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Animal Disease and the Industrialization of Agriculture

David A. Hennessy and Tong Wang

Working Paper 10-WP 512

September 2010

**Center for Agricultural and Rural Development
Iowa State University
Ames, Iowa 50011-1070
www.card.iastate.edu**

David A. Hennessy is a professor in the Department of Economics and Center for Agricultural and Rural Development, and Tong Wang is a PhD candidate in the Department of Economics, Iowa State University.

This manuscript is forthcoming as a book chapter in *Human and Environmental Health and the Future of Animal Agriculture*, to be published by the Food and Agriculture Organization of the United Nations, edited by David Zilberman, Joachim Otte, David Roland-Holst, and Dirk Pfeiffer.

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Questions or comments about the contents of this paper should be directed to David A. Hennessy, 578C Heady Hall, Iowa State University, Ames, Iowa 50011-1070; Ph: (515) 294-6171; Fax: (515) 294-6336; E-mail: hennessy@iastate.edu.

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Abstract

The industrialization of animal agriculture has fundamentally transformed animal health markets while animal health innovations have promoted this industrialization. The subtlety of these interactions shows how little we know about agricultural industrialization. To illustrate, we consider three stylized features of industrialized animal agriculture. These are the closing off of production activities from external effects, emphasis on control, and use of biosecurity measures. We find that animal disease externalities should lead to higher stocking on any given farm, and also to *deficient* entry into animal production. Eradicating the disease in a region increases both the stocking rate per farm and the number of farms. We show that antibiotics as a control strategy should promote intensity of production and the substitution of capital for labor. Also, in long-run market equilibrium a reduction in the price of a biosecurity input could plausibly reduce both operation scale and per-animal input use, i.e., biosecurity inputs can behave like a Giffen good. External biosecurity inputs provided through public animal disease management policy may promote on-farm biosecurity, rather than crowd it out.

Keywords: animal disease, biosecurity, biotechnology, competitiveness, confined animal agriculture, economies of scale, tragedy of the commons, veterinary inputs.

JEL Classification Numbers: D2, O1, Q1

Introduction

Descartes' perspective that animals are machines, and perhaps little more, is a matter of great ethical disquiet in contemporary society (Cottingham 1978). Sweeping developments in the life sciences since about 1950 have provided technical insights on how to control life and growth in ways that have made the animal-as-machine analogy more real. The moral principles and economic tradeoffs at issue have become more clearly defined, in large part because production sciences and the systems they support demand clear definition of the production environment. Animal disease confounds control efforts, and also belies the attitude that an animal's technical performance can be abstracted from its environs.

Demand for technical performance in animal protein production is large and growing. Global meat consumption has increased at about 2.4% per annum over the period 1975-2007 owing in equal measure to population growth and growth in per capita consumption, and this pattern is projected to continue through to 2017 (Trostle 2008). In part as a response to market pressures, the dominant animal production format has changed markedly in developed countries in recent times. The newer format, often referred to as industrial animal agriculture, has also made inroads beyond the developed world (Steinfeld *et al.* 2010; Li 2009). While controversial in many ways, the approach has proved to be remarkably successful in providing animal produce suitable for processing at low market prices (Key, McBride and Mosheim 2008; MacDonald and McBride 2009; Mosheim and Knox Lovell 2009).

The general matter of this chapter is how industrial animal agriculture and animal health interact. This is a broad topic where detailed economic scrutiny has been largely absent. As typically considered, industrialization refers to a growing focus on and specialization in defined tasks accompanied by scale expansion, market development and structural realignment. While modern theories of industrial development encompass a wide set of phenomena, technical change remains central (e.g., Galor and Moav 2002). Although the endogeneity of technical

change is a primary concern of this literature, in our case we may assume it to be exogenous. This is because animal agriculture is a comparatively small sector of the global economy. The primary sources of technical change in the sector are likely to have been spillovers from innovations in the much larger human medicine, biotechnology, and manufacturing sectors.

Industrialization in animal agriculture has involved confinement in climate-controlled buildings. So confined, animals expend less energy on foraging, defense against predators and temperature regulation. The opportunity also exists to build physical protections against infectious and other diseases. In short, nature's influences can be at least partly controlled. Additionally, genetic innovations can seek to modify an animal's make-up so as to optimize production given the physical conditions under which production occurs.

The specific focus of this chapter is to provide a general understanding of how the closing off of animal herds affects production. We will do so by looking at three, among many possible, dimensions to how innovations intended to control infectious animal disease can affect the nature of production. Each dimension is modeled in a separate section. The first dimension we will consider pertains to how disease externalities affect the equilibrium structure of production. By this we mean the stocking rate and the number of farms in the sector. Surprisingly little in the way of formal analysis has been conducted on the topic, perhaps because the result was deemed obvious. As infectious disease is a public bad, one might expect there to be free riding in the form of excessive stocking per farm. In a rather standard model of commons behavior, we show that this is true. But we also show that there are *too few* farms in the sector, precisely because there is excessive stocking per farm. We develop the analysis to address how efforts to close off herds to disease exposure should affect sector structure.

The second aspect looked at is the use of control technologies. On any given farm, one way to mitigate the effects of external disease is through sub-therapeutic use of antibiotics.¹

Infectious disease and animal density are of course related. High animal density is a feature of confined animal production. Research has found animal density on a farm and/or farm density in a region to be factors in increased disease risk (Mortensen *et al.* 2002; Rose and Madec 2002; Vandekerckhove *et al.* 2004). Infectious disease among confined animals can lead to sector-wide losses of up to 70%, as in China's shrimp sector during the early 1990s (p. 178 in Smil 2000). Although scale expansion had been underway in poultry since the 1930s, the advent of antibiotics and other biosecurity innovations likely propelled the growth of confined agriculture in much of the developed world since World War II (Finlay 2004).

The use of antibiotics has come under scrutiny in recent years because of concerns that excess use could increase resistance among animal and human infection agents (Miller, McNamara, and Singer 2006; Graham, Boland and Silbergeld 2007). A prominent feature of the technology is that it promotes uniformity in animals, since a random disease event is less likely to differentiate animals in growth rate and product quality (Hayes and Jensen 2003). It is not alone in this trait, as feed uniformity-promoting technologies also promote animal performance uniformity (Ciftci and Ercan 2003; Madsen and Pedersen 2010).

Uniformity allows producers to avoid penalties for marketing lightweight animals and/or the capital costs of keeping some animals in half empty barns. Increased uniformity should also promote the substitution of capital for labor, especially when wages are high. In addition, slaughter animal uniformity allows processors to better automate packing lines. In short, uniformity-promoting technologies increase process control and so might be viewed as a factor contributing to an industrial approach. We provide a brief model to argue that the presence of

¹ The precise mechanisms through which sub-therapeutic antibiotics affect performance are unclear (Proctor 2010). They may inhibit bacteria as sources of sub-clinical disease, or suppress gut bacteria that prevent food absorption, or some combination thereof. Under any of these settings, non-use of antibiotics increases intra-herd performance variability.

antibiotics should increase scale of production, and also that antibiotics should lead to an increase in the capital-to-labor ratio.

The third dimension surrounds incentives to guard against infectious disease risk and how these incentives interact with scale of production. Once it enters a large feeding operation, disease can spread rapidly throughout the operation. Scale, biosecurity and other forms of process control tend to go hand in hand. For example, World Bank (2006) and Beach, Poulos and Pattanayak (2007) accept the Dolberg, GuerneBleich and McLeod (2005) classification of four stylized global poultry production systems. In that classification, the biosecurity level increases as production scale increases from backyard format to industrial format.

Subject to engineering constraints, the construction cost of a storage vessel scales up in proportion to the square of the scaling factor (Besanko *et al.* 2004). But capacity scales up in proportion to the cube of the scaling factor so that the unit capital cost of storage declines with an increase in scale. Similarly, a feedlot's perimeter length per unit production capacity declines with an increase in production capacity.² To the extent that biosecurity regards protecting an enterprise's perimeter, there should be scale economies in doing so.

