\{V_L\}}{\partial \gamma^{i}_{j,cL}} q^{i}_{j,cL} + \frac{\partial E\{V_H\}}{\partial \gamma^{i}_{j,cL}} q^{i}_{j,cH} + \frac{\partial E\{V_N\}}{\partial \gamma^{i}_{j,cL}} q^{i}_{j,n} - \frac{\partial C^{i}_{j,cL}}{\partial \gamma^{i}_{j,cL}} = 0,$$

which implies

$$\frac{\partial C^{i}_{j,cL}}{\partial \gamma^{i}_{j,cL}} = \rho^{0}_{cL} Q_{cL} \left(\frac{E\{V_L\}}{(1-\rho_{cL})} \frac{q^{i}_{j,cL}}{Q_{cL}} - m\Big((1-\rho_{cH}) q^{i}_{j,cH} + (1-\rho_{n}) q^{i}_{j,n}\Big) \right). \qquad (5)$$

This equation reveals several aspects of the multi-firm, multi-region care problem. First, the smaller is the firm's market share within the location, $q^{i}_{j,cL} / Q_{cL}$, the less incentive it has to contribute to risk reduction in that location. In the Appendix, we show that the cumulative effects of this free-riding lead to a higher likelihood of disease outbreak as production in the location becomes more dispersed. A potential exception is if there are large production scale effects that increase the marginal cost of care. Thus, market power within a region, *ceteris paribus*, decreases the likelihood of a disease outbreak in a similar spirit to how market power can ameliorate certain environmental externalities (Buchanan 1969).

Second, for a given level of production in location *cL*, the single-location firm (i.e., $i = O,$ 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-location firm, since a crash in location *cL* raises prices for location *cH*. Similarly, the 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-location price effects can be offset in part to the extent that the multi-location firm is a bigger producer in *cL* than the single-location firm. However, it is important to note that these cross-location effects are not dependent on market share in *cL*: the collective nature of risk management essentially gives even small firms market power over global prices, since they contribute equally to collective risk, and an outbreak that destroys production throughout the location will have an impact on global prices.

Third, 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 has even less incentive to provide care in this Chilean location. Note that other firm incentives are still affected indirectly by the Norwegian regulation, because it influences the expected global price.

Higher baseline outbreak probabilities among the Chilean locations both tend to increase risk-reduction effort. Within a location, a higher probability raises the return to care. The greater the probability of an outbreak in the other domestic location (*cH*), the less is the expected gain from price compensation in the event of the loss of production in the first location (*cL*).

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

$$\frac{\partial \pi^{i}_{j,cL}}{\partial q^{i}_{j,cL}} = E\{V_L\} - \frac{\partial C^{i}_{j,cL}}{\partial q^{i}_{j,cL}} + \frac{\partial E\{V_L\}}{\partial q^{i}_{j,cL}} q^{i}_{j,cL} + \frac{\partial E\{V_H\}}{\partial q^{i}_{j,cL}} q_{i,cH} + \frac{\partial E\{V_N\}}{\partial q^{i}_{j,cL}} q^{i}_{j,n} = 0$$

or

$$\begin{aligned} \frac{\partial C^{i}_{j,cL}}{\partial q^{i}_{j,cL}} = {} & E\{V_L\} - m(1-\rho_{cL})\left(q^{i}_{j,cL} + (1-\rho_{cH})q^{i}_{j,cH} + (1-\rho_{n})q^{i}_{j,n}\right) \\ & -\eta_{cL}\rho_{cL}\left(\frac{E\{V_L\}}{(1-\rho_{cL})}\frac{q^{i}_{j,cL}}{Q_{cL}} - m\left((1-\rho_{cH})q^{i}_{j,cH} + (1-\rho_{n})q^{i}_{j,n}\right)\right) \end{aligned} \qquad (6)$$

These marginal conditions will be used in the next section to understand firm incentives, but they also offer important interpretations about the effects of production decisions on prices and risk.

