Economically Determined Livestock Quarantine Zones

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Selected Paper for presentation at the Western Agricultural Economics Association Annual Meeting, Honolulu, Hawaii, June 30-July 2, 2004

Abstract

This paper examines economic factors present when setting quarantine zones for contagious livestock diseases like foot-and-mouth disease (FMD). A conceptual model explores the trade-offs as zone size expands. One trade-off is between the cost of economic activity inside the zone and the benefits of reduced disease spread. There are also agricultural and non-agricultural price effects to consider. Two hypothetical counties are constructed to illustrate the ideas. Town or city location is critical to the size. Livestock density is inversely related to zone size with low density regions able to reduce disease spread at relatively low cost.

Key Words: livestock disease, economic impacts, quarantines

Economically Determined Livestock Disease Quarantine Zones

Several livestock diseases are contagious with transmission vectors including animal to animal contact, transmission through air, ground, or water, or via carriers such as insects, equipment, and clothing. When an outbreak of a highly contagious disease, like foot-and-mouth disease (FMD) occurs, the customary practice used to control the disease is to establish quarantine and surveillance zones surrounding infected premises. The intention of such zones is to limit, hopefully halt, the spread of the disease to prevent larger losses to the livestock sector. Off-farm movements are prohibited and trade outside the zone may be banned or restricted. The recent FMD outbreak in the United Kingdom demonstrates how costly such zones can be to non-agricultural industries. Poe (2002) gives costs figures indicating that of the $12 billion total cost, $8 billion fell on the tourist industry due to the policy of establishing movement restrictions.

Existing rules call for zones of fixed radii surrounding the site of an outbreak. But the British experience suggests that there is an optimum size for a quarantine zone which balances the losses incurred by those in the zone with the benefits in terms of reduced losses from the disease by livestock growers outside the zone. As the size of a quarantine zone expands losses inside the zone mount while the loss avoidance outside the zone increases. A smaller zone would reduce the losses inside the zone but would multiply the potential losses outside the zone.

This paper develops a model for determining the size of a quarantine zone for a contagious livestock disease, like FMD. It presents an intervention rule that determines the size of a zone where the economic losses by those firms and farms inside the zone balance the "gains" by farms and firms outside the zone. A numerical example follows the conceptual model. The results indicate that the size of the zone varies with economic activity inside and outside of any zone. Location of towns or cities is critical because they create sharp increases in zone cost if included. Surprisingly, outbreaks in regions with lower animal densities result in larger quarantine zones.

Model Development

Assume a livestock disease occurs on a farm at a specific site and the policy to control the disease is to form a quarantine zone of radius, R, around the farm.[1] The total area encompassed by the quarantine zone is πR^2. Area outside the quarantine zone is the fixed total area, A, less the area inside the zone, $(A-\pi R^2)$. Define D_ℓ and D_n as the density of livestock farms and the density of non-livestock farms and firms per unit of area. To keep the analysis tractable, assume that the densities of farms and firms are uniform throughout the nation.[2]

Next specify the welfare measures for firms and livestock farms. This formulation follows the structure presented by Chambers and Paarlberg (1991). Farms and firms are assumed to employ mobile and sector specific factors of production under constant returns to scale technology to produce a single output. At the national level these factors are in fixed supply and are not internationally traded. The mobile factor, denoted L, is paid a price of w. The factor specific to the livestock farm, k_ℓ, receives a rent of r_ℓ while the factor specific to the non-livestock firm, k_n, returns a rent of r_n. Each livestock farm uses l_ℓ and its stock of the specific factor, k_ℓ, to produce livestock, q_ℓ. As a result the return to the livestock farms generate a profit of:

(1) $\pi_\ell(p_\ell, w, k_\ell) = k_\ell\, r_\ell(p_\ell, w)$,

where $k_\ell r_\ell(p_\ell, w)$ is the quasi-rent accruing to owners of the specific factor.

Non-livestock firms use the mobile factor, l_n, and the non-livestock sector specific factor, k_n, to produce the non-livestock output, q_n. Hence, non-livestock firms have a return of:

(2) $\pi_n(p_n, w, k_n) = k_n\, r_n(p_n, w)$,

where $k_n r_n(p_n, w)$ is the quasi-rent to owners of the non-livestock specific factor. Application of the derivative properties of profit functions gives the per firm outputs:

(3) $q_\ell = k_\ell(\partial r_\ell(p_\ell,w)/\partial p_\ell)$;

$q_n = k_n(\partial r_n(p_n,w)/\partial p_n)$.

In the presence of a livestock disease quasi-rents may not indicate the welfare change for livestock farms inside the quarantine zone. Paarlberg, Lee, Seitzinger (2003) argue that because livestock farmers produce the animals for sale, but are prohibited from marketing those animals, the loss to farmers includes both variable and fixed costs. That is, foregone sales revenue measures the loss to these producers, so their welfare, W_ℓ^I is:

(4) $W_\ell^I = - p_\ell k_\ell(\partial r_\ell(p_\ell, w)/\partial p_\ell)$.