Our third model provides two counterintuitive results. In light of discussions to this point one may infer that if the unit cost of a biosecurity input declines with an increase in capacity then production capacity and the level of biosecurity should go hand in hand. We show that the inference is not valid. One may also infer that if biosecurity risks originating off-farm are high then there will be an incentive to use biosecurity inputs more intensively on-farm, i.e., internal biosecurity substitutes for external biosecurity. To the contrary, we show that an internal biosecurity input may complement biosecurity inputs external to a farm so that efforts to

² Consider a square animal feedlot with side of length l and perimeter $4l$. If animal stocking density is 1 per unit area then animal capacity per lot is $Q = l^2$ so that $l = Q^{0.5}$. With annual maintenance cost per unit side length as $0.25z$, total annual maintenance cost is $zl = zQ^{0.5}$ or $zQ^{-0.5}$ per animal. Maintenance cost per animal is decreasing in scale.

improve the external biosecurity environment do not crowd out efforts to do so on-farm. We provide reasonable conditions under which this is so.

The chapter's format comprises a section for each of the three issues studied. We conclude with a summary and a brief discussion.

Model 1: The Commons, Social Efficiency and Deficient Entry

In a region there are N , a large number, identical livestock farms labeled as $n \in \{1, 2, \dots, N\} \equiv \mathcal{N}$. Each farm stocks s_n animals at cost $c(s_n)$, a strictly increasing and convex function.

Disease afflicts the region, with negative animal health spillovers such that output per farm is^{3,4}

$$(1) \quad q_n = F(s_n, \lambda S_{\setminus n}); \quad S_{\setminus n} = \sum_{i=1}^N s_i - s_n.$$

Here $F(s_n, \lambda S_{\setminus n})$ is strictly increasing and concave in its first argument, to reflect positive marginal product and decreasing returns to the input. It is strictly decreasing in its second argument, to reflect the adverse region-wide effects of stocking density on disease prevalence and so on productivity. Parameter $\lambda \in [0, 1]$ is an index of how open production is to disease externalities, where external disease effect $\lambda S_{\setminus n}$ has value 0 under $\lambda = 0$.

With decreasing inverse demand function $P(Q)$ and fixed cost per farm K , private profit is

$$(2) \quad \pi_n = P(Q)F(s_n, \lambda S_{\setminus n}) - c(s_n) - K; \quad Q = \sum_{n=1}^N F(s_n, \lambda S_{\setminus n}).$$

³ Throughout, all functions are assumed to be twice continuously differentiable whenever differentiability is found to be convenient for analysis.

⁴ Hardin's (1968) 'Tragedy of the Commons' pastoral example notes that common grazing "may work reasonably satisfactorily for centuries because tribal wars, poaching, and disease keep the numbers of both man and beast well below the carrying capacity of the land." But when these problems are solved "the inherent logic of the commons remorselessly generates tragedy." In this, he didn't view the disease externality environment to be the same as that of an over-exploiting resource and nor do we. But both problems involve unaccounted for negative spillovers so that the formal presentation of both problems can be similar, where the technology in (1) is very similar to the commons analysis in, e.g., p. 27 of Gibbons (1992).

The assumptions made to this point on demand and technology are henceforth referred to as the monotonicity assumptions. We posit a two-stage game in which potential entrants make the entry decision simultaneously. Knowing the number of entrants, each entering firm then decides on stocking rate. The information structure is closed loop in that information from the stage 1 entry decision is known to all who make the stage 2 stocking rate decision.

Under simultaneous-move Nash behavior, and given that N is large, the stage 2 problem involves setting s_n at level \hat{s}_n solving

$$(3) \quad P(Q)F_1(s_n, \lambda S_{\setminus n}) - c'(s_n) = 0,$$

where $F_i(\cdot)$ is the partial derivative with respect to the i th argument, $c'(s_n)$ is marginal cost and producers have been assumed to take price as given.

Since

$$(4) \quad \frac{\partial^2 \pi_n}{\partial s_n^2} = P(Q)F_{11}(s_n, \lambda S_{\setminus n}) - c''(s_n) < 0,$$

it follows that private profit is concave in its own action. Notice too that, for $i \neq n$,

$$(5) \quad \frac{\partial^2 \pi_n}{\partial s_n \partial s_i} = P(Q)\lambda F_{12}(s_n, \lambda S_{\setminus n}),$$

so that the actions are strategic substitutes whenever the cross-derivative of $F(\cdot)$ is non-positive. The sign $F_{12}(\cdot) \leq 0$, which we assume, indicates that the marginal product of own stocking rate becomes less positive whenever other farms in the region stock more. With common firms, the symmetric solution to (3) given N region firms (labeled as \hat{s}^N) requires

$$(6) \quad P(\hat{Q}^N)F_1[\hat{s}^N, \lambda(N-1)\hat{s}^N] - c'(\hat{s}^N) = 0; \quad \hat{Q}^N = NF[\hat{s}^N, \lambda(N-1)\hat{s}^N].$$

Here \hat{Q}^N is region-wide aggregate output while it is understood that $F[\hat{s}^N, \lambda(N-1)\hat{s}^N]$ is the evaluation of $F[s_n, \lambda S_{\setminus n}]$ at point $(s_n, \lambda S_{\setminus n}) = (\hat{s}^N, \lambda(N-1)\hat{s}^N)$.

Given stocking rate \hat{s}^N per firm, social welfare is

$$(7) \quad W(N) = \int_0^{\hat{Q}^N} P(u)du - Nc(\hat{s}^N) - NK; \quad \hat{Q}^N = NF[\hat{s}^N, \lambda(N-1)\hat{s}^N].$$

Writing farm profit at Nash equilibrium as

$$(8) \quad \hat{\pi}^N \equiv P(\hat{Q}^N)F[\hat{s}^N, \lambda(N-1)\hat{s}^N] - c(\hat{s}^N) - K,$$

the derivative of social welfare with respect to farm number is

$$(9) \quad \begin{aligned} W'(N) = & \hat{\pi}^N + N(N-1)\lambda P(\hat{Q}^N)F_2[\hat{s}^N, \lambda(N-1)\hat{s}^N] \frac{d\hat{s}^N}{dN} \\ & + N \left\{ P(\hat{Q}^N)F_1[\hat{s}^N, \lambda(N-1)\hat{s}^N] - c'(\hat{s}^N) \right\} \frac{d\hat{s}^N}{dN}. \end{aligned}$$

Under free entry it follows that $\hat{\pi}^N = 0$. Furthermore we may apply Nash optimality condition (3) so that derivative (9) reduces to

$$(10) \quad W'(N) = N(N-1)\lambda P(\hat{Q}^N)F_2[\hat{s}^N, \lambda(N-1)\hat{s}^N] \frac{d\hat{s}^N}{dN},$$

when evaluated at Nash equilibrium. Because $F_2(\cdot) \leq 0$, it follows that $W'(N) \geq 0$ whenever

$d\hat{s}^N / dN \leq 0$. So as to avoid technicalities at the expense of insight we make⁵

Assumption 1. Nash equilibrium exists, is unique and is locally stable.

In particular, we assume that the function

$$(11) \quad L(s; \lambda) = P(NF[s, \lambda(N-1)s])F_1[s, \lambda(N-1)s] - c'(s)$$

is decreasing in s .

Note that

$$(12) \quad L_1(s; \lambda) = P(\cdot) \{ F_{11}[\cdot] + \lambda(N-1)F_{12}[\cdot] \} + P'(\cdot) \{ F_1[\cdot] + \lambda(N-1)F_2[\cdot] \} NF_1[\cdot] - c''(\hat{s}^N).$$

⁵ See pp. 47-52 in Vives (1999) for details on uniqueness and stability in non-cooperative games.

