Economies of Feedlot Scale, Biosecurity, Investment, and Endemic Livestock Disease

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Abstract

Infectious livestock disease creates externalities for proximate animal production enterprises. The distribution of production scale within a region should influence and be influenced by these disease externalities. Taking the distribution of the unit costs of stocking an animal as primitive, we show that an increase in the variance of these unit costs reduces consumer surplus. The effect on producer surplus, total surplus, and animal concentration across feedlots depends on the demand elasticity. A subsidy to smaller herds can reduce social welfare and immiserize the farm sector by increasing the extent of disease. While Nash behavior involves excessive stocking, disease effects can be such that aggregate output declines relative to first-best. Disease externalities can induce more adoption of a cost-reducing technology by larger herds so that animals become more concentrated across herds. For strategic reasons, excess overall adoption of the innovation may occur. Larger herds are also more likely to adopt biosecurity innovations, explaining why larger herds may be less diseased in equilibrium.

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Infectious disease survives more readily when hosts congregate. It is widely believed that many zoonotic diseases transferred to humans when humans commenced living in cities large enough to sustain the infectious agents despite deaths and the acquisition of immunity (McNeill 1976). Cities provide economic opportunities through scale and agglomeration economies but, for most of urban history, at an increased risk of disease. Urban population centers grew largely because of migration from rural hinterlands. In recent times, public works, including water and sewage works, and other public health measures have allowed longer life spans in the cities of a growing number of countries.[1]

In livestock agriculture, there has been a similar trade-off between scale economies and infectious disease. Densely housed animals and birds may be fed and cared for at a comparatively low unit cost, but also at the risk of production losses through mortality and morbidity.[2] Industrial streamlining and animal healthcare innovations have caused an increase in the efficient herd size. In animal healthcare, these innovations include the availability of commercial herds known to be free of a specific disease, housing systems that better secure against disease entry, sanitation technologies, and the use of antibiotics.

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[1] Densely crowded locations with populations in transit, e.g., hospitals, continue to be common infection sites (Gaydos *et al.* 2006; McDonald, Owings, and Jernigan 2006).

[2] For evidence on this relationship when the infection agent is bovine viral diarrhea virus (BVDV), see Houe *et al.* (1995) and Valle *et al.* (1999). This disease causes lower milk output, reproduction rates and growth rates, as well as deaths among young stock and earlier culling. For the effect of housing density on the general health and growth rate of dairy calves, see Svensson and Liberg (2006). The U.S. Department of Agriculture (2001) surveyed feedlots and found that larger feedlots had higher incidence of all six diseases reported in the survey summary. This is despite evidence that larger feedlots took more precautions. One of these diseases is bovine respiratory disease complex, a condition of major economic concern in the United States. Thomsen *et al.* (2006) report higher risk of mortality from any cause among larger dairy herds. See, too, Rushen (2001), who has surveyed the literature on production losses in dairying due to diseases associated with confinement, such as lameness and mastitis. Kossaibati and Esslemont (1997) reported that 36% of lameness cases in 90 English dairy herds they studied were due to some infectious disease.

A large literature exists on cost-benefit analysis for animal diseases, but very little has been written about the economic externalities that infectious diseases give rise to. For infectious human diseases, Kremer (1996) and Geoffard and Philipson (1996) do model private behavioral incentives. The public good dimension to infectious animal diseases was recognized by Ekboir (1999). For vineyards, Brown, Lynch, and Zilberman (2002) study optimal private and public efforts to control a spatially propagated plant disease but do not consider interactions across farms. A related literature is on the optimal management of exotic species; see Mumford (2002), Olson and Roy (2002), and Perrings (2005). This literature is most concerned with whether to stamp out an invasion and, if so, how to stamp it out. It has not addressed interacting behavior across affected enterprises for a disease that is already well established.

Two issues are addressed in Hennessy, Roosen, and Jensen (2005). The consequences of trade in feeder livestock are considered when such trade increases the overall level of losses from disease. In addition, scale of production as a risk factor for disease entry is considered in a model without accounting for behavior on other farms, i.e., that holds the disease to be an exogenous risk. Hennessy (2006) provides a dynamic model of disease management in which disease spillover externalities are modeled and regulation can be through punishment for becoming infected. This study finds that a certain technology class, namely, technologies that increase the probability a herd becomes free of a disease, is welfare reducing. The paper does not model herd structure heterogeneity.

The questions addressed in this paper concern how herd structure, disease losses, and technology choices relate in a livestock production region. At the center of the paper's problem are adverse disease spillovers across herds. It is assumed that farms decide farm stock numbers privately according to Nash behavior, taking these disease spillovers as given. In the absence of further technology adoption opportunities, it is shown that greater dispersion in unit stocking costs across the region likely reduces market output and consumer surplus. But overall social welfare may increase because smaller herds become increasingly marginalized and this leads to

lower stocking costs in the aggregate. The demand function's slope determines, in large part, whether total surplus rises or falls.

It is also shown that a poll tax on small herds can decrease region output, decrease region costs, and increase region welfare. But a poll tax on larger herds will immiserize producers in the aggregate because production is diverted toward less-efficient farms. Somewhat anomalous results arise because smaller farms are stocked too heavily since more disease effects are external to them. Overall, a tragedy-of-the-commons occurs whereby the average stocking rate is too high in the region. But some large herds may be stocked below first-best, again because smaller farms take least account of disease externalities. In light of the fact that average stocking under first-best is lower than under Nash behavior and the latter incurs more disease loss, it is not immediate as to whether aggregate output under first-best is larger. In fact, it need not be larger in our model.

Cost-reducing technologies are also considered. The stocking decision and the extent of technology adoption are shown to complement when the technology involves a high fixed-cost component. This is despite non-complementary interactions from the stocking decisions of other farms. Thus, technology may better enable larger farms to become larger still. It is shown too that the extent of technology adoption will be socially excessive because farms adopt in part so as to discourage stocking and disease spillovers from other farms.

The paper also considers choices over a technology that reduces exposure to a disease, i.e., a biosecurity technology. Here too it is shown that larger farms are more likely to adopt. Despite the built-in negative technical relation between feedlot size and output per farm for given technical choices, larger feedlots may have larger outputs. The stronger incentive to adopt biosecurity technologies makes the difference. The inclusion of biosecurity technology choices in the model explains some peculiarities in United States hog and dairy productivity data, to be discussed shortly.

This paper is sequenced as follows. After presenting and discussing some aggregate data, the main model is laid out. The model is solved under Nash behavior and under first-best choices. Cost-reducing and biosecurity technologies are introduced in separate sections. A short discussion concludes.

Some Data on Scale and Productivity

By contrast with many European countries, it is only recently that the United States has commenced systematic surveys of actual farm production and financial performance. Agricultural Resources and Management Survey data were collected for dairy production enterprises in 2000 and 2004. Short (2004) has reported and analyzed data from the 2000 survey, and table 1 extracts data from tables 4 and 5 of that report. Output per cow increases with an increase in herd size, while labor and feed technical efficiency ratios also improve. These efficiencies are likely due in part to technology choices that only larger herds can justify making. Regarding other technology choice issues, producers with larger herds are also keener to adopt practices that are likely to have a large fixed-cost component. But in spite of evidence that larger farms take more precaution with respect to veterinary medicine practices, veterinary expenses do not display a definite pattern. Points to note are that producers with larger herds may have access to their own veterinarian and are likely to obtain bulk discounts on drugs.

Table 2 reports pigs per litter in U.S. sow herds, by size of operation. Data are from various issues of the USDA *Quarterly Hogs and Pigs* reports. Other technical statistics, such as feed conversion efficiency, would perhaps be more telling, but the author knows of no source for these statistics over time and by size of operation. The smallest size category is now of no commercial significance while 7.2 was a more typical reported average litter size circa 1996 for that smallest category. Large herds report higher technical efficiency, on average. As with dairy herds, one interpretation of this data is that producers with larger herds have better access to superior genetics. Another is that the disease disadvantages faced by producers with the larger

sow herd when using a given technology base are overcome by scale economies in the adoption of technologies that assist in better securing the herd against production losses due to disease. Most likely both of these effects, as well as some other effects, contribute to the difference in performance.

Model

Inverse market demand for a livestock product is given as $P(Q)$. This is a weakly decreasing function, i.e., $P'(Q) \leq 0$. On the supply side, the market is comprised of N farms, $N \geq 3$, in each of M disease regions where M is a large number. We require M to be large so that price-taking behavior can be assumed. Each farm has a constant unit cost of production. The disease regions are replicas of each other so that in each region the nth farm has unit stocking cost c_n. Since the M regions are replicas, only one of these regions needs to be considered in detail, and notation identifying the region can be discarded. Farms are identified as $n \in \{1, \dots, N\} \equiv \Omega_N$.