First, consider the price-related effects (the first line in Equation (6), after the expected value of additional production). Since incremental increases in expected 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: when a firm increases production in one location, the expected price effect is strongest in that location because the production decision has a direct effect on expected output. The expected price effects for other locations are only relevant when those stocks survive, in addition to the *cL* stock surviving. Thus, for a given total level of planned production, a firm with a diverse production portfolio has somewhat less incentive to hold back in location *cL* than a firm with all of its production in *cL*. However, lowering the risk of outbreaks in other locations increases the large firm's incentives to maintain higher prices with less production. Greater regulatory stringency in Norway can thus increase the exercise of market power in Chile by multinational firms.

Next, consider the risk-related effects of production (the second line in Equation (6)). If $\eta_{cL} > 0$, the larger the local market share, the greater the incentive to hold back production as a risk-reduction measure. By contrast, producers active in other locations will be more willing to increase production in *cL*, despite—or because of—the increased likelihood of outbreak, since that raises the probability of higher prices for their other stocks. These results are essentially the same as those regarding risk prevention measures, since here restricting production can be considered another type of prevention activity.

Thus, market power through collective risk can be a friend or foe. If stocking density does not increase the probability of an outbreak, market power necessarily implies underprovision of output. If collective stocking density does increase risk, then this underprovision of output may help contain risks of outbreaks. That is, the firm's desire to withhold production will reduce the probability of a major outbreak and associated major supply disruption. However, if the odds of an outbreak are too sensitive to production, say in a high-risk location, then firms with large amounts of production in other locations may be content to overproduce in the high-risk location (and underprovide risk reduction through production restraint).

4.2 Optimal provision of care

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

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

where $U(Q_h) = (y + P_h)Q_h / 2 = (y - mQ_h / 2)Q_h = P_h Q_h + mQ_h^{\,2} / 2$ is the area under the demand curve (gross consumer surplus). Expected utility can be written as

$$E\{U(Q)\} = \sum_l E\{V_l\}Q_l + \frac{m}{2} E\{Q^2\}$$

Thus, expected utility has one component reflecting the expected revenues from salmon production and an extra term reflecting consumer surplus.[3]

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

$$\frac{\partial W}{\partial \gamma^{i}_{j,cL}} = \left(\frac{\partial E\{V_L\}}{\partial \rho_{cL}} Q_{cL} + \frac{\partial E\{V_H\}}{\partial \rho_{cL}} Q_{cH} + \frac{\partial E\{V_N\}}{\partial \rho_{cL}} Q_n + \frac{m}{2} \frac{\partial E\{Q^2\}}{\partial \rho_{cL}} \right) \frac{\partial \rho_{cL}}{\partial \gamma^{i}_{j,cL}} - \frac{\partial C^{i}_{j,cL}}{\partial \gamma^{i}_{j,cL}}$$

Substituting and simplifying, we see that at the optimal level of care,

$$\frac{\partial C^{i}_{j,cL}}{\partial \gamma^{i}_{j,cL}} = \rho^{0}_{cL} Q_{cL} \left(\frac{E\{V_L\}}{(1-\rho_{cL})} + \frac{m}{2} Q_{cL} \right). \qquad (7)$$

Note that optimal prevention recognizes the spillover benefits to all firms producing in location *cL*. If the salmon price were fixed (as is assumed in many common property location models), the optimal level of care would simply equalize marginal costs with the expected change in revenue for all production from location *cL*. However, with downward-sloping demand (and thus concave utility), there is an added benefit to consumers from reducing the probability of low-output outcomes, which tends to make the welfare-maximizing contributions more precautionary. Meanwhile, the spillover effects to production in other locations are offset by equal and opposite effects on consumer surplus and thus do not factor into the welfare maximization.

---

[3] Note that $\sum_h z_h P_h Q_h = \sum_l E\{V_l\} Q_l$. Furthermore, $E\{Q^2\} = \sum_h z_h {Q_h}^2$, $\partial E\{Q^2\} / \partial \rho_{cL} = -Q_{cL} \left(Q_{cL} + 2\left(Q_{cH}(1-\rho_{cH}) + Q_n(1-\rho_n) \right) \right)$ and $\partial E\{Q^2\} / \partial q_{cL} = 2(1-\rho_{cL}) \left(Q_{cL} + Q_{cH}(1-\rho_{cH}) + Q_n(1-\rho_n) \right) + (\partial E\{Q^2\} / \partial \rho_{cL}) \partial \rho_{cL} / dQ_{cL}$.