Given $F_{11}[\cdot] < 0$, $F_{12}[\cdot] \leq 0$, $P'(\cdot) < 0$, $F_1[\cdot] > 0$ and $c''(\cdot) > 0$ it follows that $F_1[\cdot] + \lambda(N-1)F_2[\cdot] \geq 0$ ensures $L_1(s; \lambda) < 0$. If $L_1(s; \lambda) < 0$ and an equilibrium is unique, then a differentiation of (11) establishes that $d\hat{s}^N / dN$ has the sign of

$$(13) \quad \begin{aligned} & P(\cdot)F_{12}[\cdot]\lambda\hat{s}^N + P'(\cdot)\{F_1[\cdot] + N\lambda\hat{s}^N F_2[\cdot]\}F_1[\cdot] \\ & = \left(\sigma + \frac{1}{\xi_d} \right) \frac{\lambda\hat{s}^N F_1[\cdot]F_2[\cdot]}{F_1[\cdot]} P(\cdot) + P'(\cdot)F_1[\cdot]F_1[\cdot], \end{aligned}$$

when evaluated at $s_n = \hat{s}^N \forall n \in \mathcal{N}$. Here, ξ_d is the own-price elasticity of demand and $\sigma = F_{12}[\cdot]F_1[\cdot] / (F_1[\cdot]F_2[\cdot]) \geq 0$ is the elasticity of substitution between own stocking rate and other stocking rates. So $\sigma \geq -1 / \xi_d$ suffices to ensure that $d\hat{s}^N / dN \leq 0$. Condition $\sigma \geq -1 / \xi_d$ is likely to apply, as a region's absolute demand elasticity is likely to be small.

Thus, we have shown that marginal social welfare, when evaluated at Nash equilibrium participation level \hat{N} , is likely positive or $W'(\hat{N}) \geq 0$. In conclusion, we have shown

Proposition 1: Given Assumption 1, the monotonicity assumptions, $L_1(s; \lambda) < 0$ and $\sigma \geq -1 / \xi_d$, then the free entry number of livestock farms is below the number that is socially optimal.

An analogy exists with the well-known excess entry result in the theory of imperfectly competitive markets, as developed by Mankiw and Whinston (1986) and others. There the private incentive is to account for own price effects by producing too little. Foreseeing this, firms enter in anticipation of high profits. In our case, the situation is quite the reverse. The private incentive is to ignore external disease effects by stocking too densely. In anticipation of low profits due to disease, too few farms enter production.

Finally we turn to assessing how closing off the herd, or decreasing the value of λ , will impact equilibrium. The stage 2, or stocking rate, effect is established through differentiating

$$(14) \quad P\left(NF[\hat{s}^N, \lambda(N-1)\hat{s}^N]\right)F_1[\hat{s}^N, \lambda(N-1)\hat{s}^N] - c'(\hat{s}^N) = 0$$

with respect to \hat{s}^N and λ given the value of N set in stage 1. This allows us to identify the stage 2 response, or reaction function sensitivity, as

$$(15) \quad \begin{aligned} \left. \frac{\partial \hat{s}^N}{\partial \lambda} \right|_{\text{stage 2 reaction}} &= - \frac{\{P(\cdot)F_{12}[\cdot] + NP'(\cdot)F_2[\cdot]F_1[\cdot]\}(N-1)\hat{s}^N}{L_1(\hat{s}^N; \lambda)} \\ &= - \left(\sigma + \frac{1}{\xi_d} \right) \frac{P(\cdot)(N-1)\hat{s}^N F_1[\cdot]F_2[\cdot]}{F[\cdot]L_1(\hat{s}^N; \lambda)}. \end{aligned}$$

So a necessary and sufficient condition for $\partial \hat{s}^N / \partial \lambda \big|_{\text{stage 2 reaction}} \leq 0$ is that $\sigma + 1 / \varepsilon_d \geq 0$.

Proposition 2: Given Assumption 1, the monotonicity assumptions and $L_1(s; \lambda) < 0$, then the participation-conditioned stocking rate \hat{s}^N increases (decreases) with a closing off of production to infectious disease whenever $\sigma + 1 / \varepsilon_d \geq (\leq) 0$.

While the presence of the externality may encourage overstocking, the marginal effect of a more open system is to decrease stocking. The stage 1 effect is then obtained from differentiating free-entry condition $\hat{\pi}^N = 0$ with respect to N and λ when recognizing the implications for \hat{s}^N . In order to do so, use (3) to write the effect of a change in stocking rate only on farm profit under symmetric actions as

$$(16) \quad \begin{aligned} \frac{\partial \hat{\pi}^N}{\partial s} &= \{P(\cdot) + P'(\cdot)NF[\cdot]\} \{F_1[\cdot] + \lambda(N-1)F_2[\cdot]\} - c'(\cdot) \\ &= P'(\cdot)NF[\cdot]F_1[\cdot] + \{P(\cdot) + P'(\cdot)NF[\cdot]\} \lambda(N-1)F_2[\cdot], \end{aligned}$$

when evaluated at Nash equilibrium.

The total differential of firm profit with respect to participation and the disease openness parameter is

$$\begin{aligned}
& \left\{ P(\cdot)F_2[\cdot]\lambda\hat{s}^N + P'(\cdot)NF_2[\cdot]\lambda\hat{s}^N F[\cdot] + P'(\cdot)(F[\cdot])^2 \right\} dN \\
(17) \quad & + \frac{\partial \hat{\pi}^N}{\partial s} \left\{ \frac{\partial \hat{s}^N}{\partial N} \Big|_{\text{stage 2 reaction}} dN + \frac{\partial \hat{s}^N}{\partial \lambda} \Big|_{\text{stage 2 reaction}} d\lambda \right\} + \{P(\cdot) + P'(\cdot)NF[\cdot]\} F_2[\cdot](N-1)\hat{s}^N d\lambda = 0.
\end{aligned}$$

Here the middle expression acknowledges that stage 1 entrants recognize in Stackelberg fashion the stage 2 effects on stocking rate that take the number of entrants as given.

Expression (17) may be written as

$$\begin{aligned}
(18) \quad & \left\{ P(\cdot)F_2[\cdot]\lambda\hat{s}^N + P'(\cdot)NF_2[\cdot]\lambda\hat{s}^N F[\cdot] + P'(\cdot)(F[\cdot])^2 \right\} \frac{dN}{d\lambda} + \frac{\partial \hat{\pi}^N}{\partial s} \frac{\partial \hat{s}^N}{\partial N} \Big|_{\text{stage 2 reaction}} \frac{dN}{d\lambda} \\
& = - \frac{\partial \hat{\pi}^N}{\partial s} \frac{\partial \hat{s}^N}{\partial \lambda} \Big|_{\text{stage 2 reaction}} - \{P(\cdot) + P'(\cdot)NF[\cdot]\} F_2[\cdot](N-1)\hat{s}^N.
\end{aligned}$$

If demand is infinitely elastic then (18), with use of (16), simplifies to

$$(19) \quad \left(\hat{s}^N + (N-1) \frac{\partial \hat{s}^N}{\partial N} \Big|_{\text{stage 2 reaction}} \right) \lambda \frac{dN}{d\lambda} = -(N-1) \left(\hat{s}^N + \lambda \frac{\partial \hat{s}^N}{\partial \lambda} \Big|_{\text{stage 2 reaction}} \right).$$

When demand is infinitely elastic then, by equation (15),

$$\begin{aligned}
(20) \quad & \frac{\partial \hat{s}^N}{\partial N} \Big|_{\text{stage 2 reaction}} = - \frac{P(\cdot)F_{12}[\cdot]\lambda\hat{s}^N}{P(\cdot)\{F_{11}[\cdot] + \lambda(N-1)F_{12}[\cdot]\} - c''(\hat{s}^N)}, \\
& \frac{\partial \hat{s}^N}{\partial \lambda} \Big|_{\text{stage 2 reaction}} = - \frac{P(\cdot)F_{12}[\cdot](N-1)\hat{s}^N}{P(\cdot)\{F_{11}[\cdot] + \lambda(N-1)F_{12}[\cdot]\} - c''(\hat{s}^N)}.
\end{aligned}$$

so that

$$(21) \quad \hat{s}^N + (N-1) \frac{\partial \hat{s}^N}{\partial N} \Big|_{\text{stage 2 reaction}} = \hat{s}^N + \lambda \frac{\partial \hat{s}^N}{\partial \lambda} \Big|_{\text{stage 2 reaction}} = \frac{\{P(\cdot)F_{11}[\cdot] - c''(\hat{s}^N)\}\hat{s}^N}{P(\cdot)\{F_{11}[\cdot] + \lambda(N-1)F_{12}[\cdot]\} - c''(\hat{s}^N)} > 0.$$

It follows from (19) that $dN/d\lambda < 0$ and the number of entrants increases as the production system is closed off.