The intention of establishing the quarantine zone is to reduce the spread of the livestock disease. Let ξ be the probability of the disease "jumping" the barrier formed by the quarantine zone and appearing outside the zone with a severity denoted by $\acute{\alpha}$. This probability is a non-increasing function of the size of the quarantine zone. That is, as the size of the quarantine zone expands, it is more effective at reducing the probability that the disease will spread to farms outside of the zone:

(5) $\xi = \xi(\pi R^2)$; $\partial\xi/\partial\pi R^2 \leq 0$, $\partial^2\xi/\partial R^2 = (\partial\xi/\partial\pi R^2)2\pi R \leq 0$.

The livestock farm outside the quarantine zone obtains a quasi-rent when $\acute{\alpha} = 0$ and a loss of sales revenue when $\acute{\alpha} > 0$. Thus, the livestock farm outside the quarantine has an expected welfare of:

(6) $E[W_\ell^O] = (1-\xi(\pi R^2))k_\ell\, r_\ell(p_\ell,w) - \xi(\pi R^2)k_\ell(\partial r_\ell(p_\ell,w)/\partial p_\ell)p_\ell$.

The welfare of non-livestock firms both inside and outside the quarantine zone can also be affected by the outbreak of the livestock disease. Non-livestock firms are assumed to be able to endogenously adjust output.[3] Those firms inside the quarantine zone cease producing so experience a loss in quasi-rent so their welfare, W_n^I, is:

(7) $W_n^I = - k_n r_n(p_n,w)$.

Non-livestock firms outside the quarantine zone measure their welfare, W_n^O, by their quasi-rent:

(8) $W_n^O = k_n r_n(p_n,w)$.

Operating the quarantine zone incurs costs, C^I, borne by public agencies. Some costs are contingent of the type of control strategy – stamping-out, vaccination, or no control – denoted by t. Other costs are independent of the control strategy adopted, but do depend on the size of the quarantine zone. The personnel required to control entry/exit points along the boundary of the quarantine zone are an example of such costs. Thus, control costs for the zone are a non-decreasing function of the size of the quarantine zone:

(9) $C^I = C^I(\pi R^2, t); \partial C^I/\partial \pi R^2 \geq 0$.

Disease control cost can also be incurred outside the quarantine zone. If the disease does not jump the boundary formed by the quarantine zone, there is no cost associated with controlling the disease in the outside region. If the disease does move beyond the quarantine zone, the cost of control depends of the control strategy used, t, and the severity of the outbreak, ά. Thus, the expected cost of controlling the disease in areas outside of the quarantine zone, $E[C^O]$, is given as:

(10) $E[C^O] = (1-\xi(\pi R^2))0+\xi(\pi R^2)C^O(\acute{\alpha},t) = \xi(\pi R^2)C^O(\acute{\alpha},t)$.

Total welfare (W) is the sum of the production welfare less the control costs:[4]

(11) $W = \pi R^2 D_\ell W_\ell^I(p_\ell,w,R) + (A-\pi R^2)D_\ell E[W_\ell^O(p_\ell,w,R{:}\acute{\alpha})] + \pi R^2 D_n W_n^I(p_n,w,R) +$

$(A-\pi R^2)D_n W_n^O(p_n,w,R) - C^I(\pi R^2;t) - \xi(\pi R^2)(C^O(\acute{\alpha}, t))$.

Comparative Static Results

To find the optimum radius for the quarantine zone expression (11) is totally differentiated and set equal to zero. The clearest way to proceed is to treat expression (11) as consisting three parts – the welfare of the livestock sector, the welfare of the non-livestock sector, and the control costs. Each part is totally differentiated and discussed individually to highlight the trade-offs.

Begin with the change in the welfare of the livestock sector. The total differential of that component is:

(12) $dW_\ell = [\sigma_1 - \sigma_2]\, dp_\ell - [\sigma_3 + \sigma_4]\, dR + [\sigma_5 - \sigma_6]\, dw$,

where: $\sigma_1 = D_\ell k_\ell(A-\pi R^2)[(1-\xi(\pi R^2))(\partial r_\ell(p_\ell,w)/\partial p_\ell)$

$-\xi(\pi R^2)(p_\ell(\partial^2 r_\ell(p_\ell,w)/\partial p_\ell^2)+(\partial r_\ell(p_\ell,w)/\partial p_\ell)] \leq/\geq 0$;

$\sigma_2 = D_\ell k_\ell \pi R^2(p_\ell(\partial^2 r_\ell(p_\ell,w)/\partial p_\ell^2)+(\partial r_\ell(p_\ell,w)/\partial p_\ell)) \geq 0$;