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

With respect to output, optimal production solves

$$\frac{\partial W}{\partial q^{i}_{j,cL}} = E\{V_L\} - \frac{\partial C^{i}_{j,cL}}{\partial q^{i}_{j,cL}} + \frac{m}{2}\frac{\partial E\{Q^2\}}{\partial q^{i}_{j,cL}} + \frac{\partial E\{V_L\}}{\partial q^{i}_{j,cL}} Q_{cL} + \frac{\partial E\{V_H\}}{\partial q^{i}_{j,cL}} Q_{cH} + \frac{\partial E\{V_N\}}{\partial q^{i}_{j,cL}} Q_n = 0$$

which implies

$$\frac{\partial C^{i}_{j,cL}}{\partial q^{i}_{j,cL}} = E\{V_L\} - \eta_{cL}\rho_{cL}\left(\frac{E\{V_L\}}{(1-\rho_{cL})} + \frac{m}{2}Q_{cL}\right) \tag{8}$$

Thus, the welfare-maximizing level of production for a firm in location *cL* equalizes marginal costs with the expected value of output from that location, less the risk spillover effects for the entire location and for consumers.

4.3 Predictions

Derivation of the optimal policy reveals that there are multiple channels through which risk reduction will be provided in this setting. Market power is not a necessary condition for the underprovision of care, and as a result, market power is not necessary for expected production to be below the social optimum. As such, empirical findings of competition in the output market do not imply that industry behavior mimics the social optimum. Nevertheless, market power can exacerbate distortions.

For future empirical work, our model generates several testable predictions regarding firms' behavior and market outcomes, based on equation (5):

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

With firm-, location-, and country-specific data on stocking densities, production, and biosecurity measures, these predictions would be empirically testable. In our Norway-Chile case, the model implies that Chilean locations with greater intensity of Norwegian multinationals would have less prevention and higher risk, assuming low concentration within each location. With high concentration in a location, predictions are less sharp because market power leads to countervailing effects on care. Locations with many small producers can have higher risk if spillovers are a big problem, even if the portfolio factor of multi-location production is not an issue. Finally, more stringent regulation in Norway exacerbates disease risk in Chilean locations where large multinational firms are significant players. This last prediction may not be empirically identifiable in our particular case but may motivate empirical work in other settings with multiple changes in regulations and measurable risks.

5. Discussion

Our theoretical model provides three key insights about disease risk, market structure, and environmental regulation. First, with multinational firms, regulation in one country can influence risk management decisions in other countries. Specifically, a tighter standard in one country can induce less care in the other country. The necessary conditions for this to occur are that market demand has some downward slope and there is potential for a supply disruption to move the market price. Second, traditional measures of competitive output markets are not sufficient to rule out market power that manifests through disease risk management. Even small firms have the potential to influence global prices if their lack of care contributes to a disease outbreak and major supply disruption. Third, market power is a double-edged sword. Within a location, market concentration increases incentives to avoid disease by reducing the free rider problem in disease avoidance. But across countries, a firm with greater market power can use the highly regulated market as a hedge and has less incentive to avoid disease in the less regulated market. Firms that are not multinational do not have this hedge and thus have greater incentives to avoid disease. Taken together, these insights strongly suggest that the market is unlikely to provide optimal disease risk management.

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 had an 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. Although we are unable to test the mechanisms empirically in this paper, the complications of this market that incentivize underprovision of care seem more compelling than conspiracy theories.

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, namely that companies lobbied for and demanded strict regulation in Norway. Or, it could simply be well-intentioned policy aimed only at protecting domestic environmental quality. Either way, 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 to this question directly. 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 structure and firms' behavior in response to environmental standard setting could have contributed to the problem. Our model is clear that in the absence of downward-sloping market demand, we would see more provision of disease avoidance on the part of multinational players; it does not indicate that with perfectly elastic demand disease outbreaks would not occur. Indeed, having many competing players operating within a location can exacerbate the risk of outbreaks, so there are features of perfect competition that also contribute to collective action risk problems. Our theoretical model nests the conventional explanation for the Chilean disease outbreak—weak governance combined with the collective action 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.