Proposition 3: Given Assumption 1, the monotonicity assumptions, $L_1(s; \lambda) < 0$, and infinitely elastic demand, then the number of entrants increases as the production system is closed off.

Closing off farms to external disease increases profit directly, and so promotes entry. As laid out in Proposition 2, closure increases the stocking rate on each farm. By itself, this would indirectly decrease entry. The direct effect of closing out disease dominates. Thus, closing off the production system both increases stocking rate per farm and the number of farms in a region. In other words, the growth of animal production in response to clearing a region of an infectious disease occurs at both the extensive and intensive margins.

Model 2: Antibiotics, Capitalization and Scale Come as a Package

Antibiotics facilitate control in that their use reduces product heterogeneity. Control is important because automation requires consistency (Chandler 1992). Machines cannot be readily adapted to the heterogeneities that nature allows, even among progeny. In what follows we adapt Hennessy's (2005) model of how animal heterogeneity affects processing efficiency to study how the antibiotics technology might impact the labor capital relation in animal production. There he studied the effect of animal heterogeneity on time allocated to food and worker safety on the packing line. Our present interest is with the effects that a uniformity-promoting technology, such as antibiotic treatments, have on capitalization in animal grow-out.⁶

We characterize labor as being the more flexible resource in that humans can intervene to accommodate disease-induced irregularities when machines cannot. There are two animal types, A and B, in respective proportions θ and $1 - \theta$. The labor requirement for each animal is ψ

⁶ Capital-labor substitution is but one aspect of the profound effects that uniformity-promoting technologies can have in protein and other bulk commodity markets. Other aspects, dealt with elsewhere, are their effects on the efficient extent of value added processing and technological experimentation (Hennessy, Miranowski and Babcock 2004; Hennessy 2007).

hours regardless of type under a flexible technology, which we refer to as FLEX. This technology uses no capital. The hourly wage rate is w so that the cost per animal is $C^{FLEX} = \psi w$ under FLEX.

There are two components to the labor requirement per animal under an alternative technology, referred to as CAP. The baseline component arising from intensive capitalization is $\psi - \varsigma$ where $\psi - \varsigma > 0$ and $\varsigma > 0$. Here machinery settings must be adjusted whenever the animal type encountered changes, where each adjustment consumes time α . We may imagine the machine-assisted worker moving down the barn attending to (drawing) animal types that are drawn independently where, for the sake of concreteness, the task at issue might involve using a Döppler machine to ascertain pregnancy.

If the animal being treated at any time is type A, which occurs with probability θ , then the probability that the machine has to be adjusted is $1 - \theta$. If the animal being treated is type B, which occurs with probability $1 - \theta$, then the probability that the machine has to be adjusted is θ . On average, the number of adjustments per animal treated is $\Pr(A)\Pr(B \text{ follows } A) + \Pr(B)\Pr(A \text{ follows } B) = \Theta$, $\Theta \equiv 2(1 - \theta)\theta$. So the expected number of adjustments is zero whenever animals are uniformly of either type. The expected labor cost per animal under CAP is then $(\psi - \varsigma)w + \Theta\alpha w$. Of course, capitalization comes at a cost where we specify the per-animal cost for capital intensity at $\mathcal{G}(s)$ and s is herd size as before. The total cost per animal under CAP is $C^{CAP}(\Theta) = (\psi - \varsigma)w + \Theta\alpha w + \mathcal{G}(s)$. We defer consideration on how herd size is chosen until later.

Finally, a uniformity-promoting technology (antibiotics) exists that can replace animal heterogeneity parameter θ with either 0 or 1, where the choice among 0 and 1 is of no consequence. The technology costs τ per animal.⁷ In this case the technology is $C^{ANT} =$

⁷ Antibiotics also increase feed conversion efficiency and so reduce feed costs. We might reduce

$C^{CAP}(\Theta)|_{\Theta=0} + \tau = (\psi - \varsigma)w + \mathcal{G}(s) + \tau$. That is, the antibiotics technology complements capitalization as it mitigates the adjustment costs that can attend the industrial approach. In a sense, industrialization is a form of deskilling technology (Vandeman 1995) in that the animal husbandry skill of conditioning a response to the animal type is obviated. The FLEX technology does not benefit from the antibiotics technology because there are no adjustment costs to mitigate. The two parameters we will focus on are wage w and heterogeneity status Θ . In this light, the overall cost function may be written as

$$(22) \quad U(s; w, \Theta) = \min \begin{cases} \psi w & \text{(Labor flexible, or FLEX);} \\ \mathcal{G}(s) + (\Theta\alpha + \psi - \varsigma)w & \text{(Industrialization only, or CAP);} \\ \mathcal{G}(s) + \tau + (\psi - \varsigma)w & \text{(Industrialization + Antibiotics, or ANT).} \end{cases}$$

The technology with the highest non-wage cost is ANT, at $\mathcal{G}(s) + \tau$ per animal. FLEX has the lowest non-wage cost, at 0 per animal. ANT is the technology with the lowest wage cost, as represented by $(\psi - \varsigma)w$. If $\Theta\alpha < \varsigma$ then $\Theta\alpha + \psi - \varsigma < \psi$ and CAP has the second lowest wage cost.⁸ If $\Theta\alpha > \varsigma$, or there is a large amount of heterogeneity, then the FLEX technology dominates CAP in that the per-animal fixed cost and the wage bill are both smaller. In that case, industrialization will only occur in the presence of the complementary antibiotics technology. The complementary technologies come in quantum packages. Thus, we consider two cases.

Case I: Under $\Theta\alpha > \varsigma$ we need only compare FLEX with package technology ANT. The breakeven wage such that ANT is chosen is $w' = [\mathcal{G}(s) + \tau] / \varsigma$. Were $w > w'$ then ANT would be preferred, as the gains from industrialization in the presence of the uniformity-promoting technology more than compensate for the additional fixed costs associated with the technology

τ by feed costs to accommodate this effect, and the result could be negative, in which case feed cost savings alone would justify technology adoption. This effect is not related to the industrialization phenomenon as we study it here. For the sake of focus, we ignore it.

⁸ Knife-edge cases of indifference, such as when $\Theta\alpha = \varsigma$, are ignored as the implications warrant no additional comments.

package. Were $w < w'$ then FLEX would be preferred, as labor cost savings do not justify the capital investment made.

Case II: Under $\Theta\alpha < \varsigma$ it is possible, but not assured, that CAP is the technology for some wage. Were $w < \tau / (\Theta\alpha)$ then CAP would dominate labor-saving ANT because the labor-saving benefits of making raw materials more uniform are small when compared with the per-animal cost. Then we need only compare CAP with FLEX. If $w > \tau / (\Theta\alpha)$ then ANT dominates CAP and we need only compare ANT with FLEX.

Were $w < \min[\tau / (\Theta\alpha), \mathcal{G}(s) / (\varsigma - \Theta\alpha)]$ then FLEX, being the least labor-saving technology, would be preferred overall, as the reduction in the wage bill under CAP, $(\varsigma - \Theta\alpha)w$, does not justify the capital needed to effect this reduction, $\mathcal{G}(s)$. Were $\mathcal{G}(s) / (\varsigma - \Theta\alpha) < w < \tau / (\Theta\alpha)$ then CAP would be preferred. Here, wages are low enough to prefer CAP over labor-saving ANT but high enough to prefer CAP over FLEX, which is labor intensive relative to CAP.

Under wage interval $[\mathcal{G}(s) + \tau] / \varsigma > w > \tau / (\Theta\alpha)$, then wages are sufficiently low that FLEX dominates labor-saving ANT yet sufficiently high that ANT dominates CAP, so that FLEX is preferred overall. If $w > \max[\tau / (\Theta\alpha), [\mathcal{G}(s) + \tau] / \varsigma]$ then wages are sufficiently high that ANT, being the most labor-saving technology of all, dominates.