$\sigma_3 = D_\ell k_\ell 2\pi R[(1-\xi(\pi R^2))r_\ell(p_\ell,w) + (1-\xi(\pi R^2))p_\ell(\partial r_\ell(p_\ell,w)/ \partial p_\ell)] \geq 0$;

$\sigma_4 = D_\ell k_\ell 2\pi R(A-\pi R^2)(\partial \xi/\partial(\pi R^2))(r_\ell(p_\ell,w)+p_\ell(\partial r_\ell(p_\ell,w)/\partial p_\ell) \leq 0$;

$\sigma_5 = D_\ell k_\ell(A-\pi R^2)((1-\xi(\pi R^2))(\partial r_\ell(p_\ell,w)/\partial w) - \xi(\pi R^2)p_\ell(\partial^2 r_\ell/\partial p_\ell \partial w)) \leq 0$

$\sigma_6 = D_\ell k_\ell \pi R^2 p_\ell(\partial^2 r_\ell(p_\ell,w)/\partial p_\ell \partial w) \leq 0$.

There are a number of sign conflicts in expression (12), both within terms and among terms.

Consider the impacts of an increase in the livestock price, $dp_\ell > 0$. The term σ_2 captures the change in sales revenue as the livestock price changes and shows that an increased livestock price causes a welfare loss from greater foregone sales revenue for farms infected by the disease inside the quarantine zone. The term σ_1 indicates the expected change in welfare for livestock producers outside the quarantine zone that results from a change in the livestock price. Because there are conflicting effects the sign of this term is ambiguous. The first part of the term gives the change in quasi-rent and indicates that when the livestock price rises, quasi-rent increases.[5] The second part of σ_1 shows the sales revenue loss for producers outside the quarantine zone if the disease jumps the barrier created by the quarantine zone.

The terms indicating the direct impact of expanding the radius of the quarantine zone, $dR \geq 0$, also conflict. The σ_3 term says that an expansion of the quarantine zone causes a welfare loss as more livestock farms fall into the zone. The σ_4 has the opposite sign because it indicates the welfare gain occurring as a larger quarantine zone reduces the probability of the disease appearing outside the zone.

The impact of an increase in the price of the mobile factor, $dw \geq 0$, is ambiguous. Livestock farms outside the quarantine zone experience a loss in expected welfare if the mobile factor's price rises, σ_5. Farms inside the quarantine zone also show a greater loss via higher costs, σ_6. The net effect depends on whether the welfare loss outside the zone dominates the loss inside or vice versa.

The total differential of the welfare for non-livestock sectors, dW_n, is simpler because those sectors are not directly affected by the livestock disease:

(13) $dW_n = D_nk_n[(A-\pi R^2)-\pi R^2](\partial r_n(p_n,w)/\partial p_n)dp_n - 4\pi RD_nk_nr_n(p_n,w)dR$

$+ D_nk_n[(A-\pi R^2)-\pi R^2](\partial r_n(p_n,w)/\partial w)dw.$

The first term indicates how an increase in the price of non-livestock goods, $dp_n \geq 0$, affects the welfare and shows that the gain to firms outside the quarantine zone is balanced against the loss by those inside the zone. Whether the price increase generates a welfare gain or loss depends on the relative sizes of the quarantine zone and the area excluded. If the area outside the zone exceeds the area inside the quarantine zone, a price increase causes a welfare gain. The second term shows the impact on welfare of expanding the quarantine zone, $dR \geq 0$, and demonstrates a clear welfare loss as more firms are encompassed by the zone. The final term gives the impact of an increase in the price of the mobile factor. Again the effect on welfare is governed by the relative sizes of the zones. Since $(\partial r_n/\partial w) \leq 0$, if the outside zone is larger than the quarantine zone there is a welfare loss to the non-livestock sector as the mobile factor price rises. Simplifying the terms shows a welfare loss since $A \geq \pi R^2$.

The remaining parts of the welfare expression given by (11) deal with control costs. Differentiating control costs for the quarantine zone gives:

(14) $dC^I = (\partial C^I/\partial(\pi R^2))2\pi RdR > 0.$

As the size of the quarantine zone expands, control costs for the zone increase. This operates to reduce total welfare. The total differential for control costs for areas outside of the quarantine zone is:

(15) $dC^O = (\partial C^O/\partial\xi)(\partial\xi/\partial(\pi R^2)2\pi RdR < 0.$

Control costs in non-quarantined areas increase as the probability of the disease breaking out in those areas increases, but that probability falls as the size of the quarantine zone expands. Thus, the net effect is that the control costs for areas outside the zone fall as the size of the zone expands and total welfare rises.