In the baseline model, the only action taken by the nth farm is the number of animals stocked, denoted by a_n. Quantity a_n shall be referred to as feedlot or herd size or scale. Because of communicable disease, output per animal falls with the number of animals in one's own herd and with the number of other animals in the disease region. These effects are captured in linear form by specifying output per animal as

(1) $\qquad q(a_i; A_{\backslash i}) = \alpha_0 - \alpha_1 a_i - \alpha_2 A_{\backslash i}; \qquad A_{\backslash i} = \sum_{\substack{n \in \Omega_N, \\ n \neq i}} a_n;$

where $\alpha_0 > 0$ and $\alpha_1 \geq \alpha_2 \geq 0$. Inequality $\alpha_1 \geq \alpha_2$ is intended to capture imperfect disease spillovers from other farms. Output on the ith feedlot is, therefore,

(2) $\qquad q(a_i; A_{\backslash i}) a_i = \alpha_0 a_i - \alpha_1 a_i^2 - \alpha_2 a_i A_{\backslash i}.$

The first two right-hand terms, $\alpha_0 a_i - \alpha_1 a_i^2$, provide a quadratic farm production function. The remaining term, $-\alpha_2 a_i A_{\backslash i}$, represents the negative externality that is imposed on this farm by other farms in the region.

Output per region is $\sum_{n \in \Omega_N} q(a_n; A_{\backslash n})a_n$, market output is $Q = M \sum_{n \in \Omega_N} q(a_n; A_{\backslash n})a_n$, and market price is

(3) $\qquad P = P\left(M \sum_{n \in \Omega_N} q(a_n; A_{\backslash n})a_n\right).$

To establish welfare effects in equilibrium, it is necessary to characterize the implications of disease externalities for behavior.

Nash Equilibrium

The ith farm profit is $\pi_i = Pq(a_i; A_{\backslash i})a_i - c_i a_i$. If the grower behaves according to Nash conjectures by taking the behavior of other growers as given, then the grower chooses to

(4) $\qquad \max_{a_i} \pi_i = \max_{a_i} P\alpha_0 a_i - P\alpha_1 a_i^2 - P\alpha_2 a_i A_{\backslash i} - c_i a_i.$

With $\bar{a} = (1/N)\sum_{n \in \Omega_N} a_n$, Nash optimality conditions identify pure-strategy solutions to this system of equations as $a_i^*, i \in \Omega_N$:

(5) $\qquad a_i^* = \bar{a}^* + \dfrac{\bar{c} - c_i}{PK_0} = \dfrac{P\alpha_0 - \bar{c}}{PK_1} + \dfrac{\bar{c} - c_i}{PK_0}; \qquad \bar{a}^* = \dfrac{P\alpha_0 - \bar{c}}{PK_1};$

$\qquad K_0 \equiv 2\alpha_1 - \alpha_2; \qquad K_1 \equiv 2\alpha_1 + \alpha_2(N-1).$

These solutions are held to be interior, i.e., it is assumed that unit stocking costs support $a_i^* > 0$ $\forall i \in \Omega_N$.

Notice that the stocking rate on small farms is more elastic with respect to price than the stocking rate on large farms. This is because smaller farms are operating on a smaller margin and a price increase is proportionately more significant. Upon making substitutions and cancellations,

$$(6a) \quad q(a_i^*; A_{\backslash i}^*) = \alpha_0 - \frac{(K_1 - \alpha_1)(P\alpha_0 - \overline{c})}{PK_1} + \frac{(\alpha_2 - \alpha_1)(\overline{c} - c_i)}{PK_0};$$

$$(6) \quad (6b) \quad q(a_i^*; A_{\backslash i}^*)a_i^* = \left[\frac{P\alpha_0\alpha_1 + (K_1 - \alpha_1)\overline{c}}{K_1} + \frac{(\alpha_2 - \alpha_1)(\overline{c} - c_i)}{K_0} \right] \frac{(P\alpha_0 - \overline{c})}{P^2 K_1}$$

$$+ \alpha_0 \frac{(\overline{c} - c_i)}{PK_0} - \frac{(K_1 - \alpha_1)(P\alpha_0 - \overline{c})}{K_1} \frac{(\overline{c} - c_i)}{P^2 K_0} + \frac{(\alpha_2 - \alpha_1)(\overline{c} - c_i)^2}{P^2 K_0^2}.$$

Bearing in mind that $N\overline{c} = \sum_{n \in \Omega_N} c_n$, aggregate output in the disease region is

$$(7) \quad \sum_{n \in \Omega_N} q(a_n^*; A_{\backslash n}^*)a_n^* = \frac{1}{N} \sum_{n \in \Omega_N} q(a_n^*; A_{\backslash n}^*) \sum_{n \in \Omega_N} a_n^* + N\mathrm{Cov}\left(q(a_n^*; A_{\backslash n}^*), a_n^* \right)$$

$$= \frac{(P\alpha_0 - \overline{c})^2 \alpha_1 N}{P^2 K_1^2} + \frac{(P\alpha_0 - \overline{c})N\overline{c}}{P^2 K_1} + \frac{(\alpha_2 - \alpha_1)N\sigma_c^2}{P^2 K_0^2}; \quad \sigma_c^2 \equiv \mathrm{Var}(c_n) \equiv \frac{1}{N} \sum_{n \in \Omega_N} (c_n - \overline{c})^2.$$

Aggregate output is $Q^* = M \sum_{n \in \Omega_N} q(a_n^*; A_{\backslash n}^*)a_n^*$. Since $\alpha_2 \leq \alpha_1$, for a given output price, then an

increase in the variance of unit costs leads to a decline in aggregate output. This is because more

dispersion in unit stocking costs leads to more dispersion in herd sizes. From eqn. (5), an

implication of the model is that (conditional on a fixed output price) average herd size is

independent of unit cost variance. But eqn. (1) identifies declining output per animal in larger

herds.[3] Aggregate output, and so average output per animal, declines with larger variance in unit

stocking costs. Why this is so is clear from studying the covariance term in eqn. (7), where

$$(8) \quad \left. \frac{\partial q(a_n^*; A_{\backslash n}^*)}{\partial c_i} \right|_{\overline{c}\ fixed} = \frac{\alpha_1 - \alpha_2}{PK_0} \geq 0; \quad \left. \frac{\partial a_n^*}{\partial c_i} \right|_{\overline{c}\ fixed} = -\frac{1}{PK_0} \leq 0;$$

so that $\mathrm{Cov}(q(a_n^*; A_{\backslash n}^*), a_n^*) \leq 0$. Output per animal is larger on farms with high unit stocking costs

while feedlot scale is lower on these farms. This is compatible with some experimental data—see

Svensson and Liberg (2006)—but is not consistent with the data reported in tables 1 and 2.

Notwithstanding eqn. (8) above, (6b) and a straightforward computation confirm that a farm with

an above-average unit stocking cost has a below average profit.

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[3] This is absent the possibility of adopting scale-complementing technologies, an issue that will
be addressed later.

Note from eqn. (7) that the (partial, and not equilibrium) effect of an increase in P on supply is

$$(9) \quad \frac{\partial Q^*}{\partial P} = \frac{MN\overline{c}}{P^3 K_1^2}\left[2(K_1 - \alpha_1)\overline{c} - P\alpha_0\alpha_2(N-1)\right] + 2\frac{(\alpha_1 - \alpha_2)MN\sigma_c^2}{P^3 K_0^2}.$$

This is certainly positive if $2(K_1 - \alpha_1)/[\alpha_0\alpha_2(N-1)] \geq P/\overline{c}$.[4] If either of $\alpha_2(N-1)$ or $P/\overline{c}$ are small, then positivity is assured. The first of these requirements is that the disease spillover be small. The second is due to $A_{\setminus n}^*$ being large when $P/\overline{c}$ is large. If $\partial Q^*/\partial P \geq 0$ for all P in derivative (9), then there is a unique equilibrium price and quantity, given in fig. 1 as "initial equilibrium."[5] Note that, from eqn. (7) and $\alpha_2 \leq \alpha_1$, supply is adversely affected by an increase in σ_c^2 so that an increase in σ_c^2 increases this unique equilibrium price and decreases this unique equilibrium quantity. Furthermore, (9) implies that $\partial(\partial Q^*/\partial P)^{-1}/\partial\sigma^2 \leq 0$ so that an increase in σ_c^2 shifts the inverse supply up and flattens it out, depicted in fig. 1 as the "shifted equilibrium."