What can be stated about the industrialization process from the above? First, as w increases then the incentive to switch out of FLEX increases; witness the collapse of peasant farming in China over the past two decades. A more interesting story surrounds the role of biotechnology in industrialization. Here Θ is likely to decrease upon adoption of such genetic technologies as artificial insemination and sex sorting. It is useful to write

$$(23) \quad U(s; w, \Theta) = \psi w + \min[0, \mathcal{G}(s) + (\Theta\alpha - \varsigma)w, \mathcal{G}(s) + \tau - \varsigma w].$$

Figure 1, with wage on the horizontal axis and $U(s; w, \Theta) - \psi w$ on the vertical axis, shows what happens as the value of Θ declines. Particular attention is paid to CAP cost $\mathcal{G}(s) + (\Theta\alpha - \varsigma)w$. The breakeven wage when comparing FLEX with ANT is at $w = [\mathcal{G}(s) + \tau] / \varsigma$, as identified by \times in the figure. The value of Θ such that $\mathcal{G}(s) + (\Theta\alpha - \varsigma)w = 0$ at $w = [\mathcal{G}(s) + \tau] / \varsigma$ is $\hat{\Theta} = \varsigma\tau / ([\mathcal{G}(s) + \tau]\alpha)$. Were $\Theta > \hat{\Theta}$ then CAP would not be the optimal technology at any wage. But any wage above $w = \mathcal{G}(s) / (\varsigma - \Theta\alpha)$ will support package technology ANT while any wage below that will support FLEX. Two lines are provided for the CAP cost, one where $\Theta > \hat{\Theta}$ and one where $\Theta < \hat{\Theta}$. Were $\Theta < \hat{\Theta}$ then there would be a positive wage interval for which CAP is optimal. If wages are low enough, but not too low, and animal biotechnology is sufficiently well developed then industrialization can occur without the use of antibiotics. But in a high-wage economy the package technology will be chosen unless antibiotics are banned.

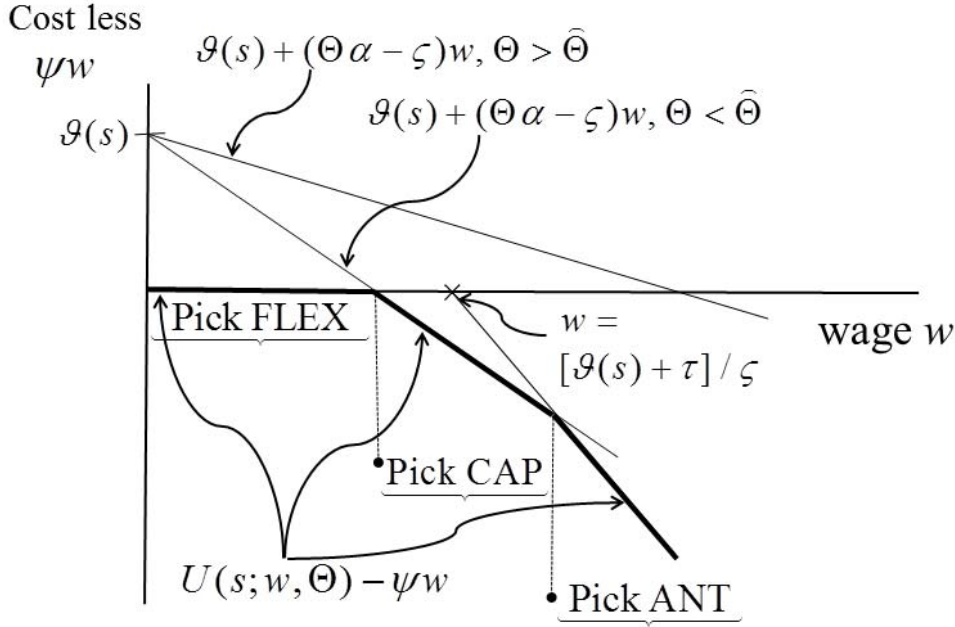


Figure 1. Wage, technology choice and animal uniformity

Now we consider optimal herd size s . Let unit capacity cost be $\kappa(s)$, which is assumed to be U shaped. These costs pertain to environmental compliance, agency costs due to management control and input acquisition costs. It is quite plausible that scale economies are associated with capitalization, so we assume that $\mathcal{G}(s)$ is decreasing such that total unit costs, $U(s; w, \Theta) + \kappa(s)$, remain U shaped. Unit costs are then

$$(24) \quad U(s; w, \Theta) + \kappa(s) = \psi w + \min[0, \mathcal{G}(s) + (\Theta\alpha - \zeta)w, \mathcal{G}(s) + \tau - \zeta w] + \kappa(s).$$

Under technology homogeneity among a large number of farms and free entry, equilibrium scale involves minimizing average cost. If Θ and τ are large enough then the production format is FLEX and the scale problem is that of choosing s to minimize $\kappa(s)$. If Θ and/or τ fall because of animal health or biotechnology innovations, or if wages rise, then the problem will change to that of choosing s to minimize $\mathcal{G}(s) + \kappa(s)$ with $\arg \min \mathcal{G}(s) + \kappa(s) > \arg \min \kappa(s)$. A discrete increase in scale can attend the adoption of the uniformity-promoting technology, as suggested by Finlay (2004). So antibiotics, capitalization and scale can come as a complementary package, the adoption of which depends on external forces.

Model 3: Biosecurity and Scale

Biosecurity costs take many forms, including design and use of procedures, guarding against animal and other pathogen vectors, using quarantine and showering facilities, and vaccinating. Most are likely to display declining costs per unit production capacity. For example, truck wash facilities will be mostly idle for a small production unit, an annual employee training endeavor may as easily accommodate five or ten attendees, and it may be possible to obtain additional feed from the same source without scaling up attribute tests.

We develop a model of how scale economies in biosecurity costs affect size of operation and use of biosecurity inputs. Hennessy, Roosen and Jensen (2005) study scale in a unit cost

minimization model where each animal brings an independent and identically distributed disease risk while any diseased animal infects the entire feedlot. It is distinguished from the model to be presented in that (a) the biosecurity input's unit cost is scale neutral, (b) the independent, identical distribution feature creates a source of scale diseconomy rather than a source of scale economy, and (c) it is less articulated in characterizing the roles of biosecurity inputs.

Our model assumes that the animal output market is perfectly competitive and all producers are identical in the technology available to them. Let $G(z;v) > 0$ represent expected output from one animal. Here z is some biosecurity input that comes with scale economies and v is some pertinent beneficial external natural or socioeconomic factor. Possibilities for v include the state of biosecurity on other farms, the quality of animal public health infrastructure, or animal transportation regulations. Both arguments are beneficial so that $G_z(\cdot) > 0$ and $G_v(\cdot) > 0$.

With Q animals, expected output is $QG(\cdot)$. We require the input's marginal productivity to decline, or $G_{zz}(\cdot) < 0$. Since we set $G(z;v)|_{z=0} \equiv f(v) > 0$, the input is not essential for production. The effective unit price of z is $J(Q)r$ where $r > 0$ is a cost parameter reflecting the state of knowledge on producing the biosecurity input and where $J(Q) > 0$. Conditions $0 < J_Q(Q) < \bar{J}(Q)$, $\bar{J}(Q) \equiv J(Q)/Q$, are imposed to reflect scale economies in the biosecurity input. This means that $\bar{J}(Q)$, which reflects how biosecurity unit costs change with scale, is decreasing. Costs other than the biosecurity input amount to $C(Q)$, which can be viewed as the standard minimized cost of farming Q animals and $\bar{C}(Q) \equiv C(Q)/Q$ is the unit cost for these non-biosecurity inputs.