The next task is to find dp_ℓ/dR, dp_n/dR, and dw/dR. To accomplish that task, a national general equilibrium model using duality theory is formulated and differentiated (Dixit and Norman). Simplifying assumptions are used to keep the model and its comparative static results tractable. One assumption is that the model is normalized on w so $dw = 0$. A real general equilibrium model must be normalized and in this particular case the analysis focuses on the real price changes for the livestock good and that for the composite non-livestock good so the price of the mobile factor is a logical choice for the numeraire. Another assumption is that national income is only generated by farms and firms outside of the quarantine zone. That is, within the quarantine zone all movements are frozen so all economic production ceases. A pattern of trade is assumed. With the livestock disease outbreak exports are prohibited so the country is an importer of the livestock good, $M_\ell > 0$.[6] Paying for imports requires exports of the non-livestock good, $X_n > 0$. Exports of livestock products by the rest of the world to the country with the livestock disease, X_ℓ^*, are described by a simple excess supply function:

(16) $X_\ell^* = X_\ell^*(p_\ell); \partial X_\ell^*/\partial p_\ell > 0.$

Imports of the non-livestock good by the rest of the world, M_n^*, are represented by a simple excess demand function:

(17) $M_n^* = M_n^*(p_n); \quad \partial M_n^*/\partial p_n < 0.$

Given these assumptions the global equilibrium can be described by three equations. Equation (18) is the national budget identity requiring national production value to equal national expenditure as given by an expenditure function, $E(p_\ell, p_n, u)$, where u denotes national utility as given by a homothetic social welfare function:

$$(18)\ E(p_\ell, p_n, u) = (A-\pi R^2)D_\ell k_\ell[(1-\xi(\pi R^2))r_\ell(p_\ell,1)-\xi(\pi R^2)(\partial r_\ell(p_\ell,1)/\partial p_\pi)p_\ell] + (A-\pi R^2)D_n k_n r_n(p_n,1) + [(A-\pi R^2)/A]L$$

where L denotes the fixed national endowment of the mobile factor which is assumed uniformly distributed by area. The first derivatives of the expenditure function with respect to prices gives the Hicksian demand functions. Equations (19) and (20) are the global market clearing conditions for the two commodities:

$$(19)\ X_\ell^*(p_\ell) = (\partial E(p_\ell, p_n, u)/\partial p_\ell) - (A-\pi R^2)D_\ell k_\ell(\partial r_\ell(p_\ell,1)/\partial p_\ell).$$

$$(20)\ M_n^*(p_n) = (A-\pi R^2)D_n k_n(\partial r_n(p_n,1)/\partial p_n) - (\partial E(p_\ell, p_n, u)/\partial p_n).$$

The comparative static results for an increase in the radius of the quarantine zone, $dR > 0$, are found by differentiating equations (18) – (20). Rearranging the differential of equation (18) gives:

$$(21)\ (\partial E/\partial u)du = -M_\ell dp_\ell + X_n dp_n - 2\pi R\Gamma dR,$$

where:

$$M_\ell = (\partial E/\partial p_\ell)+(A-\pi R^2)D_\ell k_\ell[(2\xi(\pi R^2)-1)(\partial r_\ell(p_\ell,1)/\partial p_\ell)+\xi(\pi R^2)p_\ell(\partial^2 r_\ell(p_\ell,1)/\partial p_\ell^2)] > 0,$$

$$X_n = (A-\pi R^2)D_n k_n(\partial r_n(p_n,1)/\partial p_n)-(\partial E(p_\ell, p_n,u)/\partial p_n) > 0,$$

$$\Gamma = D_n k_n r_n(p_n,1)+L/A+D_\ell k_\ell[(1-\xi(\pi R^2))r_\ell(p_\ell,1)-\xi(\pi R^2)(\partial r_\ell(p_\ell,1)/\partial p_\ell)p_\ell] +(A-\pi R^2)D_\ell k_\ell[r_\ell(p_\ell,1)+p_\ell(\partial r_\ell(p_\ell,1)/\partial p_\ell)](\partial \xi(\pi R^2)/\partial(\pi R^2)) >/< 0.$$

The interpretation of equation (21) is straightforward. The livestock product is the imported good so an increase in its price with the other variables unchanged unambiguously lowers welfare. The non-livestock good is the country's export and so an increase in that good's price with the remaining variables constant raises national utility.

The impact of an expansion of the radius of the quarantine zone with the goods prices constant is more complicated because the sign of Γ is ambiguous. There are two conflicting effects. The first three terms indicate that as the radius expands there is an income loss as more firms and farms fall into the quarantine zone. This effect means a decline in social utility. In contrast, the last term shows that as the quarantine zone expands, the probability of the disease appearing outside the zone falls and this raises the expected return to livestock firms outside the zone. This effect acts to raise social utility. For discussion it is assumed that the adverse income effects dominate the gain in expected returns from the reduced probability of the disease spreading, so $\Gamma > 0$, and an expansion of the radius of the quarantine zone lowers national utility.

