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# How Valuable are Antimicrobials for Pig Production? An Econometric Analysis

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This study analyzes the economic consequences of reduced antimicrobial use for Danish pig producers. From estimated profit functions, shadow prices of antimicrobials were derived for different groups of farms. Results suggest that the average pig farmer's access to antimicrobials represents an economic value of around 1.75–4 euro cents for the marginal standard unit dose in the short run on farms with both systematically high and low antimicrobial use but a lower value in the long run, with considerable heterogeneity among farms. Restrictions on antimicrobial use in pig production are likely to imply losses to parts of the Danish pig sector.

*Key words*: quantitative restriction, shadow price

## Introduction

Antimicrobial resistance has raised considerable concern as a threat to global public health in recent decades (World Health Organization, 2014). It has been estimated that drug-resistant infections have led to 33,000 hospital deaths annually in the European Union (Cassini et al., 2019) and that antibiotic-resistant bacteria infect nearly 2.8 million people annually in the United States (Centers for Disease Control and Prevention, 2019). Overuse of antibiotics is suspected to accelerate proliferation of antibiotic-resistant bacterial strains (Laxminarayan and Brown, 2001; Mossialos et al., 2010; Laxminarayan et al., 2013). As the livestock sector is a major user of antimicrobials, animal farming is presumed to be a major contributor to the growth in antimicrobial resistance (Korsgaard et al., 2011; Public Health Agency of Canada, 2016). In response, various regulations to reduce agricultural antibiotic use have been introduced worldwide, both in a "soft" form (e.g., guidelines, best-practice recommendations) as well as "hard" regulations, such as bans on antibiotic growth promotors (European Commission, 2005; Belay, Abate, and Jensen, 2020; Belay and Jensen, 2020).

Denmark has a relatively large and intensive pig production sector, which accounts for around half of the total quantity of antimicrobials used in Demark (Borck, Ellis-Iverson, and Sönksen, 2018). However, the last decade has seen a general decreasing trend in antimicrobial use in Danish pig production. This decrease is primarily connected with the introduction of the so-called yellow card initiative in 2011 (Korsgaard et al., 2011), which set binding upper limits to the number of antimicrobial doses allowed for pigs in different age groups (sows, weaners, finisher pigs) at the herd level. The scheme has been adjusted several times since 2011, which has also contributed to the decrease. Still, the Danish government aims to reduce the sector's use of antimicrobials further in the coming years (Government of Denmark, 2017). It is a requirement that this reduction should

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consider the contemporary EU requirement to phase out the use of medical zinc (zinc oxide) for preventing weaning diarrhea in pig production by June 26, 2022 (European Commission, 2017).

Restrictions on antimicrobial use may be expected to influence farm profitability. Sneeringer et al. (2015) reviewed a number of studies on such effects, mainly focusing on partial productivity measures such as animal mortality, average daily weight gain, or feed conversion rates. Several studies have found improving effects of subtherapeutic antimicrobial use on pig survival (Brorsen et al., 2002; Cromwell, 2002; Miller et al., 2005), average daily weight gain (Thomke and Elwinger, 1998; Dritz et al., 2002; Liu et al., 2005; Miller et al., 2005; Nemechek et al., 2013), and feed conversion rates (Brorsen et al., 2002; Dritz et al., 2002; Miller et al., 2005). According to these studies, the effects of antimicrobial use seem to be stronger in piglet and weaner production; other studies have found rather small effects in finisher pigs (Thomke and Elwinger, 1998; Dritz et al., 2002; Larsen, 2002). Few studies have focused on more aggregate productivity measures such as total factor productivity (McBride, Key, and Mathews, 2008; Key and McBride, 2014) or profit (Miller et al., 2005; Liu et al., 2005); these studies also found positive productivity effects of antimicrobial use. It should be noted that most of the cited studies have focused on the use of subtherapeutic (growth promoting) doses of antimicrobials, which have been banned in the European Union for almost 2 decades. Recent research by van Asseldonk et al. (2020)—performed after this EU ban—could not find a significant relationship between antimicrobial use and various indicators of sow farms' economic performance. Rojo-Gimeno et al. (2016) indicated that antimicrobial use reductions in pig production might be achieved without loss of productivity, if the reduction were accompanied by a targeted effort to improve biosecurity management.