Aggregate cost in the disease region is, from eqn. (5) and some computations,

$$(10) \quad \sum_{n \in \Omega_N} c_n a_n^* = N\overline{a}^*\overline{c} - \frac{N\sigma_c^2}{PK_0}.$$

Expression $-N\sigma_c^2/(PK_0)$ is the cost-efficiency gain from expanding low-cost herds and contracting high-cost herds. It is the benefit associated with the production loss given by $N\text{Cov}(q(a_n^*; A_{\setminus n}^*), a_n^*)$ in eqn. (7) above. So aggregate output and aggregate cost both decline with an increase in dispersion of unit costs. But output price effects need also to be taken into account. Evaluate sum (10) at equilibrium price and totally differentiate with respect to σ_c^2;

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[4] Remember, $\partial Q^*/\partial P \geq 0$ does not follow from the law of supply because that law is developed absent externalities. If $\alpha_2 = 0$, then externalities are absent and derivative (9) does indeed have a positive sign.

[5] The area under the supply response does not have the standard cost interpretation.

(11) $\quad \dfrac{d}{d\sigma_c^2} \sum_{n\in\Omega_N} c_n a_n^* = \left(\dfrac{N(\overline{c})^2}{[P(Q^*)]^2 \, K_1} + \dfrac{N\sigma_c^2}{[P(Q^*)]^2 \, K_0} \right) P'(Q^*) \dfrac{dQ^*}{d\sigma_c^2} - \dfrac{N}{P(Q^*)K_0}.$

The price effects, i.e., the first right-hand expression, act to increase costs because an increase in output price will elicit larger expenditures on animal inputs. Thus, the direct and indirect effects have opposing signs.

Turning to the welfare consequences of more cost dispersion, welfare measures are

(12)
  (12a) Consumer Surplus: $\quad S^{con}(Q) = \int_0^Q P(u)du - P(Q)Q;$

  (12b) Producer Surplus: $\quad S^{pro}(Q) = P(Q)Q - M\sum_{n\in\Omega_N} c_n a_n^*;$

  (12c) Total Surplus: $\quad S^{tot}(Q) = \int_0^Q P(u)du - M\sum_{n\in\Omega_N} c_n a_n^*.$

With $Q^{*,eq}$ as the equilibrium market output level and $\varepsilon_d = P(Q^{*,eq})/[Q^{*,eq}P'(Q^{*,eq})]$ as the demand elasticity, total derivatives are

(13)
  (13a) $\dfrac{dS^{con}(Q^{*,eq})}{d\sigma_c^2} = -Q^{*,eq} P'(Q^{*,eq}) \dfrac{dQ^{*,eq}}{d\sigma_c^2};$

  (13b) $\dfrac{dS^{pro}(Q^{*,eq})}{d\sigma_c^2} = Q^{*,eq} P'(Q^{*,eq}) \dfrac{dQ^{*,eq}}{d\sigma_c^2} + P(Q^{*,eq}) \dfrac{dQ^{*,eq}}{d\sigma_c^2} - M \dfrac{d\sum_{n\in\Omega_N} c_n a_n^*}{d\sigma_c^2}$

  $\qquad\qquad = (1 + \varepsilon_d)Q^{*,eq} P'(Q^{*,eq}) \dfrac{dQ^{*,eq}}{d\sigma_c^2} - M \dfrac{d\sum_{n\in\Omega_N} c_n a_n^*}{d\sigma_c^2};$

  (13c) $\dfrac{dS^{tot}(Q^{*,eq})}{d\sigma_c^2} = P(Q^*) \dfrac{dQ^{*,eq}}{d\sigma_c^2} - M \dfrac{d\sum_{n\in\Omega_N} c_n a_n^*}{d\sigma_c^2}.$

It is immediate that consumer surplus declines with an increase in σ_c^2 whenever the derivative in (9) is positive. The first expression between equality signs in (13b), involving $P'(Q^{*,eq})$, is then positive. It is just a distribution effect and the distribution is away from consumers. If demand has unit elasticity, or $\varepsilon_d = -1$, then the expression for producer surplus response simplifies to the negative of the cost response. But, in light of derivative (11), this cost response has an indeterminate sign. If output is very elastic, then the equilibrium price hardly moves and, using eqn. (7),

$$(14) \quad P(Q^*)\frac{dQ^*}{d\sigma_c^2} - M\frac{d\sum_{n\in\Omega_N}c_n a_n^*}{d\sigma_c^2} \approx \frac{(\alpha_2-\alpha_1)MN}{P(Q^*)K_0^2} + \frac{MN}{P(Q^*)K_0} = \frac{MN\alpha_1}{P(Q^*)K_0^2} \geq 0.$$

So total welfare and producer surplus both increase whenever the equilibrium price is not very sensitive to unit cost variance. However, the price response can be (in the absolute sense) arbitrarily large so that total surplus can decline with an increase in unit cost variance.

Upon applying eqn. (5), the Herfindahl index for herd shares in a region is[6]

$$(15) \quad \mathcal{H}^{herd} = \sum_{n\in\Omega_N}\left(\frac{a_n^*}{N\bar{a}^*}\right)^2 = \frac{1}{N} + \frac{K_1^2\sigma_c^2}{NK_0^2[P(Q^*)\alpha_0-\bar{c}]^2},$$

with derivative

$$(16) \quad \frac{d\mathcal{H}^{herd}}{d\sigma_c^2} = \left(1 - \frac{2\alpha_0\sigma_c^2}{[P(Q^*)\alpha_0-\bar{c}]}P'(Q^*)\frac{dQ^*}{d\sigma_c^2}\right)\frac{K_1^2}{NK_0^2[P(Q^*)\alpha_0-\bar{c}]^2}.$$

If the equilibrium price is not responsive to the variance of unit costs then the Herfindahl index for herd shares increases, as one would expect. This positive response is also the case whenever firms have common unit costs so that $\sigma_c^2 = 0$ at the point of evaluation. But there is also a price effect such that a higher price has a stronger effect on small farm stocking rates than on large farm stocking rates; see the comment under eqn. (5) above. It is conceivable that the price effect overwhelms the direct effect and the index declines.

In summary:[7]

RESULT 1. *Let the sum of unit animal costs be held fixed, let all outputs remain interior, and let Nash equilibrium supply offered at any price be increasing in output price. Then an increase in the variance of unit stocking costs (a) decreases the equilibrium level of market output, and (b) increases equilibrium market price and decreases consumer surplus.*

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[6] The Herfindahl index for production shares is not as straightforward. Then, since per animal output multiplies stock per farm, the skewness and kurtosis of unit stocking costs also matter.
[7] The interested reader should contrast this result with the effects of variance in unit costs on

If, in addition, the equilibrium price response to an increase in unit cost variance is sufficiently small then (c) all of producer surplus, total surplus, and the Hirfindahl index of herd concentration increase with an increase in the variance of unit stocking costs.

The result asserts that, although aggregate output declines and animals can become increasingly concentrated in large herds when unit stocking costs become more dispersed, this *can* lead to an increase in social welfare. As will be developed upon later, larger herds are more cost efficient. Disease spillover concerns motivate these farms to stock less than they ought to given the region's average stocking rate. Even so, more dispersion in unit stocking costs encourages more stocking by those farms that should stock more. The average stocking rate is not affected since the (interior) equilibrium stocking rate is linear in unit cost.

From this point on the assumption is made that the equilibrium price is exogenous to the moments of unit stocking costs. This may be because a change in unit cost variance occurs in just one disease region or because the demand elasticity is very large. In order to reduce notation by omitting M, the perspective will be taken that the disease region is a small contributor to total market output.

ASSUMPTION 1. *Equilibrium price is not affected by the moments of unit stocking costs in a disease region that produces a small share of total market output.*

All of what will be asserted from this point on can be modified in the manner of Result 1 above to account for an output price response. Considered next is the effect of a change in just one unit stocking cost. In the appendix the following is shown.

RESULT 2. *Under Assumption 1, a decrease in some farm unit stocking cost can decrease the sum of farm profits, increase the sum of farm costs, and decrease the sum of farm revenues. In*

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welfare in the standard Cournot oligopoly, as studied in Salant and Shaffer (1999).

particular, if c_i decreases and a_i^* is sufficiently close to zero then all of the above will occur. The sum of farm costs increases if $c_i < \overline{c}/2$.