As in Model 2, equilibrium scale is that which minimizes unit costs. The objective function is therefore

$$(25) \quad T(Q, z; r, v) = \frac{\bar{B}(Q, z; r)}{G(z; v)}; \quad \bar{B}(Q, z; r) \equiv \bar{C}(Q) + \bar{J}(Q)rz.$$

For example, if $J(Q) = Q$, a case we have ruled out, then the biosecurity indicator is scale neutral such that scale and biosecurity choices will be determined independently. Expression $\bar{B}(Q, z; r)$ is held to be strictly convex in Q at an optimum, i.e., $C_{QQ}(\cdot) + J_{QQ}(\cdot)rz > 0$ where it is standard to assume $C_{QQ}(\cdot) > 0$. The optimality conditions are

$$(26) \quad (26a) \quad T_Q(\cdot) = \frac{\bar{B}_Q(\cdot)}{G(\cdot)} = 0; \quad (26b) \quad T_z(\cdot) = \frac{G(\cdot)\bar{J}(\cdot)r - G_z(\cdot)\bar{B}(\cdot)}{[G(\cdot)]^2} = 0.$$

The optimizing choices are written as z^* and Q^* . Second-order conditions are developed in the appendix and convexity is assumed. It is noteworthy that

$$(27) \quad T_{Qz}(\cdot) = \frac{\bar{J}_Q(\cdot)r}{G(\cdot)} < 0.$$

This means that an increase in the biosecurity input makes average cost less sensitive to scale. The decisions are technical complements in that more of z tends to make an increment of scale more beneficial in reducing average cost.⁹

Effect of Subsidy or Biosecurity Innovation

Intuition would suggest that the optimal choice of biosecurity input level should increase with a decrease in the input's price while the effect on scale of production is less clear. In the appendix we show that either of (i) a biosecurity input subsidy or (ii) an improvement in the biosecurity input production technology that leads to a reduction in its market price, have ambiguous effects on input use and production scale.

⁹ As we shall show, technical complementarity does not imply economic complementarity. An increase in biosecurity price r may increase the optimum level of scale.

Consider the effect of an increase in biosecurity price r on biosecurity level z^* when production scale is fixed. Input choice z^* declines with an increase in own price, as one might expect. However, the indirect effect on choice z^* when mediated through scale is positive. This is because, from (27) above and owing to scale economies, an increase in scale Q lowers the unit cost $J(Q)r$ of the biosecurity input z . Which effect dominates in practice is a matter that needs to be established by empirical analysis.

Regarding scale, the direct effect of an increase in r when holding the value of input z fixed is positive because an increase in scale reduces the input's effective unit cost. However, the indirect effect on scale when allowing biosecurity level z to adjust optimally is negative. This is because relation (27) shows that the input complements production scale so that an increase in price r should decrease the incentive to scale up through a direct negative effect on use of the biosecurity input.

Effect of Improvement in External Biosecurity Environment

In the appendix we show that improvements in the external biosecurity environment in which the firm operates are likely to increase both (i) operation scale and (ii) use of the biosecurity input. The finding hinges on a technical assumption, the requirement that¹⁰

$$(28) \quad R(z;v) \equiv \frac{\partial^2 \ln[G(z;v)]}{\partial z \partial v} \geq 0$$

where defined. If productivity function $G(z;v)$ satisfies (28) then it is said to be log-supermodular (Athey 2002) where $R(z;v) \geq 0$ may be viewed as a complementary technical relation between the levels of internal and external biosecurity.¹¹ The condition requires that an increase in argument v generate an increase in the input's productivity when expressed in

¹⁰ The derivatives are partial to acknowledge that an optimally chosen value of z will indeed depend on v . So a total derivative with respect to v would account for this indirect effect.

¹¹ Of course, (27) does not imply that $dz^* / dv > 0$ as scale effects need to be considered.

fractional terms. In view of monotonicity assumptions $G_z(\cdot) > 0$ and $G_v(\cdot) > 0$, a necessary condition for (28) is $G_{zv}(\cdot) > 0$.¹²

There is reason to believe that $R(\cdot) \geq 0$. We have previously presented v as an external factor that increases productivity. It could do so stochastically, and so could represent the probability of avoiding some external source of productivity loss. Let the realization of an adverse event lead to constant productivity level $G(z; v)|_{v=0} = \hat{G} \geq 0$. Absent the adverse event, productivity would be $G(z; v)|_{v=1} = \hat{G}(z)$, an increasing function. The productivity function is then $G(z; v) = (1 - v)\hat{G} + v\hat{G}(z)$ so that $R(\cdot) = \hat{G}\hat{G}_z(z) / [G(z; v)]^2 \geq 0$.

Further support for property $R(\cdot) \geq 0$ arises from an economic perspective on species genetic manipulation. Animals bred to perform well in confinement can be viewed as allocating feed inputs largely toward market outputs (meat, eggs, milk). Free-range animals will need to allocate more energy toward other bodily functions, such as a robust skeleton and immune system. This is the resource allocation hypothesis.¹³ Thus, breeding innovations may be Hicks biased in favor of high biosecurity use, tilting productivity function $G(\cdot)$ up when z is high but down when z is low. Figure 2 illustrates requirement $R(z; v) \geq 0$. In it, output for confined animals will be higher only if on-farm biosecurity is high. Free-range animals are presented as performing well in comparison when biosecurity is low because they are hardier. But they perform poorly in comparison when biosecurity inputs reduce the need for allocating energy toward bodily protection.

¹² The condition is satisfied whenever $v_2 > v_1$ and $G_z(z; v_2)$ is larger than $G_z(z; v_1)$ in the monotone likelihood ratio sense, an ordering widely used in information economics (p. 485 in Mas-Colell, Whinston and Green 1995). Note that z can be a concretely defined quantity, as with veterinarian hours per 1,000 animals. So too can v , perhaps as a government animal public health infrastructure metric at the national level. A rich data set would allow for statistical tests on condition (28).

¹³ See p. 254 in Greger (2007) for a brief review of evidence on the hypothesis.

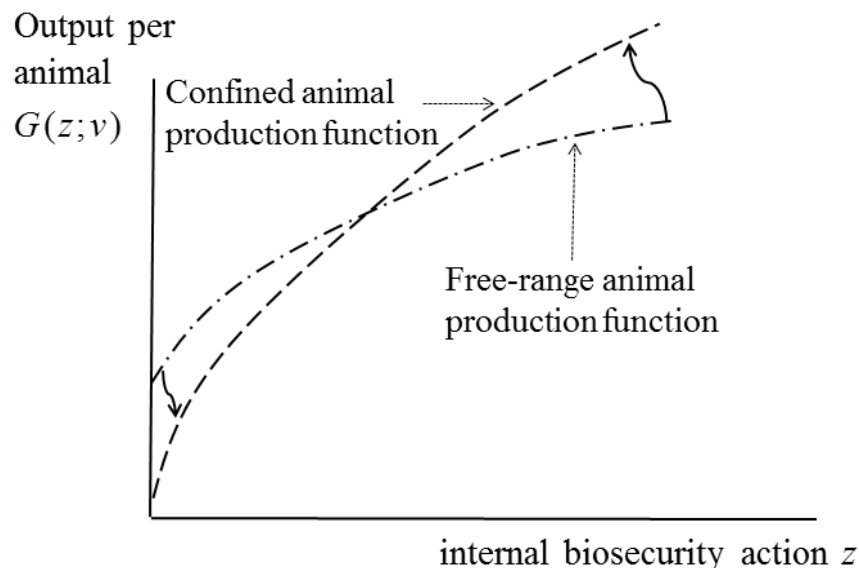


Figure 2. Relation between biosecurity input and productivity under resource allocation hypothesis

Why should an increase in external biosecurity increase both internal biosecurity and scale? If external biosecurity is poor then a grower may reckon her herd will almost inevitably contract the disease and may see little point in seeking to protect her farm. If external biosecurity is good then the grower may feel more in control of the farm's destiny. The grower will increase use of the biosecurity input, and complementarity relation (27) then justifies an increase in scale. A similar point has been made in Ifft, Roland-Holst and Zilberman (forthcoming 2011), who find validation in behavior on Viet Nam poultry farms.