Differentiation of equation (19) yields:

(22) $s_{\ell\ell}dp_\ell + s_{\ell n}dp_n + (\partial^2E(p_\ell, p_n, u)/\partial p_\ell\partial u)du = - D_\ell k_\ell 2\pi R(\partial r_\ell(p_\ell,1)/\partial p_\ell)dR$,

where:

$s_{\ell\ell} = (\partial^2E(p_\ell, p_n, u)/\partial p_\ell^2)-(\partial X_\ell^*(p_\ell)/\partial p_\ell)-(A-\pi R^2)D_\ell k_\ell(\partial^2 r_\ell(p_\ell,1)/\partial p_\ell^2) \leq 0$,

$s_{\ell n} = (\partial^2E(p_\ell, p_n, u)/\partial p_\ell\partial p_n) \geq 0$.

Given the derivative properties of the expenditure function, $s_{\ell\ell}$, is the slope of the Hicksian demand and must be non-positive. The pure substitution effect in demand is $s_{\ell n}$ and in this two-good model must be non-negative. Equation (22) shows that with p_n and u constant, an increase in the radius of the exclusion zone raises the price of the livestock good because the supply shrinks.

A similar expression is found when the market clearing condition for the non-livestock good is differentiated:

(23) $s_{nn}dp_n + s_{n\ell}dp_\ell + (\partial^2E(p_\ell, p_n, u)/\partial p_n\partial u)du = - D_n k_n 2\pi R(\partial r_n(p_n,1)/\partial p_n)dR$,

where:

$s_{nn} = (\partial M_n^*(p_n)/\partial p_n)+(\partial^2 E(p_\ell, p_n, u)/\partial p_n^2)-(A-\pi R^2)D_n k_n(\partial^2 r_n(p_n,1)/\partial p_n^2) \leq 0,$

$s_{n\ell} = (\partial^2 E(p_\ell, p_n, u)/\partial p_n \partial p_\ell) \geq 0.$

The own price effects in consumption, production, and foreign purchases are given by s_{nn} which is non-positive. The cross-price substitution effect is $s_{n\ell}$ which is non-negative in this two-good model. Thus, when the price of the livestock good and the social utility are constant an increase in the radius raises the price of the non-livestock good. This occurs because expanding the radius increases the number of firms in the quarantine zone so marketable output falls.

Substituting equation (21) into equations (22) and (23) and solving simultaneously give the changes in prices for a change in the radius of the quarantine zone:

$$(24)\ (dp_\ell/dR) = (2\pi R/\Delta)[\Gamma(s_{nn}(\partial C_\ell/\partial y)-s_{\ell n}(\partial C_n/\partial y))-(s_{nn}+X_n(\partial C_n/\partial y))D_\ell k_\ell(\partial r_\ell(p_\ell,1)/\partial p_\ell)$$
$$+(s_{\ell n}+X_n(\partial C_\ell/\partial y))D_n k_n(\partial r_n(p_n,1)/\partial p_n)],$$

$$(25)\ (dp_n/dR) = (2\pi R/\Delta)[\Gamma(s_{\ell\ell}(\partial C_n/\partial y)-s_{n\ell}(\partial C_\ell/\partial y)+(s_{n\ell}-M_\ell(\partial C_n/\partial y))D_\ell k_\ell(\partial r_\ell(p_\ell,1)/\partial p_\ell)$$
$$-(s_{\ell\ell}-M_\ell(\partial C_\ell/\partial y))D_n k_n(\partial r_n(p_n,1)/\partial p_n)],$$

where:

$\Delta = [s_{\ell\ell}-M_\ell(\partial C_\ell/\partial y)][s_{nn}+X_n(\partial C_n/\partial y)]-[s_{\ell n}+X_n(\partial C_\ell/\partial y)][s_{n\ell}-M_\ell(\partial C_n/\partial y)]$, and $(\partial C_i/\partial y)$, $i = \ell, n$, indicates the income effect in the demand for good i.

Interpretation of equations (24) and (25) begins with Δ. Each of the terms in brackets is recognizable as one of the Slutsky de-compositions in a general equilibrium model of international trade. The first two bracketed terms are the Slutsky de-compositions with respect to the own prices of the livestock good and the non-livestock good, respectively. With downward sloping Marshallian demand functions these terms are both non-positive. The last two terms are the Slutsky de-composition of demand with respect to the price of the substitute good and are positive. To insure mathematical stability, the own-price effects should dominate the cross-price effects and hence, $\Delta > 0$.