The result brings out the importance of strategic interactions in the disease region. The sum of profits depends in two ways on the moments of c_n. There is a component that depends only on the average of unit stocking costs. It is, of course, decreasing in average stocking cost. There is also a component that depends on the variance of unit stocking costs. Aggregate profit is increasing in variance because cost efficiencies due to animal concentration induced by cost dispersion outweigh the reduced level of aggregate output that arises when animals become more concentrated. A reduction in some c_i will reduce mean cost $\overline{c}$ and it will reduce σ_c^2 if c_i exceeds $\overline{c}$. If c_i is large enough, i.e., a_i^* is small enough, then the adverse impact on cost variability efficiencies can outweigh the positive impact on mean unit stocking cost. Taking a strategic perspective, when the small *i*th farm becomes more competitive then stock numbers decline among larger herds. Even though they are more diseased, larger herds internalize more of the disease externality and so the extent of economic losses due to disease increases with a decrease in c_i. Of course, the adverse impact on profits could be due to revenue effects or cost effects. The result shows that it can be due to both.

There is an antecedent to Result 2 in the oligopoly pricing literature. In the standard Cournot model with constant (but firm-specific) unit costs, Lahiri and Ono (1988) and Zhao (2001) have demonstrated that a decline in some firm's unit cost can reduce industry profits and total surplus. Although the details differ, the reasoning is broadly the same. Large firms have low unit costs and so are efficient. Consumers benefit from a lower unit cost on the part of a small firm, but strategic interactions are such that production is diverted from low-cost producers toward that high-cost producer with the now lower unit cost. The welfare loss due to diverted production can

outweigh the welfare gain on the consumer side. In our case, aggregate output can fall so that it is not even necessarily true that the consumer is better off following the decline in the unit cost.

First-Best

By contrast with problem (4), growers behaving under first-best should take account of how they affect productivity on other farms in the disease region. First-best is when actions satisfy

(17) $\quad \max_{a_1, a_2, \dots, a_N} P \sum_{n \in \Omega_N} q(a_n; A_{\backslash n}) a_n - \sum_{n \in \Omega_N} c_n a_n.$

First-best optimality conditions identify choices $a_i^{fb}, i \in \Omega_N$, satisfying

(18)
$$a_i^{fb} = \bar{a}^{fb} + \frac{\bar{c} - c_i}{2P(\alpha_1 - \alpha_2)} = \frac{P\alpha_0 - \bar{c}}{PK_3} + \frac{\bar{c} - c_i}{2P(\alpha_1 - \alpha_2)}; \qquad \bar{a}^{fb} = \frac{P\alpha_0 - \bar{c}}{PK_3}.$$
$$K_3 = 2\alpha_1 + 2\alpha_2(N-1).$$

Note that

(19) $\quad \bar{a}^* - \bar{a}^{fb} = \frac{(P\alpha_0 - \bar{c})\alpha_2(N-1)}{2P[2\alpha_1 + \alpha_2(N-1)][\alpha_1 + \alpha_2(N-1)]} \geq 0,$

i.e., animals are overstocked except when $\alpha_2 = 0$. This will be called the tragedy-of-the-commons effect or simply the commons effect (Hardin 1968). Eqn. (18) and eqn. (5) imply

(20) $\quad a_i^* - \bar{a}^* = a_i^{fb} - \bar{a}^{fb} + \frac{(c_i - \bar{c})\alpha_2}{2P(2\alpha_1 - \alpha_2)(\alpha_1 - \alpha_2)}.$

Thus, $a_i^* - a_i^{fb} \geq \bar{a}^* - \bar{a}^{fb} \geq 0$ whenever $c_i \geq \bar{c}$. In summary:

RESULT 3. *(a) On average, farms are overstocked, (b) $sign(a_i^* - \bar{a}^* - a_i^{fb} + \bar{a}^{fb}) = sign(c_i - \bar{c})$, and (c) if a farm's unit stocking cost is larger than the average unit stocking cost then the Nash equilibrium stocking rate exceeds first-best.*

The result exhibits the tendency for high-cost farms to stock too heavily, but it leaves open the possibility that some farms are under-stocked relative to first-best. It can be seen from eqn.

(19) and eqn. (20) that this possibility can occur when $c_i - \bar{c}$ is sufficiently negative, e.g., when $\bar{c}$ is large and $c_i = 0$.

Of course, stocking rates and outputs are not the same. In addition, (19) by itself does not imply that aggregate cost is lower under first-best. Output and cost levels satisfy the following:

RESULT 4. *(a) Aggregate output under first-best less aggregate output under Nash behavior is decreasing in the variance of unit stocking costs.*

(b) Aggregate output under first-best behavior is less than under Nash behavior if

$$(21) \quad \sigma_c^2 > \frac{4P^2 K_0^2 (\alpha_1 - \alpha_2)(\bar{a}^{fb} - \bar{a}^*)\left[\alpha_0 - (K_1 - \alpha_1)(\bar{a}^{fb} + \bar{a}^*)\right]}{\alpha_2 (4\alpha_1 - 3\alpha_2)}.$$

This is possible.

(c) When compared with aggregate cost under Nash equilibrium, aggregate cost under first-best is always smaller. Furthermore, the difference in aggregate costs becomes more negative when the variance of unit stocking costs increases.

Result 4 asserts that at least part of the efficiency gain on moving to first-best must come from cost efficiencies. These cost efficiencies are due to (a) reducing the average stocking rate and (b) shifting stock toward lower-cost farms; see Result 3 above. But output may fall under first-best because of the commons effect. In that case, and allowing for a downward-sloping demand curve, consumers would lose under first-best. Producers would gain from higher prices and, even absent higher prices, cost efficiencies adequate to offset lower production. If, though, the variance of unit stocking costs is so low that aggregate output increases slightly, then both consumer surplus and producer surplus are larger under first-best.[8]

---

[8] A condition on $\bar{c}/(P\alpha_0)$ is also required. The condition is explained under (A9) in the appendix.

Considered next is a policy intervention to support first-best. A stock, or poll, tax is used to ensure first-best actions by acting on a_i^*. Let the unit stocking cost, inclusive of the poll tax, be $c_i^{\$}$ so that the tax is $\tau_i = c_i^{\$} - c_i$. The tax can come in two forms: (a) a farm-specific tax that takes account of the farm's unit stocking costs, or (b) a farm-invariant tax.

RESULT 5. *(a) First-best is supported by a farm-specific animal poll tax of*

$$(22) \quad \tau_i = \overline{\tau} - \frac{\alpha_2(\overline{c} - c_i)}{2(\alpha_1 - \alpha_2)}; \qquad \overline{\tau} \equiv \frac{(P\alpha_0 - \overline{c})\alpha_2(N-1)}{2[\alpha_1 + \alpha_2(N-1)]}.$$

Consequently, the first-best poll tax is larger on farms with higher unit stocking costs.

(b) If an animal poll tax must be farm-invariant, then the conditional first-best tax is $\overline{\tau}$ as given in (22).

(c) The welfare gain due to the ability to condition on the c_i is

$$(23) \quad \frac{N(4\alpha_1 - 3\alpha_2)\alpha_1\alpha_2\sigma_c^2}{4P(\alpha_1 - \alpha_2)^2(2\alpha_2 - \alpha_1)^2} > 0,$$

which is increasing in the variance of unit stocking costs.

The first-best poll tax reduces the average stocking rate, and especially stocking rates in smaller herds. This is consistent with Result 3, and the differential tax on smaller herds arises because cost efficiencies in larger herds overcome at least some disease inefficiencies. Part (*b*) shows that the gains from conditioning on farm unit stocking costs are due only to the ability to spread effective costs out so as to better allocate stock across farms. From (6*a*) it is clear that the unweighted average output per animal does not depend on specific taxes. But the average, when weighted by herd size, decreases upon imposing the farm-specific poll tax. As for part (*c*), it is natural that the gain should depend on the variance of unit stocking costs because if $\sigma_c^2 = 0$ then farms do not differ and there should be no gain from exercising the capacity to tax farms differently.

Cost-Reducing Technology

Studied next is how the endemic disease can affect technology adoption, feedlot scale, and the interaction between these farm decisions. A cost-reducing technology becomes available. Its adoption involves a variable cost component and a fixed cost component, i.e., that does not vary with the stocking rate. The technology can be adopted in varying amounts, which will be labeled as z_i. The fixed cost incurred is $0.5Fz_i^2$ per farm. There is also a variable cost incurred, at $\phi_1 z_i$ per animal with $\phi_1 > 0$. The benefit of adoption is that a farm's variable costs decline from c_i to $c_i - \phi_2 z_i$, $\phi_2 > \phi_1$. Netting out, unit cost becomes $c_i - \delta z_i$, $\delta = \phi_2 - \phi_1$. Notice that the lower-cost farms will have a stronger incentive to adopt because these farms have larger herds, i.e., scale complements the innovation.