These results can be considered more broadly applicable than to just fish farming and seafood supplies. The necessary market conditions are (1) multinational (or multi-region) producers; (2) 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 (3) meaningful differences in regulation across jurisdictions. The relevance is heightened for (4) industries with a high degree of market concentration. For managed aquatic ecosystems, the third 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. The shrimp case also may simply represent the importance of the collective action nature of disease risk in unconcentrated markets. As our model illustrates, provision of care is decreasing in a firm's market share within a region.

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. 2008 Market Shares in Farmed Salmon, including Atlantic salmon, Pacific salmon, and salmon trout

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 Salmon, 2008

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

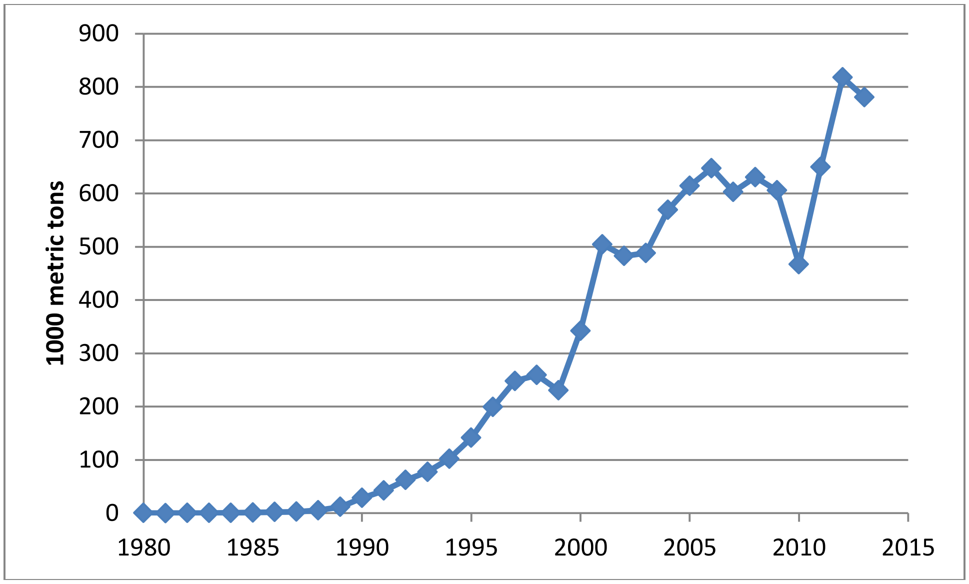

Figure 1. Chilean Production of Farmed Salmonids
Includes Atlantic salmon, Pacific salmon, and salmon trout.
Data source: FAO Fisheries and Aquaculture Department, online query
http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en