Turning to the numerator of equation (24), the last two terms indicate the impact on the price of the livestock good from an expansion in the radius of the quarantine zone flowing through the effect on supply. An increase in the radius reduces output and raises the price of the livestock good. The first term in equation (24) is more complicated. With $s_{nn} < 0$ and $s_{\ell n} > 0$, the sign of the terms in the parentheses is negative, but Γ is strictly ambiguous. Recall that Γ balances the loss in national utility as the quarantine zone expands against the gain in utility as the probability of the disease appearing outside the quarantine zone falls. Earlier it is argued that the most plausible situation is that the utility loss dominates so $\Gamma > 0$. If that is the case, then the first term acts to reduce the price of the livestock good via the income effects in demand. Whether the price of the livestock good rises or falls depends on whether the price increasing effects of the output loss dominate or are dominated by the price reducing effects of any loss in national utility operating through the income effects.

The same story is given by equation (25) which shows the effect of an increase in the radius of the quarantine zone on the price of the non-livestock good. The last two terms capture the output reduction effects and boost the price. The first term indicates how the expansion of the zone affects national utility and hence, price. Again, if the output effects dominate, then the price of the non-livestock good rises.

These equations provide the information required to determine the optimum R for the quarantine zone. The comparative static price impacts are substituted into equations (12), (13), (14), and (15) to express the change in each part of the welfare function as depending only on dR. These parts are then inserted into the differential of equation (11) to indicate how the total welfare changes as R changes. That expression is set equal to zero and solved for R.

To summarize the conceptual results, begin with the case where the zone is so small that the price effects can be ignored. There are three effects to consider as the size of the zone expands. One effect is the losses incurred as firms and farms are included in the zone. The second effect is the benefits from a reduced risk of the disease appearing outside of the zone. These benefits include the gains in expected welfare to livestock producers outside the zone and the reduced expected control costs outside the zone. The third effect is the added cost of operating the quarantine zone as its size expands.

When the zone is large enough to generate global price changes additional effects appear. In the context of this analysis a larger zone implies larger price increases. Price increases benefit those fortunate enough to lie outside the zone. At the same time larger price increases represent greater foregone opportunities for those farms and firms inside the zone.

Numerical Model

This section presents a hypothetical numerical model of a foot-and-mouth disease (FMD) outbreak to illustrate the issues identified above. Two hypothetical counties are constructed based on reported county data. The characteristics of these counties are used to separate the economic effects. One way of separating the economic effects is by urban or rural. Another separation occurs based on the density of livestock production. An outbreak is assumed to occur at a single point and the gains and losses are calculated as the radius of a quarantine zone expands in 1 kilometer increments using a disease spread model, a national agricultural sector model, and a geographic information system. The initial outbreaks are located such that the city and towns do not fall into a quarantine area until the radius of the zone is 6 kilometers.

Hypothetical Country Characteristics

The two hypothetical counties represent a range of farm and non-farm economic activity. These different characteristics can be linked to the size of any quarantine zone.

County 1 is a county with no urban center, but rather a few small towns of which the largest has less than 2,500 people. Road and rail infrastructure is limited. Soil quality is high throughout the county so farming focuses on crops and the role of livestock in county income is small and animal densities are low.

County 2 has several towns, but it also has a city with over 16,000 residents. It is a substantial manufacturing center with numerous federal and state highways as well as being served by multiple railroads. It has much highly productive cropland with substantial livestock production.

Experimental Design

The analysis is conducted in three phases. Phase 1 uses a disease spread model to establish the probability that the disease spreads beyond quarantine zones of pre-determined sizes by finding the numbers of animals and herds de-populated. From this information the national impacts are found using an agricultural sector model. The third phase involves calculating the costs inside each quarantine zone.

The starting point in this numerical illustration is the disease spread model for cattle. That model links information on herd numbers, density, size, and pre-determined quarantine zone size to the spread of foot-and-mouth disease using a Markov process (Schoenbaum and Disney, 2003). For this illustration the probabilities of de-population outside the quarantine zone based on cattle are assumed to apply to all species.

De-population circle radii of 1, 3, 5, and 10 kilometers are set and for each radius the disease spread model is solved 100 times. Mean de-population values are used in the illustration. The values for zones with radii in between are interpolated. Two distinct patterns emerge for the probability of an animal outside the initial zone being de-populated. In county 2 with a larger population and larger average herd size the probability falls from 0.34 to 0.17 as the radius of the quarantine zone expands from 1 kilometer to 10 kilometers. This pattern is termed the high density outcome.[7] Where there are fewer animals and a smaller average herd size, the low density outcome, the probability falls from 0.35 to 0.11. The disease spread model also gives the length of the outbreak. For the high density population the outbreak lasts 52 days for a 1 kilometer zone and 34 days for the 10 kilometer zone. The low density population shows a 1 day shorter duration.

Because the disease spread model has a total population based on an 18 kilometer radius circle the probabilities of spread are interpreted as applying to smaller state animal populations rather than the national herd. Thus, state animal numbers are reduced using the spread probabilities and the state losses are used in a national agricultural sector model to find the impact on national value-added. The national agricultural sector model is a version of the model used by Paarlberg, Lee, and Seitzinger (2002) benchmarked to

2003/04 values. In all solutions it is assumed that any FMD outbreak triggers a ban on exports of cattle, swine, lambs, sheep, beef, pork, and lamb and sheep meat. Exports of dairy products are not banned.