The game has two stages; in the first the level of the cost-reducing innovation is chosen and in the second the level of output is chosen. It is, of course, solved backwards and the strategic dimension arises because stage 1 choices affect the stage 2 stocking decisions of other farms. Instead of problem (4), the ith grower's stage 2 optimization problem becomes

$$(24) \quad \max_{a_i} \pi_i = \max_{a_i} P\alpha_0 a_i - P\alpha_1 a_i^2 - P\alpha_2 a_i A_{\backslash i} - (c_i - \delta z_i) a_i.$$

From eqn. (5), the optimum feedlot scale is

$$(25) \quad a_i^* = \bar{a}^* + \frac{\bar{c} - \delta\bar{z} - c_i + \delta z_i}{PK_0}; \qquad \bar{a}^* = \frac{P\alpha_0 - \bar{c} + \delta\bar{z}}{PK_1}; \qquad \bar{z} = \frac{\sum_{n \in \Omega_N} z_n}{N}.$$

So ($6a$) becomes

$$(26) \quad q(a_i^*; A_{\backslash i}^*) = \alpha_0 - \frac{(K_1 - \alpha_1)(P\alpha_0 - \bar{c} + \delta\bar{z})}{PK_1} + \frac{(\alpha_2 - \alpha_1)(\bar{c} - \delta\bar{z} - c_i + \delta z_i)}{PK_0}.$$

The stage 1 problem is then

$$(27) \quad \max_{z_i} Pq(a_i^*; A_{\backslash i}^*) a_i^* - (c_i - \delta z_i) a_i^* - 0.5Fz_i^2,$$

with maximizing argument z_i^* and optimality condition

$$
(28) \quad \left[Pa_i^* \left.\frac{dq(a_i;A_{\backslash i}^*)}{da_i}\right|_{a_i=a_i^*} + Pq(a_i^*;A_{\backslash i}^*) - c_i + \delta z_i^* \right] \frac{da_i^*}{dz_i} + Pa_i^* \left.\frac{dq(a_i^*;A_{\backslash i})}{dA_{\backslash i}}\right|_{A_{\backslash i}=A_{\backslash i}^*} \frac{dA_{\backslash i}^*}{dz_i}
$$
$$
+ \delta a_i^* - Fz_i^* = 0.
$$

Since the term in square brackets is zero under Nash behavior, eqn. (28) reduces to

$$
(29) \quad \left[P \frac{dq(a_i^*;A_{\backslash i}^*)}{dA_{\backslash i}^*} \frac{dA_{\backslash i}^*}{dz_i} + \delta \right] a_i^* - Fz_i^* = 0; \qquad \frac{dq(a_i^*;A_{\backslash i}^*)}{dA_{\backslash i}^*} = -\alpha_2; \qquad \frac{dA_{\backslash i}^*}{dz_i} = -\frac{(N-1)\delta\alpha_2}{PK_0 K_1};
$$

or

$$
(30) \quad z_i^* = \frac{2\alpha_1 \delta K_4 a_i^*}{F}; \qquad \bar{z}^* = \frac{2\alpha_1 \delta K_4 \bar{a}^*}{F}; \qquad K_4 = \frac{2\alpha_1 + \alpha_2(N-2)}{K_0 K_1}.
$$

In light of eqn. (25) and eqn. (30), the means of solution values are

$$
(31) \quad \bar{a}^* = \frac{(P\alpha_0 - \bar{c})F}{PFK_1 - 2\alpha_1\delta^2 K_4}; \qquad \bar{z}^* = \frac{2(P\alpha_0 - \bar{c})\alpha_1\delta K_4}{PFK_1 - 2\alpha_1\delta^2 K_4};
$$

which implies:

RESULT 6. *If* $\delta \in \left(0, \sqrt{PFK_1/(2\alpha_1 K_4)}\right)$, *then average stocking rate and average extent of adoption of the cost-reducing technology are (a) increasing in unit innovation benefit* δ *and (b) decreasing in fixed-cost parameter* F.

The result holds that the two decisions facing the farm are, in a sense, complements. While cost function $-(c_i - \delta z_i)a_i$ suggests a complementary relationship between stocking rate and extent of technology adoption, bear in mind that stocking decisions by other farms do not complement the own-farm stocking decision. So an increase in δ could conceivably have adverse indirect consequences for a farm. Thus, the unambiguous nature of Result 6 is somewhat surprising.

Turning to adoption decisions on particular farms, eqn. (25) and eqn. (30) imply

$$(32) \quad a_i^* - \bar{a}^* = \frac{(\bar{c} - c_i)F}{PFK_0 - 2\alpha_1\delta^2 K_4}; \qquad z_i^* - \bar{z}^* = \frac{2(\bar{c} - c_i)\alpha_1\delta K_4}{PFK_0 - 2\alpha_1\delta^2 K_4}.$$

It is immediate that $Cov(a_n^*, c_n) \leq 0$, $Cov(z_n^*, c_n) \leq 0$, and $Cov(a_n^*, z_n^*) \geq 0$, i.e., the two actions correlate positively across farms. A large herd absent the innovation begets a larger herd in the presence of the innovation. Another way of characterizing this relation is to consider the restriction $z_i^* = \hat{z} \; \forall i \in \Omega_N$. In that case, eqn. (32) becomes $a_i^* - \bar{a}^* = (\bar{c} - c_i)/[PK_0]$ so that

$$(33) \quad \left| Cov(a_n^*, c_n) \right|_{z=\hat{z}} = \frac{N\sigma_c^2}{PK_0} \leq \frac{N\sigma_c^2}{PK_0 - 2\alpha_1\delta^2 K_4 / F} = \left| Cov(a_n^*, c_n) \right|,$$

and feedlot scale becomes less responsive under imposition of the constraint. Summarizing:

RESULT 7. *If* $\delta \in \left(0, \sqrt{PFK_0/(2\alpha_1 K_4)}\right)$, *then (a) any farm with initial unit stocking cost lower (higher) than average both (i) stocks and (ii) invests more (less) than the average farm so that* $Cov(a_n^*, c_n) \leq 0$, $Cov(z_n^*, c_n) \leq 0$, *and* $Cov(a_n^*, z_n^*) \geq 0$ *; (b) relative to covariance between stocking rate and unit stocking cost when* z *is imposed at some value* $\hat{z}$, *the capacity to choose the value of* z_i *increases the absolute value of this covariance.*

This result conveys that the availability of technology choices with a variable-for-fixed cost trade-off will act to increase the dispersion of feedlot scale. Turning next to how investment under Nash behavior compares with first-best investment levels, the first-best problem is to

$$(34) \quad \max_{\substack{a_1, a_2, \ldots, a_N \\ z_1, z_2, \ldots, z_N}} P\sum_{n\in\Omega_N} q(a_n; A_{\backslash n})a_n - \sum_{n\in\Omega_N} (c_n - \delta z_n)a_n - 0.5F\sum_{n\in\Omega_N} z_n^2.$$

Upon adapting eqn. (18), first-best optimality conditions identify choices $a_i^{fb}, i \in \Omega_N$, that satisfy

$$(35) \quad a_i^{fb} = \bar{a}^{fb} + \frac{(\bar{c} - \delta\bar{z}^{fb}) - (c_i - \delta z_i^{fb})}{2P(\alpha_1 - \alpha_2)}; \qquad \bar{a}^{fb} = \frac{P\alpha_0 - \bar{c} + \delta\bar{z}^{fb}}{PK_3}; \qquad z_i^{fb} = \frac{\delta a_i^{fb}}{F}.$$

A comparison with (28)-(30) reveals that an effect is absent. This effect represents the strategic effort to manipulate the stocking decisions on the part of other herds. The solution of system (35) for means is

$$(36) \quad \overline{a}^{fb} = \frac{(P\alpha_0 - \overline{c})F}{PFK_3 - \delta^2}; \qquad \overline{z}^{fb} = \frac{(P\alpha_0 - \overline{c})\delta}{PFK_3 - \delta^2}.$$

Comparisons with averages under Nash equilibrium provide

$$(37) \quad \overline{z}^* - \overline{z}^{fb} = \frac{[2\alpha_1 + \alpha_2(N-1)]^2 + 2\alpha_1[2\alpha_1(N-2) + \alpha_2(N-3)(N-1)]}{K_0 K_1 (PFK_1 - 2\alpha_1\delta^2 K_4)(PFK_3 - \delta^2)} \alpha_2 (P\alpha_0 - \overline{c})PF\delta.$$

It follows, from evaluation at $\delta = 0$ and also a straightforward derivation, that (a) $\overline{z}^*|_{\delta=0} = \overline{z}^{fb}|_{\delta=0}$, and ($b$) $d\overline{z}^*/d\delta \geq d\overline{z}^{fb}/d\delta$ whenever $\overline{z}^* > 0$ and $\overline{z}^{fb} > 0$.