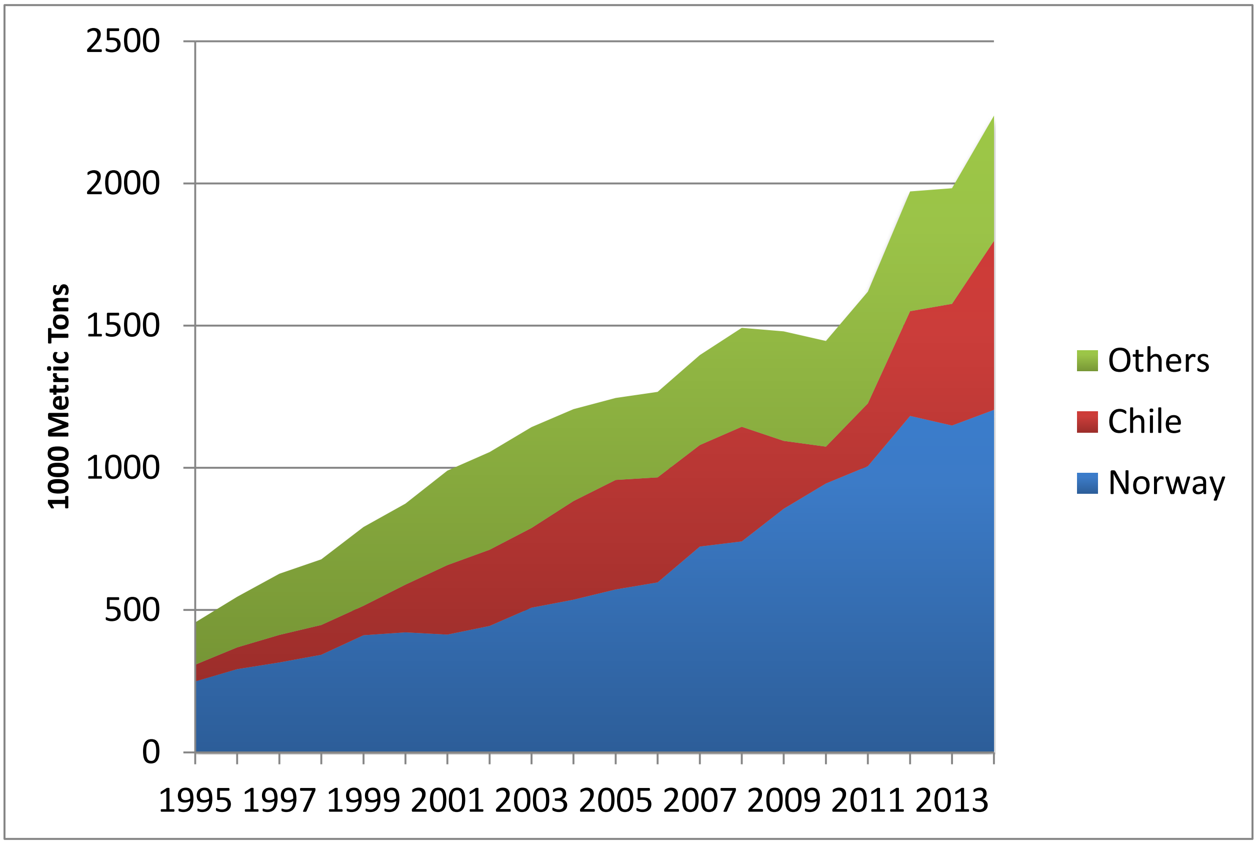

Figure 2. Atlantic Salmon *(Salmo salar)* Production, by Country

The disease crisis in Chile that began in 2007 interrupted the upward trend in global Atlantic salmon supplies after 2008. The trend resumed when Chile returned to historic levels of production in 2012.
Data source: Kontali, FAO, and the Norwegian Fisheries Directorate