The final task is to value the costs of the outbreak inside the zone. From the disease spread model and the county data the number of animals de-populated inside the zone can be calculated. These animals are valued at their market prices. An assumption is that nothing moves out of any zone. Thus, crop producers incur losses as well. These losses are calculated as the daily value of annual sales by acre in the zone over the duration of the outbreak. An additional cost included is access control. The assumption is that every access point is controlled by 1 person 24 hours per day for the length of the outbreak. The surveillance cost for county road access is $15 per hour and the cost for state and federal roads is $20 per hour.

City/town location and cost are critical to the results. The costs are measured as daily earnings by residents multiplied by the outbreak duration. To keep the illustration symmetric, initial outbreaks are located such that a 5 kilometer zone excludes any such costs, but beginning with a 6 kilometer zone cities and towns can fall within quarantine zones.

Results

Tables 1 and 2 present the numerical results for these hypothetical counties. The tables show the costs incurred and how those costs change for an outbreak. As the zone size expands the costs to agriculture outside the zone, measured as value-added, fall and the rate of decline lessens. This pattern largely reflects lower animal de-population as larger zones are more effective at reducing the spread. The costs inside the quarantine zone rise as the radius increases and the rate of increase accelerates. It is also clear from the tables that the costs are not a smooth function of the radius. In this illustration there are two major causes. The dominant cause is the inclusion of cities and towns. When the quarantine zone expands to include a city or a town, there is a one-time jump in the cost. Surveillance also plays a role because the number of access points does not rise in a smooth pattern.

Table 1 reports the impact of expanding the radius for county 1. These values indicate a quarantine zone with a radius of 5 kilometers. With R at 5 kilometers the costs incurred by those outside the zone are $1.9 million , or $0.9 million below the cost of a 4 kilometer zone. The costs inside the zone are $1.202 million which is $0.352 million greater than the costs of the 4 kilometer zone. For a zone of 6 kilometers, the outside costs drop to $1.45 million, $0.450 million below the 5 kilometer zone. The cost inside the zone is $3.581 million or $2.379 million greater than the 5 kilometer zone. This sudden large jump occurs because the largest town falls inside the quarantine zone. Thus, the additional cost of expanding the zone from 5 to 6 kilometers exceeds the benefit of lowering the cost outside the zone. If the town is ignored, the balance between inside and outside costs occurs at a radius of 5.7 kilometers with each incurring a cost of $1.55 million.

Table 2 examines county 2 which has a high livestock density. Because of the high animal density, the city and town locations relative to the assumed origin of the outbreak do not play a role determining the radius. A quarantine zone of 4 kilometers causes a loss outside the zone of $4.3 million which is $1.2 million below that for the 3 kilometer zone. The cost inside the 4 kilometer zone is $2.3 million or $0.844 million higher than the 3 kilometer zone. At 5 kilometers the outside cost falls to $3.6 million, $0.7 million lower than the 4 kilometer zone. Costs inside the zone rise to $3.482 million, or by $1.182 million. The added cost incurred by expanding the zone from 4 to 5 kilometers exceeds the benefit gained in terms of lost national value-added. As can be seen in table 2, the outside cost and the inside costs are roughly equal with a 5 kilometer zone.

The effect of animal density in this illustration can be inferred by removing the town in county 1 from the cost. The quarantine zone in that case is 5.7 kilometers due to the low density animal population. The zone size for the high density animal population is less than 5 kilometers. When the density of animals is low, the cost, in terms of animals de-populated, of reducing the probability of spread is low. The spread of FMD can be considerably reduced at low cost. More dense animal populations mean a larger cost and result in a higher risk of spreading. This relationship can be reversed. If the probability of spread in a high density population is lower than that for a low density population or falls faster, the pattern found here could reverse.

Limitations

This example is to illustrate the ideas of trade-offs developed in the conceptual framework and has several limitations. One set of limitations comes from the disease spread modeling. That model only included cattle, but the FMD spread probabilities are applied to all species. Also the disease spread model has a small universe and extension to the national population or even the state population presents difficulties. An important issue is spatial dimension. The illustration is in terms of radii and not area. The same area in different radii would be expected to have different probabilities of transmitting FMD.

Several assumptions are made in the cost analysis. Animal and crop densities are assumed to be uniform across each county when actual herds are clustered. The outbreak location is assumed and different locations relative to urban areas would affect the outcomes. Assumptions are made about surveillance costs and these are very location specific. Urban areas are assumed to enter at discrete lump sum points with economic activity measured as income. Actual spatial data would show a more heterogeneous pattern with non-farm income generated outside of the city/town. The quarantine zone is absolute with no allowance for exempting some low risk activities. No measure of economic benefits to non-agricultural sectors outside of the zones is included.