RESULT 8. *The average level of technology adoption is socially excessive.*

Similar to the above, Elberfeld (2003) identified socially excessive technology adoption for firms in Cournot oligopoly with ex ante identical unit production costs. The intuition for Result 8 is that farms know that low costs on their own part will deter other farms from choosing high stocking rates. So there is a strategic motive for each farm to increase the extent of technology adoption.[9] In the end, of course, farmers are unlikely to be better off because stocking rates and disease losses increase with the mean level of technology adoption.

The above technology choice has nothing to do with disease management, and it cannot explain why larger farms could have higher output per animal. The next section presents a disease management technology that can explain this phenomenon.

Biosecurity Technology

Considered is a biosecurity innovation that comes at a cost. If the firm pays amount $0.5Fz_i^2$, then the extent of negative spillover changes from $A_{\backslash i}$ to $A_{\backslash i} - z_i$. As before, the game is played in

two stages. The biosecurity innovation choice level is made at stage 1 and the scale choice is made at stage 2. Solving backwards, the stage 2 problem for the ith farm is

(38) $\quad \max_{a_i} \pi_i = \max_{a_i} P\alpha_0 a_i - P\alpha_1 a_i^2 - P\alpha_2 a_i (A_{\backslash i} - z_i) - c_i a_i.$

The stage 2 choice satisfies

(39) $\quad P\alpha_0 + P\alpha_2 z_i - 2P\alpha_1 a_i - P\alpha_2 A_{\backslash i} - c_i = 0.$

This aggregates as before in Nash equilibrium except that $P\alpha_0$ is replaced by $P\alpha_0 + P\alpha_2 z_i$, and eqn. (5) becomes

(40) $\quad a_i^* = \dfrac{P\alpha_0 + P\alpha_2 z_i - \bar{c}}{PK_1} + \dfrac{\bar{c} - c_i}{PK_0}; \qquad K_0 \equiv 2\alpha_1 - \alpha_2; \qquad K_1 \equiv 2\alpha_1 + \alpha_2(N-1).$

Similar to eqn. (28), the stage 1 optimization problem is

(41) $\quad \left[Pa_i^* \underbrace{\left. \dfrac{dq(a_i; A_{\backslash i}^*)}{da_i} \right|_{a_i = a_i^*}}_{=0} + Pq(a_i^*; A_{\backslash i}^*) - c_i \right] \dfrac{da_i^*}{dz_i} - Pa_i^* \alpha_2 \overbrace{\left(\dfrac{dA_{\backslash i}^*}{dz_i} - 1 \right)}^{=0-1=-1} - Fz_i^* = 0,$

or

(42) $\quad Pa_i^* \alpha_2 = Fz_i^*.$

Relation (42), similar to (30), confirms the complementary relationship between the two farm-level choices. This and eqn. (40) imply

(43) $\quad a_i^* - \bar{a}^* = \dfrac{(\bar{c} - c_i)FK_1}{PK_0(FK_1 - P\alpha_2^2)}.$

Deviation in output per animal from mean output per animal is

(44) $\quad q(a_i^*; A_{\backslash i}^*) - \bar{q}^* = -(\alpha_1 - \alpha_2)(a_i^* - \bar{a}^*) - \alpha_2(\bar{z}^* - z_i^*) = (a_i^* - \bar{a}^*)\left[\alpha_2 - \alpha_1 + \dfrac{P\alpha_2^2}{F} \right],$

so that $\text{Cov}(q_n^*, a_n^*) \overset{sign}{=} \alpha_2 - \alpha_1 + P\alpha_2^2 / F.$

---

[9] This is an example of a closed-loop equilibrium; see Fudenberg and Tirole (1991, p. 132).

RESULT 9. *If* $P\alpha_2^2 > (<) (\alpha_1 - \alpha_2)F$, *then farms with above-average herd size have above-average (below-average) output per animal.*

So if the fixed-cost parameter is sufficiently low or output price is sufficiently high then Result 9 is consistent with the data reported in tables 1 and 2. The biosecurity effect dominates the adverse own-scale effect. But if F is large, perhaps early on in the history of confined agriculture for a particular species, then the own-scale effect will dominate. In particular, in the limit as $F \to \infty$ then $z_i^* = 0 \; \forall i \in \Omega_N$ and the model in this section reduces to the model studied at the outset.

Conclusion

This article has developed a model that explains relationships between regional animal disease spillovers, farm feedlot scale, farm output per animal, and technology adoption decisions. It places some curiosities on sound microeconomic foundations. For example, high-cost farms can have high productivity in the sense of output per animal while also having comparatively low profits. A second example is that an increase in the variability of unit stocking costs may well induce lower aggregate output but higher social welfare. A third example is that a per animal subsidy to smaller herds will increase the region's overall stocking rate and reduce the region's aggregate farm profits, but a subsidy to larger herds will increase farm profits over the region. This inference suggests caution when developing public policy on animal health. It is also shown that, because of disease externalities, there may be excessive adoption of a cost-reducing technology. In addition, the availability of a biosecurity-improving technology can explain why larger herds can produce more output per animal.

Many of the propositions are testable. Farm-level data could explain the relationship between unit stocking costs, output per animal, and biosecurity measures taken. Losinger *et al.*

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(1998) provide a summary of how United States National Animal Health Monitoring System (NAHMS) data on hog mortality relate to biosecurity measures taken. If this sort of data, together with production data for the same farms, were available then empirical tests could be completed. In addition, if relevant time-series data over the course of several decades could be obtained then the following could be tested for. When a biosecurity technology is first commercialized, as with antibiotics in feed during the 1950s, the technology should be adopted most extensively on larger feedlots. But the correlation between feedlot scale and output per animal should be either negative or weakly positive. As the cost of the technology declines, then it should still be the case that larger herds adopt more extensively, but the correlation between scale and output per animal should increase to become more strongly positive.

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Table 1. Summary of ARMS 2000 Dairy Survey Data

Summary statistic, all are averages	Enterprise Size			
	Small < 50 cows	Medium 50-99	Large 100-499	Industrial ≥ 500
Herd size	33	88	313	955
Output/cow (lb/year)	14,932	16,157	17,420	17,326
Labor efficiency (hours/100 lb milk)	0.84	0.44	0.19	0.11
Feed efficiency(lb feed/100 lb milk)	243	252	317	162
bST use (% of milk cows)	8	10	17	22
Genetic selection/breeding program (Yes=1, No=0)	0.56	0.68	0.70	0.89
Preventive medicine practices (Yes=1, No=0)	0.86	0.94	0.93	0.97
Veterinary expenses ($/100 lb milk)	0.66	0.71	0.58	0.60

Note: Data are as reported in tables 4 and 5 of Short (2004).

Table 2. Pigs per Litter by Size of Operation, by Quarter

Year	Quarter	Pigs per litter on operations having head					
		1-99	100-499	500-999	1,000-1,999	2,000-4,999	≥ 5,000
1996	Dec '95-Feb '96	6.9	7.8	7.9	8.4	8.8	NA
	Mar '96-May '96	7.6	8.1	8.2	8.5	8.7	NA
2001	Dec '00-Feb '01	7.5	7.8	8.2	8.5	8.7	8.9
	Mar '01-May '01	7.6	8.2	8.4	8.6	8.9	9.0
2006	Dec '05-Feb '06	7.5	8.0	8.3	8.8	9.0	9.1
	Mar '06-May '06	7.6	8.0	8.4	8.8	9.0	9.2

Note: Data are from *Quarterly Hogs and Pigs* reports by the National Agricultural Statistics Service, release dates 6/28/96, 6/29/01, and 6/30/06. In 1996, the largest size category was ≥ 5,000, i.e., the last two columns merge for that year.