Against this backdrop, the purpose of the present study was to analyze the economic consequences for pig producers of reducing the permitted use of antimicrobials and the distribution of these economic consequences among pig farms. The study is based on econometric analyses of Danish pig farms' antimicrobial use and economic performance between 2008 and 2016, and it contributes to the literature by combining farm accounts data with herd-level antimicrobial prescription register data and by attempting to control for pig farm heterogeneity and extraordinary pig disease outbreaks.

## Data and Methods

### *Data*

The study was based on a dataset that combines production and economic data from the Danish farm accounts (FADN) dataset (Statistics Denmark, 2017) with herd-level data on antimicrobial use from the Danish VETSTAT-database (Stege et al., 2003).

The farm accounts dataset comprises data from a sample of approximately 2,000 Danish farms per year (of which approximately 500 were pig farms) and includes information at farm level, such as livestock numbers (with associated herd identification numbers, CHR), land use, agricultural revenues, production costs, labor input, capital input, investments, and finances. The dataset is a rolling panel, as around 20% of the sample farms are replaced every year, to secure representativeness of the farm sample. The VETSTAT database contains information about prescriptions of antimicrobials to herds (defined by CHR numbers) measured in terms of active compound as well as number of calculated standard unit doses and with information about type of antibiotic (ATC code), livestock species, animal age category, and diagnosis category (VETSTAT). A standard unit dose is defined as the recommended amount of a particular antimicrobial for one day's treatment of 1 kilogram of live animal. This standard unit dose indicator enables comparable measurement of antimicrobial treatment intensity across age classes of pigs. Average daily doses (ADD) per animal in different age groups can then be derived by multiplying the standard unit dose by norm weights of sows (200 kg, including piglets), weaners (15 kg), or finisher pigs (50 kg). In principle, the VETSTAT database covers the entire population of Danish livestock herds, and the Danish FADN sample is (largely) a subset of the VETSTAT population. Hence, the analysis was based on the joint set of farms in the two datasets for each year, which were linked using the (pseudononymized by Statistics Denmark Research Service) CHR identification numbers. The combined dataset spanned the years 2008–2016.

### *Methods*

A basic premise underlying the analysis was that restrictions on antimicrobial use in pig production would reduce the maximum allowable use (e.g., lowered limits in the yellow card scheme). While farms with a current use clearly below this limit would only be affected to a limited extent, these restrictions would have more direct consequences for farms with a use close to the current limit. Hence, some distributional consequences of such restrictions could be anticipated.

The analysis was conducted in two steps: (i) identifying a suitable grouping of pig farms to analyze distributional consequences of changed antimicrobial use limits, with the particular aim to distinguish high-use farms (with antimicrobial use close to the limit) from low-use farms, and (ii) econometric analysis of production economic consequences of changed antimicrobial limits for the identified farm groups. Similar to treatment effect models (Greene, 2000), our methodology combines a continuous outcome variable with a discrete explanatory variable, which is not directly observable and which may be subject to self-selection. However, while the main aim of a treatment effect model is to identify the effect of this discrete variable on the outcome variable, our analysis focuses on identifying the relationship between an outcome variable and a continuous explanatory variable and whether this relationship differs according to the discrete farm group variable. Our two-step approach allows us to make a distinction between high- and low-use farms that adjusts for the potential self-selection under fairly general assumptions and, subsequently, to consider differences among these farm groups in their response to changes in the continuous explanatory variable.

#### Identification of Relevant Farm Grouping

There can be differences in the extent to which pig farms are affected by tightened restrictions on antimicrobial use, given the considerable heterogeneity in farms' current use per animal produced. In the first stage of the analysis, we distinguish high-use farms (i.e., those with a systematically high intensity level in antimicrobial use) from low-use pig farms. Part of the variation in antimicrobial use can be connected to differences in production types (e.g., weaner vs. finisher pigs), where the infection pressure and hence the need for antimicrobial treatment can differ among pig age classes. The allowable norms in the yellow card scheme are differentiated according to these age categories (sows, weaners, and finisher pigs). When the yellow card scheme was introduced in 2011, the allowed maximum numbers of average daily standard doses (ADD) per 100 animals were 5.2, 28.0, and 8.0 for sows (including piglets), weaners, and finisher pigs, respectively. These norms have been adjusted in subsequent years (see Table 1). However, it is likely that the variation within age class in antimicrobial use—and thus the probability of exceeding the norms—also differs among the three age categories. Therefore, the grouping of pig farms would have to consider the age categories of the pigs produced on the farm as well as other conditions that could lead to variation in antimicrobial use per produced pig within age categories and to variation in the effects of antimicrobial restrictions on the farms' economic performance.