We conclude that our model provides some support for the idea that a producer who is more confident that an exogenous biosecurity risk to productivity will not materialize is more likely to increase (a) own-farm biosecurity and also (b) scale of operation. Point (a) suggests that public animal health inputs may not crowd out their privately provided counterparts while point (b) posits a role public policy may unwittingly play in the industrialization process.¹⁴ Such firm-

¹⁴ To obtain a better sense for the responses developed upon in discussions to this point, bear in mind that these are market equilibrium responses where output price is endogenous and equal to unit cost.

level complementarities have long been studied in more general contexts, see Milgrom and Roberts (1990a). What is most interesting in our model is that the responses can be mutually reinforcing across farms in a region. Parameter ν may represent a summary statistic of biosecurity activities by other farms in the region. Then the $R(\cdot) \geq 0$ condition ensures that the best strategic response of a given farm to higher external protection is to increase on-farm protection, and a virtuous circle plays out. The game is one of strategic complementarities (i.e., between firms), as studied in Milgrom and Roberts (1990b). In general, there is no guarantee that any equilibrium is unique (Echenique 2007).

Conclusion

The path from pastoral agriculture toward industrial format animal farming has not been smooth. It has been faster for some farmed species, where avian produce acquiesced more quickly than hogs. Ruminants in general are still grown pastorally for at least some of their lives. Nonetheless, from a distance the rough-stroke outline of the paths taken have been quite similar where prominence must be assigned to technologies that control how inputs perform so that capital can operate efficiently. Animal health inputs must rank high among technologies that control input attributes as mortality, morbidity and cross-infection can disrupt throughput and lead to complete shutdowns for extended periods. However the quintessential control input is genetic composition for it allows the nature of primary input to be rendered homogeneous, so that only environmental considerations remain.

This chapter has sought to characterize aspects of how animal health inputs fit with production format. The interactions involved are many and varied, so, rather than trying to dine with a Swiss Army knife, we tailor three separate models. Model 1 shows that the reference view of infectious disease as a form of commons problem involving excess stocking is incomplete. The disease also induces socially suboptimal entry. Consequently, disease

management innovations such as fencing commonage and regulating livestock marts are likely to have intricate consequences for productivity and welfare. Although admittedly very simplistic, this model warrants further scrutiny.

Model 2 looks inside the farm by focusing on an innovation that mitigates disease externalities. In particular, we emphasize the role that antibiotics play as a means of reducing the irregularities that inhibit capital substitution for labor. We show how antibiotics enable capitalization to substitute for labor. We also show how antibiotics can come as part of a complementary package involving capital inputs, to be adopted entirely or not at all, when the extent of non-uniformities that antibiotics can mitigate is large. In this sense the removal of antibiotics could reduce the incentive to capitalize in high-wage countries. Innovations in genetic control, however, make this possibility less likely, at least under our model assumptions. One final comment on the model is that, in light of scale economies in physical asset investments, an external shock in technology or wage levels can see a fundamental transformation in production paradigm to the industrial format.

The third model is motivated by the observation that biosecurity investments are likely to exhibit scale economies so that scale and biosecurity investments are likely technical complements. We show that a decline in the unit cost of a biosecurity investment can reduce optimal scale. This is because one motive for increasing scale in the presence of biosecurity investments is to take best advantage of scale economies and this incentive weakens when the biosecurity investment becomes less costly. So while intuition might suggest that any subsidy or innovation in technologies associated with capital-intensive production will ensure more of it, we beg to differ. The model is also used to argue that public investments in securing a region from infectious disease can complement both scale and internal biosecurity investments. If this is the case, then an external shock could generate mutually reinforcing beneficial effects rippling through a decentralized production system. The sorts of shocks at issue could include

efforts to improve technical proficiency or to reduce government corruption in the provision of public sector veterinary health services.

Stepping back to survey the recent evolution of animal production, we readily acknowledge a variety of shortcomings in our general framework. The approach is entirely production-driven, without reference to environmental bads or demands for goods other than cheap animal produce. It ignores the role of feedstuffs. Cheap in situ forage complements low-input pastoral systems that are open to disease, and health inputs in such systems might be best embodied in hardy genetics rather than drugs or thick perimeter walls.

Finally, a tale of structural dynamics may have been missed when pointing to technology spillovers as the source of technological change. Once an industrial format takes root, much subsequent innovation is endogenous. After all, innovations translated from manufacturing processes have typically dealt with non-biological subjects while those from human medicine pertain to a very different market environment. Looking forward, the sector's horizon is overcast with environmental, animal welfare, zoonotic disease and other concerns that affect the sector in unique ways. Reservoirs of capacity for endogenous innovation will be required if animal production is to succeed in adapting.

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Appendix

Second-order conditions: Compute

$$(A1) \quad T_{qq}(\cdot) = \frac{\bar{B}_{qq}(\cdot)}{G(\cdot)} > 0; \quad T_{zz}(\cdot) = -\frac{G_{zz}(\cdot)\bar{B}(\cdot)}{[G(\cdot)]^2} > 0;$$

where optimality conditions $T_q(\cdot) = 0$ and $T_z(\cdot) = 0$ have been applied. The cross-derivative for the average cost function is $T_{qz}(\cdot) = \bar{J}_q(\cdot)r / G(\cdot) < 0$, where optimality condition (26a) and

computation $\bar{J}_Q(\cdot) = [QJ_Q(\cdot) - J(\cdot)] / Q^2 \stackrel{\text{sign}}{=} J_Q(\cdot) - \bar{J}(\cdot) < 0$ have been applied. Finally,

$$(A2) \quad \Phi \equiv T_{QQ}(\cdot)T_{zz}(\cdot) - [T_{Qz}(\cdot)]^2 = -\frac{\overbrace{G_{zz}(z)\bar{B}(\cdot)\bar{B}_{QQ}(\cdot)}^{<0}}{[G(\cdot)]^3} - \frac{\overbrace{[\bar{J}_Q(\cdot)]^2 r^2}^{>0}}{[G(\cdot)]^2}.$$

Convexity on $T(\cdot)$ requires $\Phi > 0$. If cost parameter $r > 0$ is small (i.e., the biosecurity innovation has been well developed) or economies of scale are small (i.e., $|\bar{J}_Q(Q)|$ is small) then $\Phi > 0$ is likely. Otherwise (A2) may be violated, so that discontinuous scale and input responses result from a small parameter change. Henceforth we assume $\Phi > 0$.

Subsidy and innovation: Define $H(\cdot) = G(\cdot) - G_z(\cdot)z > 0$ where $H(\cdot) > 0$ is due to $G_z(\cdot) < G(\cdot)/z$ on $z \geq 0$ whenever $G(\cdot)$ is increasing and concave in z with $G(0;v) > 0$. Using (26):

$$(A3) \quad T_{Qr}(\cdot) = \frac{\bar{J}_Q(\cdot)z}{G(\cdot)} < 0; \quad T_{zr}(\cdot) = \frac{\bar{J}(\cdot)H(\cdot)}{[G(\cdot)]^2} > 0.$$

Differentiate system (26) completely with respect to (Q, z, r) and then invert to obtain:

$$(A4) \quad \begin{aligned} \frac{dz^*}{dr} &= \frac{T_{Qz}T_{Qr} - T_{QQ}T_{zr}}{\Phi} = \frac{\overbrace{[\bar{J}_Q(\cdot)]^2 rz}^{>0}}{[G(\cdot)]^2 \Phi} - \frac{\overbrace{\bar{B}_{QQ}(\cdot)\bar{J}(\cdot)H(\cdot)}^{>0}}{[G(\cdot)]^3 \Phi}; \\ \frac{dQ^*}{dr} &= \frac{T_{Qz}T_{zr} - T_{zz}T_{Qr}}{\Phi} = \frac{\overbrace{\bar{J}_Q(\cdot)r\bar{J}(\cdot)H(\cdot)}^{<0}}{[G(\cdot)]^3 \Phi} + \frac{\overbrace{\bar{J}_Q(\cdot)\bar{B}(\cdot)G_{zz}(\cdot)z}^{>0}}{[G(\cdot)]^3 \Phi}. \end{aligned}$$

Both expressions are indeterminate in sign without further information. Plausible functional forms are readily identified such that both derivatives are positive.