Appendix

Proof of Result 2: Taking price as fixed, eqn. (7) and eqn. (10) establish that the sum of producer profits within a region is

(A1) $\quad \sum_{n \in \Omega_N} \pi_n = \left[\dfrac{(P\alpha_0 - \bar{c})^2}{K_1^2} + \dfrac{\sigma_c^2}{K_0^2} \right] \dfrac{\alpha_1 N}{P}.$

Differentiate with respect to some c_i and use eqn. (5) to obtain

(A2) $\quad \dfrac{d\sum_{n \in \Omega_N} \pi_n}{dc_i} = \dfrac{2\alpha_1 N \bar{a}^*}{K_0} \left(\dfrac{\alpha_2}{2\alpha_1 + \alpha_2(N-1)} - \dfrac{a_i^*}{N\bar{a}^*} \right).$

Furthermore,

(A3) $\quad \dfrac{d\sum_{n \in \Omega_N} c_n a_n^*}{dc_i} = a_i^* + \sum_{n \in \Omega_N} c_n \dfrac{da_n^*}{dc_i} = a_i^* - \dfrac{c_i}{PK_0}.$

This means that

(A4)
$$P\dfrac{d\sum_{n \in \Omega_N} q(a_n^*; A_{\backslash n}^*) a_n^*}{dc_i} = \dfrac{d\sum_{n \in \Omega_N} \pi_n}{dc_i} - \dfrac{d\sum_{n \in \Omega_N} c_n a_n^*}{dc_i}$$
$$= \dfrac{2\alpha_1 \alpha_2 N \bar{a}^*}{K_0 K_1} - \dfrac{2\alpha_1 a_i^*}{K_0} - a_i^* + \dfrac{c_i}{PK_1} = \dfrac{2\alpha_1 \alpha_2 N \bar{a}^*}{K_0 K_1} - \left(\dfrac{2\alpha_1 + K_0}{K_0} \right) a_i^* + \dfrac{c_i}{PK_1}.$$

When $a_i^* = 0$, then (A2) and (A4) take positive values while (A3) takes a negative value. Also, use (A3) and eqn. (5) to write $a_i^* - c_i/(PK_0) = (P\alpha_0 - \bar{c})/(PK_1) + (\bar{c} - 2c_i)/(PK_0)$, which is positive whenever $\bar{c}/2 > c_i$. ∎

Proof of Result 4: Eqn. (1) and eqn. (18) imply

(A5a) $\quad q(a_i^{fb}; A_{\backslash i}^{fb}) = \alpha_0 - \dfrac{(K_1 - \alpha_1)(P\alpha_0 - \bar{c})}{PK_3} + \dfrac{c_i - \bar{c}}{2P};$

(A5)

(A5b) $\quad q(a_i^{fb}; A_{\backslash i}^{fb}) a_i^{fb} = \dfrac{(P\alpha_0 - \bar{c})\alpha_0}{PK_3} - \dfrac{(K_1 - \alpha_1)(P\alpha_0 - \bar{c})^2}{P^2 K_3^2} - \dfrac{(\bar{c} - c_i)(P\alpha_0 - \bar{c})}{2P^2 K_3}$
$$+ \dfrac{(\bar{c} - c_i)\alpha_0}{2P(\alpha_1 - \alpha_2)} - \dfrac{(K_1 - \alpha_1)(P\alpha_0 - \bar{c})(\bar{c} - c_i)}{2P^2 K_3(\alpha_1 - \alpha_2)} - \dfrac{(\bar{c} - c_i)^2}{4P^2(\alpha_1 - \alpha_2)}.$$

Upon summing (A5b) over farms, aggregate output in the disease region is

(A6) $\sum_{n \in \Omega_N} q(a_n^{fb}; A_{\backslash n}^{fb}) a_n^{fb} = \dfrac{N(P\alpha_0 - \overline{c})\alpha_0}{PK_3} - \dfrac{N(K_1 - \alpha_1)(P\alpha_0 - \overline{c})^2}{P^2 K_3^2} - \dfrac{N\sigma_c^2}{4P^2(\alpha_1 - \alpha_2)}.$

Aggregate output is $Q^{fb} = M \sum_{n \in \Omega_N} q(a_n^{fb}; A_{\backslash n}^{fb}) a_n^{fb}$. At a given output price, the difference

between aggregate output under first-best and that under Nash equilibrium is

$$\Delta_*^{fb} Q = \sum_{n \in \Omega_N} \left[q(a_n^{fb}; A_{\backslash n}^{fb}) a_n^{fb} - q(a_n^*; A_{\backslash n}^*) a_n^* \right]$$

$$= \alpha_0 \sum_{n \in \Omega_N} (a_n^{fb} - a_n^*) - (\alpha_1 - \alpha_2) \sum_{n \in \Omega_N} \left[(a_n^{fb})^2 - (a_n^*)^2 \right] - \alpha_2 N \sum_{n \in \Omega_N} \left[\overline{a}^{fb} a_n^{fb} - \overline{a}^* a_n^* \right]$$

$$= \alpha_0 N(\overline{a}^{fb} - \overline{a}^*) - (\alpha_1 - \alpha_2) \sum_{n \in \Omega_N} \left[(a_n^{fb})^2 - (a_n^*)^2 \right] - \alpha_2 N^2 \left[(\overline{a}^{fb})^2 - (\overline{a}^*)^2 \right]$$

$$= N(\overline{a}^{fb} - \overline{a}^*) \left[\alpha_0 - \alpha_2 N(\overline{a}^{fb} + \overline{a}^*) \right] - (\alpha_1 - \alpha_2) \sum_{n \in \Omega_N} (a_n^{fb} - a_n^*)(a_n^{fb} + a_n^*)$$

$$= N(\overline{a}^{fb} - \overline{a}^*) \left[\alpha_0 - \alpha_2 N(\overline{a}^{fb} + \overline{a}^*) \right] - (\alpha_1 - \alpha_2)(\overline{a}^{fb} - \overline{a}^*) N(\overline{a}^{fb} + \overline{a}^*)$$

(A7)
$$+ \dfrac{\alpha_2}{2P(2\alpha_1 - \alpha_2)} \sum_{n \in \Omega_N} (c_n - \overline{c})(a_n^{fb} + a_n^*)$$

$$= N(\overline{a}^{fb} - \overline{a}^*) \left[\alpha_0 - (K_1 - \alpha_1)(\overline{a}^{fb} + \overline{a}^*) \right] - \dfrac{\alpha_2 N}{2P(2\alpha_1 - \alpha_2)P} \left(\dfrac{\sigma_c^2}{2(\alpha_1 - \alpha_2)} + \dfrac{\sigma_c^2}{K_0} \right)$$

$$= N \overbrace{(\overline{a}^{fb} - \overline{a}^*)}^{-} \overbrace{\left[\alpha_0 - (K_1 - \alpha_1)(\overline{a}^{fb} + \overline{a}^*) \right]}^{?} - \overbrace{\dfrac{\alpha_2 N(4\alpha_1 - 3\alpha_2)\sigma_c^2}{4P^2 K_0^2(\alpha_1 - \alpha_2)}}^{+},$$

where eqn. (20) has been used. Part (a) is immediate from (A7). For part (b), the sign of

$\alpha_0 - (K_1 - \alpha_1)(\overline{a}^{fb} + \overline{a}^*)$ is needed. Calculate

(A8) $\overline{a}^* + \overline{a}^{fb} = \dfrac{(P\alpha_0 - \overline{c})[4\alpha_1 + 3\alpha_2(N-1)]}{2P[2\alpha_1 + \alpha_2(N-1)][\alpha_1 + \alpha_2(N-1)]},$

so that

$$\alpha_0 - (K_1 - \alpha_1)(\overline{a}^{fb} + \overline{a}^*) = \alpha_0 - \dfrac{(P\alpha_0 - \overline{c})[4\alpha_1 + 3\alpha_2(N-1)]}{2P[2\alpha_1 + \alpha_2(N-1)]}$$
(A9)
$$\overset{sign}{=} \dfrac{1}{1 - \overline{c}/(P\alpha_0)} - \dfrac{4\alpha_1 + 3\alpha_2(N-1)}{4\alpha_1 + 2\alpha_2(N-1)}.$$

Now $[4\alpha_1 + 3\alpha_2(N-1)]/[4\alpha_1 + 2\alpha_2(N-1)] > 1$. Also, $1 - \overline{c}/(P\alpha_0) \in (0,1)$ with any of these

values possible. So values of $\overline{c}/(P\alpha_0)$ can be chosen such that $\alpha_0 - (K_1 - \alpha_1)(\overline{a}^{fb} + \overline{a}^*)$ is

positive or negative. Since $\sigma_c^2 = 0$ is admissible, it follows that $\Delta_*^{fb} Q$ can be positive or negative.