Conclusion

This paper originates in the observation that the quarantine zones in the FMD outbreak that occurred in Britain imposed much larger costs on non-agricultural industries than on agriculture. That outcome suggests trade-offs between the costs incurred in a quarantine zone and the benefits resulting from reducing the disease spread. Smaller quarantine areas would have reduced the costs within the zones, but would have also increased the cost outside the zones as disease spread would have likely been greater.

A conceptual model is developed to understand the trade-offs resulting from quarantine zone size. One trade-off is that as the size of the zone expands more firms and farms fall into the zone and incur losses, but the risk of spread is diminished with benefits to those remaining outside. There is also a trade-off in control costs as the zone expands.

Further, there can be price effects. Larger zones reduce the quantity of farm and non-farm goods supplied. This generates positive price effects for producers not quarantined.

A numerical example for an FMD outbreak illustrates these points. Two hypothetical counties are created. One country has predominantly crop production and little animal agriculture. The second county has a larger manufacturing center. It too has a large crop production, but is relatively dense with livestock.

Both counties show a trade-off between the costs of quarantine zones and the benefits to agriculture outside the zone from reduced risk of FMD spreading. In county 1, the low density of livestock means the quarantine zone expands until the large town would be incorporated. Until the town is reached, the risk of FMD spreading can be reduced at relatively low cost. For county 2, the high density of livestock in the example means that the size of the quarantine zone is set before the city's cost is included. In this case the cost of expanding the zone is relatively large. The reduction in FMD risk is smaller. Abstracting from the town in county 1 indicates that the size of the quarantine zone is inversely related to the livestock density. When the livestock density is low, in this example, the size of the zone can be expanded to lower the probability of FMD spreading at a comparatively low cost in animals de-populated. The more dense animal population results in a smaller zone because the cost of lowering the probability of FMD spreading is larger.

Table 1: Costs Inside and Outside of Quarantine Zones for County 1

Radius	Costs Outside of Zone		Costs Inside Zone	
	Total	Change	Total	Change
		-- million dollars --		
1	8.96		0.199	
2	5.60	-3.36	0.350	0.151
3	4.19	-1.41	0.573	0.223
4	2.80	-1.39	0.850	0.227
5	1.90	-0.90	1.202	0.352
6	1.45	-0.45	3.581[1]	2.379[1]
7	1.05	-0.40	7.068[2]	3.487[2]
8	0.80	-0.25	8.155[3]	1.087[3]
9	0.65	-0.15	8.642	0.487
10	0.53	-0.12	9.150	0.508

[1] Large town, county seat, enters zone
[2] Second town enters zone
[3] Third town enters zone

Table 2: Costs Inside and Outside Quarantine Zones for County 2

Radius	Costs Outside of Zone		Costs Inside of Zone	
	Total	Change	Total	Change
		-- million dollars –		
1	8.28		0.446	
2	6.75	-1.53	0.900	0.454
3	5.50	-1.25	1.456	0.556
4	4.30	-1.20	2.300	0.844
5	3.60	-0.70	3.482	1.182
6	2.95	-0.65	27.145[1]	23.663[1]
7	2.45	-0.50	28.970	1.825
8	2.10	-0.35	30.830	1.860
9	1.85	-0.25	32.697	1.867
10	1.69	-0.05	34.657	1.960

[1] City enters the quarantine zone

Footnotes

[1] The zone is assumed to be circular. If cost is a function of compactness then a circle will have a lower cost than a square or rectangle since a circle is more compact. A circle accords with existing practice. Actual zone shapes may be affected by the configuration of exit/entry points.

[2] The assumption of uniform densities is not realistic, but necessary in the conceptual model. Numerical application relies on spatial data with non-uniform densities.

[3] Non-livestock farms inside the zone, like crop farms, are a dilemma because they cannot normally adjust output within the time frame considered. Here it is assumed that they can store output for later sale so sales can be adjusted at a cost.

[4] The welfare of consumers is ignored in this analysis. That welfare change is due to price changes or meat consumption foregone (Paarlberg, Lee, and Seitzinger, 2003). Those effects are mostly tied to trade policy and domestic consumer behavior rather than to the size of the quarantine zone.

[5] The focus is the zone size. Other effects, such as a ban on exports or an adverse consumer response, are independent of the zone size. Thus, the livestock price rises as the zone size expands because more animals are removed given a ban on exports or a reduction in domestic meat demand.

[6] This assumed trade pattern could be reversed. That would add complication because an export ban would need to be introduced. This formulation allows the country to continue to import livestock products and that affects the nature of the change in the livestock price.

[7] The case where county 2 has the higher livestock population density may seem counter intuitive. It is a result of the large hog population in county 2 compared to county 1.

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