For the own-price response, $-T_{QQ}T_{zr} / \Phi < 0$ characterizes the direct effect. The indirect effect, through the effect on Q , is $T_{Qz}T_{Qr} / \Phi > 0$. This is because an increase in scale lowers the unit cost of the biosecurity input owing to scale economies emphasizing that input's cost. For the scale response the direct effect is represented by $-T_{zz}T_{Qr} / \Phi > 0$. The indirect effect on scale

when mediated through the biosecurity input, is $T_{Qz}T_{zr} / \Phi < 0$.

External effects: Differentiate system (26) completely with respect to (Q, z, v) and then use the optimality conditions:

$$(A5) \quad \begin{pmatrix} \frac{\bar{B}_{QQ}(\cdot)}{G(\cdot)} & \frac{\bar{J}_Q(\cdot)r}{G(\cdot)} \\ \frac{\bar{J}_Q(\cdot)r}{G(\cdot)} & -\frac{G_{zz}(\cdot)\bar{B}(\cdot)}{[G(\cdot)]^2} \end{pmatrix} \begin{pmatrix} \frac{dQ^*}{dv} \\ \frac{dz^*}{dv} \end{pmatrix} = \begin{pmatrix} 0 \\ \frac{R(\cdot)\bar{B}(\cdot)}{G(\cdot)} \end{pmatrix}.$$

So

$$(A6) \quad \frac{dQ^*}{dv} = -\frac{\bar{J}_Q(\cdot)r\bar{B}(\cdot)}{\Phi[G(\cdot)]^2} R(\cdot)^{\text{sign}} = R(\cdot); \quad \frac{dz^*}{dv} = \frac{\bar{B}_{QQ}(\cdot)\bar{B}(\cdot)}{\Phi[G(\cdot)]^2} R(\cdot)^{\text{sign}} = R(\cdot).$$

Explicit Solution

Set $C(Q) = Q^{\beta_1+1}$, $\beta_1 > 0$, and $J(Q) = Q^{1-\beta_2}$, $\beta_2 \in (0,1)$.¹⁵ Writing $\lambda = \beta_2 / \beta_1$, eqn. (26a)

provides $Q^{\beta_1-1} = \lambda Q^{-(1+\beta_2)} r z$ and (26a)-(26b) solve as

$$(A7) \quad (A7i) \quad \frac{G(z^*;v)}{G_z(z^*;v)} = (1+\lambda)z^*; \quad (A7ii) \quad Q^*(z^*) = (\lambda r z^*)^{1/(\beta_1+\beta_2)}.$$

So for these functional forms, and regardless of the choice of some $G(z)$ function that supports an interior solution, the z that minimizes unit cost is independent of unit cost parameter r .

Finally, and as a specification distinct from $G(\cdot) = (1-v)\hat{G} + v\hat{G}(\cdot)$ previously discussed, let $G(z;v) = z / [\mu + \sigma(v)z]$. This is the logistic function form. With constant $\mu > 0$ and $\sigma(v) > 0$, the external factor influences this distribution through $\sigma_v(v) < 0$ so that $G_v(\cdot) > 0$ and an increase in the factor reduces the unit cost of output. Then $G_z(\cdot) = \mu / [\mu + \sigma(\cdot)z]^2$, $G_z(\cdot) / G(\cdot) = \mu / \{z[\mu + \sigma(\cdot)z]\}$, and $R(\cdot) = -\mu\sigma_v(\cdot) / [\mu + \sigma(\cdot)z]^2 > 0$. An improvement in external

¹⁵ Were $r = 0$, which we rule out as both unrealistic and uninteresting, then $\bar{B}(\cdot) = Q^{\beta_1}$. The scale and biosecurity choice variables would be separable and $Q^* = 0$. This is the classical setting whereby an infinity of firms each produce an infinitesimal amount, and no long-run equilibrium actually exists (p. 337 in Mas-Colell, Whinston and Green 1995).

biosecurity increases productivity, and also the marginal productivity of the biosecurity input when calculated in percentage terms.

System (A7) then solves as

$$(A8) \quad (Q^*, z^*) \in \left\{ (0,0), \left(\left(\frac{\lambda^2 \mu r}{\sigma(\cdot)} \right)^{1/(\beta_1 + \beta_2)}, \frac{\mu \lambda}{\sigma(\cdot)} \right) \right\}.$$

It will be shown later that $(Q^*, z^*) = (0,0)$ is not optimal, leaving only the interior solution.

Notice that the equilibrium value for productivity is $G(\cdot) = \lambda / [(1 + \lambda)\sigma(v)]$, which is increasing in the beneficial external natural or socioeconomic factor, v .

To understand why $dQ^* / dr > 0$ in (A8), consider the direct and indirect effects of an increase in the price of biosecurity. An increase in r increases the incentive to reduce unit costs by increasing scale. This is the direct effect on scale. The indirect effect, via complementarity relation (27), is that a higher value of r reduces the incentive to use the biosecurity input and this reduces the incentive to increase scale. Relation (A8) shows that the direct effect wins out.

Expression z^* in (A8) also indicates that the direct and indirect effects of an increase in the value of r exactly offset. Although (A8) doesn't show $dz^* / dr > 0$, this is possible, i.e., there could conceivably be a positive own-price effect in long-run equilibrium. The possibility arises because the endogenous scale choice alters the effective unit cost of the input in a manner broadly similar to how the income effect mediates price response in demand theory. As with Giffen goods, the indirect effect can overwhelm the direct effect.

It follows from $\sigma_v(\cdot) < 0$ that $dz^* / dv > 0$ and $dQ^* / dv > 0$, so that more external biosecurity coaxes out more internal biosecurity and increases scale. The example supports the hypothesis that more public health inputs do not crowd out (i.e., do complement) private activities to safeguard animal health but do promote large-scale production. In the example, strengthening the external biosecurity environment complements incentives for internal

biosecurity and also encourages a scaling up of production activities. With better external biosecurity, the animal production format is more likely to become industrial than backyard.

Finding the optimum in the explicit solution: Pose the problem as having two stages:

$$(A9) \quad \min_z \min_{Q|z} T(\cdot).$$

Upon inserting (A7ii) into the given $C(\cdot)$ and $J(\cdot)$ functions, cost function (25) becomes

$$(A10) \quad \begin{aligned} \hat{T}(\cdot) &= \frac{(Q^*)^{\beta_1} + (Q^*)^{-\beta_2} r z^*}{z^* / [\mu + \sigma(\cdot) z^*]} = \mu \frac{(Q^*)^{\beta_1}}{z^*} + \sigma(\cdot) (Q^*)^{\beta_1} + (Q^*)^{-\beta_2} r [\mu + \sigma(\cdot) z^*] \\ &= \Gamma \times \left[\mu (z^*)^{-\beta_2/(\beta_1+\beta_2)} + \sigma(\cdot) (z^*)^{\beta_1/(\beta_1+\beta_2)} \right]; \quad \Gamma \equiv \left[\lambda^{\beta_1/(\beta_1+\beta_2)} + \lambda^{-\beta_2/(\beta_1+\beta_2)} \right] r^{\beta_1/(\beta_1+\beta_2)} > 0; \end{aligned}$$

which is the solution to the inner conditional optimization problem in (A9). When $z^* = 0$ then

$(z^*)^{\beta_1/(\beta_1+\beta_2)} = 0$ but $(z^*)^{-\beta_2/(\beta_1+\beta_2)} \rightarrow \infty$ so that $(Q^*, z^*) = (0, 0)$ maximizes unit cost and cannot

be optimal. To establish the problem's overall convexity, differentiate the final expression for

$\hat{T}(\cdot)$ in (A10) twice with respect to the remaining endogenous variable, z , and insert $z^* =$

$\mu \lambda / \sigma(v)$ to obtain

$$(A11) \quad \frac{\Gamma \beta_2 \left[\mu (\beta_1 + 2\beta_2) - \sigma(\cdot) \beta_1 z^* \right] (z^*)^{-(2\beta_1+3\beta_2)/(\beta_1+\beta_2)}}{(\beta_1 + \beta_2)^2} = \frac{\Gamma \beta_2 \mu (z^*)^{-(2\beta_1+3\beta_2)/(\beta_1+\beta_2)}}{\beta_1 + \beta_2} > 0.$$

Thus the problem is indeed convex and the interior solution is optimal.