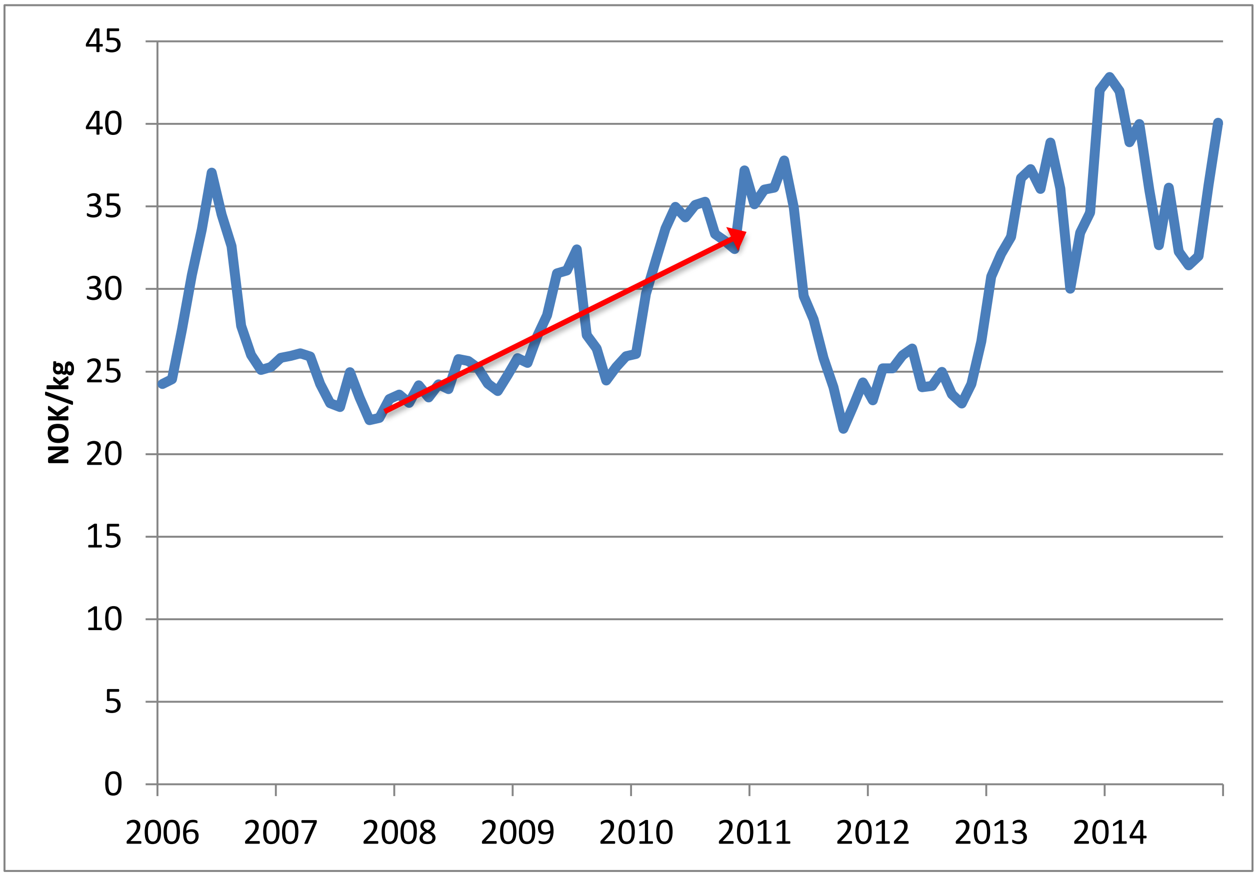

Figure 3. Norwegian Farmed Atlantic Salmon Export Prices (Norwegian Kroner per kilogram)

Export prices are volatile throughout the time series but appeared to trend upward during the disease crisis.
Data source: Fishpool

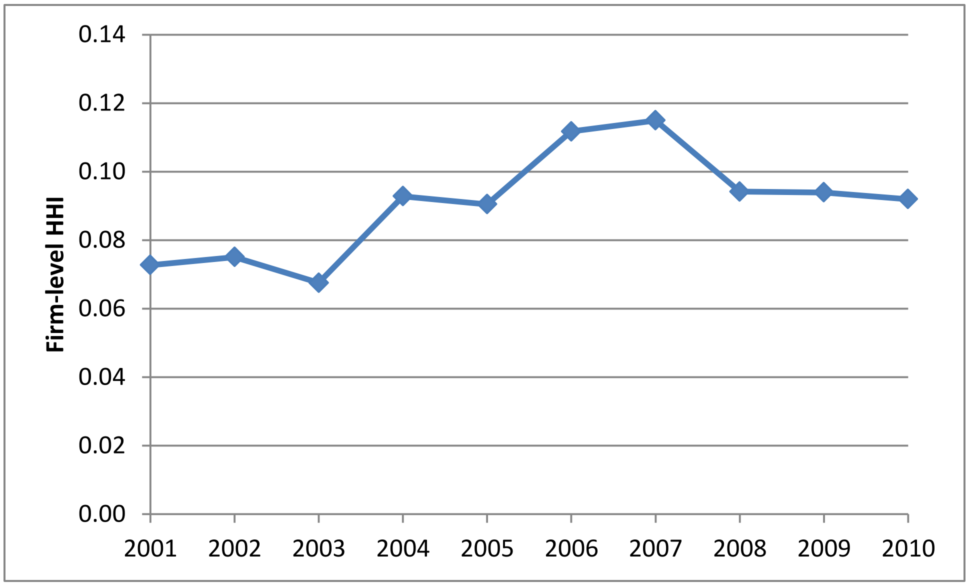

Figure 4. Salmon industry concentration over time (HHI measured at the firm level)

Data source: Intrafish industry reports.

Appendix

Demand function

Let $P = y_D - m_D(q_c + q_n + q_f)$ represent the total global inverse demand function. We assume linearity for analytical convenience. 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 location 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.