On part (c), the difference in average cost, first-best less Nash, is

$$
\begin{aligned}
\text{(A10)} \quad \Delta_*^{fb} C &= \sum_{n \in \Omega_N} c_n (a_n^{fb} - a_n^*) = \sum_{n \in \Omega_N} c_n \left[\bar{a}^{fb} - \bar{a}^* + \frac{(\bar{c} - c_n)\alpha_2}{2P(2\alpha_1 - \alpha_2)(\alpha_1 - \alpha_2)} \right] \\
&= N\bar{c}(\bar{a}^{fb} - \bar{a}^*) - \frac{N\alpha_2 \sigma_c^2}{2P(2\alpha_1 - \alpha_2)(\alpha_1 - \alpha_2)} \leq 0,
\end{aligned}
$$

where eqn. (20) and inequality (19) have been used. Clearly, $d\Delta_*^{fb} C / d\sigma_c^2 \leq 0$. ∎

Proof of Result 5: For part (a), see eqn. (5) and eqn. (18) to confirm that the requirement is

$$
\text{(A11)} \quad \frac{P\alpha_0 - \bar{c}^{\$}}{2\alpha_1 + \alpha_2(N-1)} + \frac{\bar{c}^{\$} - c_i^{\$}}{2\alpha_1 - \alpha_2} = \frac{P\alpha_0 - \bar{c}}{2\alpha_1 + 2\alpha_2(N-1)} + \frac{\bar{c} - c_i}{2\alpha_1 - 2\alpha_2}.
$$

Aggregation supports

$$
\text{(A12)} \quad \bar{c}^{\$} - \bar{c} = \frac{P\alpha_0 \alpha_2(N-1) + [2\alpha_1 + \alpha_2(N-1)]\bar{c}}{2\alpha_1 + 2\alpha_2(N-1)} - \bar{c} = \frac{(P\alpha_0 - \bar{c})\alpha_2(N-1)}{2[\alpha_1 + \alpha_2(N-1)]}.
$$

This is the average poll tax $\bar{\tau}$ that needs to be imposed. Insert into (A11) to obtain

$$
\text{(A13)} \quad \left[\frac{\bar{c}^{\$} - c_i^{\$}}{2\alpha_1 - \alpha_2} = \frac{\bar{c} - c_i}{2(\alpha_1 - \alpha_2)} \right] \Rightarrow \left[c_i^{\$} - c_i = \bar{\tau} - \frac{\alpha_2(\bar{c} - c_i)}{2(\alpha_1 - \alpha_2)} \right].
$$

Part (b): The problem is to identify some τ that solves the following constrained problem:

$$
\text{(A14)} \quad \max_{\tau} P \sum_{n \in \Omega_N} q(a_n^*; A_{\backslash n}^*) a_n^* - \sum_{n \in \Omega_N} c_n a_n^* \quad \text{subject to} \quad a_i^* = \frac{P\alpha_0 - \bar{c} - \tau}{PK_1} + \frac{\bar{c} - c_i}{PK_0}.
$$

Using (5) and (6*b*), the problem can be posed as

$$\tau^* = \arg\max_\tau \sum_{n \in \Omega_N} \left(\left[\frac{P\alpha_0\alpha_1 + (K_1 - \alpha_1)(\bar{c} + \tau)}{K_1} \right] \frac{(P\alpha_0 - \bar{c} - \tau)}{PK_1} + \frac{(\alpha_2 - \alpha_1)(\bar{c} - c_n)^2}{PK_0^2} \right)$$

$$-\sum_{n \in \Omega_N} c_n \left(\frac{P\alpha_0 - \bar{c} - \tau}{PK_1} + \frac{\bar{c} - c_n}{PK_0} \right)$$

(A15)
$$= \arg\max_\tau \sum_{n \in \Omega_N} \left[\frac{P\alpha_0\alpha_1 + (K_1 - \alpha_1)(\bar{c} + \tau)}{K_1} \right] \frac{(P\alpha_0 - \bar{c} - \tau)}{PK_1} - \sum_{n \in \Omega_N} c_n \left(\frac{P\alpha_0 - \bar{c} - \tau}{PK_1} \right)$$

$$= \arg\max_\tau \left[\frac{P\alpha_0\alpha_1 + (K_1 - \alpha_1)(\bar{c} + \tau)}{K_1} \right] \frac{(P\alpha_0 - \bar{c} - \tau)}{PK_1} - \left(\frac{P\alpha_0 - \bar{c} - \tau}{PK_1} \right) \bar{c}.$$

Being a quadratic optimization problem, any interior solution is unique. Differentiate and

evaluate at τ^*:

$$-\left[\frac{P\alpha_0\alpha_1 + (K_1 - \alpha_1)(\bar{c} + \tau^*)}{K_1} \right] + \frac{(K_1 - \alpha_1)(P\alpha_0 - \bar{c} - \tau^*)}{K_1} + \bar{c} = 0$$

(A16) $\Rightarrow (K_1 - \alpha_1)(P\alpha_0 - \bar{c} - 2\tau^*) = (P\alpha_0 - \bar{c})\alpha_1$

$$\Rightarrow \tau^* = \frac{(P\alpha_0 - \bar{c})\alpha_2(N - 1)}{2(K_1 - \alpha_1)} = \frac{(P\alpha_0 - \bar{c})\alpha_2(N - 1)}{2[\alpha_1 + \alpha_2(N - 1)]},$$

as specified in eqn. (22). Insert this into the objective function in (A15) to obtain

(A17) $$\frac{(P\alpha_0 - \bar{c})^2}{4P[\alpha_1 + \alpha_2(N - 1)]} + \frac{N\alpha_1\sigma_c^2}{P(2\alpha_1 - \alpha_2)^2}.$$

On the other hand, a farm-specific tax maps cost deviations to

(A18) $$c_i + \tau - \bar{c} - \bar{\tau} \Rightarrow c_i + \tau_i - \bar{c} - \bar{\tau} = c_i + \bar{\tau} - \frac{\alpha_2(\bar{c} - c_i)}{2(\alpha_1 - \alpha_2)} - \bar{c} - \bar{\tau} = \frac{(c_i - \bar{c})}{2} \left(\frac{2\alpha_1 - \alpha_2}{\alpha_1 - \alpha_2} \right).$$

Aggregate profits under this scenario amount to

(A19) $$\frac{(P\alpha_0 - \bar{c})^2}{4P[\alpha_1 + \alpha_2(N - 1)]} + \frac{N\alpha_1\sigma_c^2}{4P(2\alpha_1 - \alpha_2)^2} \left(\frac{2\alpha_1 - \alpha_2}{\alpha_1 - \alpha_2} \right)^2 = \frac{(P\alpha_0 - \bar{c})^2}{4P[\alpha_1 + \alpha_2(N - 1)]} + \frac{N\alpha_1\sigma_c^2}{4P(\alpha_1 - \alpha_2)^2}.$$

The difference in aggregated profits, (A19) less (A17), is

(A20) $$\frac{N\alpha_1\sigma_c^2}{4P(\alpha_1 - \alpha_2)^2} - \frac{N\alpha_1\sigma_c^2}{P(2\alpha_1 - \alpha_1)^2} = \frac{N(4\alpha_1 - 3\alpha_2)\alpha_1\alpha_2\sigma_c^2}{4P(\alpha_1 - \alpha_2)^2(2\alpha_1 - \alpha_2)^2} > 0,$$

as reported. ∎

Shifted equilibrium, at
higher unit cost variance
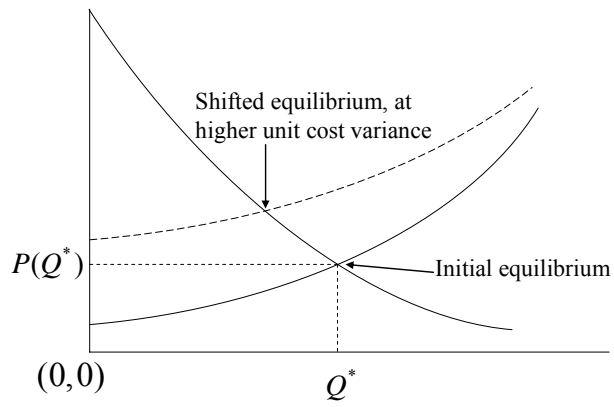
$P(Q^*)$

Initial equilibrium

$(0,0)$

Q^*

Figure 1. Demand and supply if supply increases in price