It might appear obvious to categorize pig farms (within types of pig production) directly on the basis of current antimicrobial use. However, such an approach could be problematic, as actual antimicrobial use is expected to be an endogenous outcome of farms' economic optimization, which also determines economic variables such as costs or profit. An exogenous shock (e.g., disease outbreak) would affect the farms' economic variables but would also determine whether the farm belongs to the low- or high-use category. Grouping farms according to actual use would thus imply

**Table 1. Maximum Allowed Number of Antimicrobial Doses (ADD per 100 animals)**

| | Sows | Weaners | Finishers |
|---|---|---|---|
| 2008[a]–2012 | 5.2 | 28.0 | 8.0 |
| 2013[b] | 5.1 | 26.3 | 7.4 |
| 2014[b] | 4.9 | 24.7 | 6.8 |
| 2015–2016 | 4.3 | 22.9 | 5.9 |
| 2017[b] | 4.2 | 22.1 | 5.7 |

*Notes:* [a]For the years 2008–2010, the same limits are assumed as immediately after the launch of the yellow card scheme. [b]For years in which limits were adjusted during the year, limits are converted to average for the calendar year.
*Source:* Danish Food and Veterinary Administration, https://www.foedevarestyrelsen.dk/Leksikon/Sider/Gr%C3%A6nsev%C3%A6rdier-for-antibiotikaforbrug-og-d%C3%B8delighed.aspx

a risk of selection bias in the grouping and consequently in the results of subsequent econometric estimations of the relationship between antimicrobial use and economic performance.

Therefore, the distinction between low- and high-use farms (within a category of pig production) was made on the basis of the farms' *statistically expected use of antimicrobials*, which was estimated based on a risk factor analysis describing the relationship between antimicrobial use and a set of hypothesized determinants (risk factors).

Two alternative statistical models were used to investigate such relationships. First, a linear relationship of the type

$$f\left(\frac{y_{it}}{\overline{y_{it}}}\right) = \alpha_0 + \sum_j \alpha_j \cdot x_{ijt} + \varepsilon_{it} \tag{1}$$

was analyzed. Here, $y_{it}$ is farm $i$'s antimicrobial use in year $t$, $\overline{y_{it}}$ is the farms' calculated maximum allowed use (according to the yellow card norms), $x_{ijt}$ is a set of exogenous explanatory variables (risk factors), and $\varepsilon_{it}$ is random variation (which is assumed to be normally distributed with mean 0). The maximum allowed use $\overline{y_{it}}$ will depend on the farm's composition of production (e.g., the shares of finisher and weaner pigs). The farms' degree of compliance with the yellow card scheme is thus assumed to be a function of the $x$-variables, such that a positive $\alpha$-parameter implies that the variable contributes to increase the use, relative to the allowed maximum, and thus the risk of exceeding the limit. The function $f(\cdot)$ represents a possible transformation of the ratio between use and norm (e.g, a logarithmic transformation). Relationships like equation (1) can be examined statistically (e.g., by linear regression) to obtain estimates of the $\alpha$-parameters. These parameter estimates can subsequently be used to predict individual farms' statistically expected antimicrobial use relative to the yellow card limit, given the exogenous farm-level risk factors. Subsequently, farms can be grouped according to how close their statistically expected use of antimicrobials is to the allowed maximum, $\overline{y_{it}}$, which is calculated as

$$\bar{y_{it}} = \left(sows_{it} \cdot \bar{y}_t^{sows} + weaners_{it} \cdot \bar{y}_t^{weaners} + finishers_{it} \cdot \bar{y}_t^{finishers}\right) \cdot 365/100, \tag{2}$$

where $\bar{y}_t^{sows}, \bar{y}_t^{weaners}$, and $\bar{y}_t^{finishers}$ represent the maximum allowed number of doses (ADD per 100 animals) in the three age categories for each year (see Table 1), and $sows_{it}$, $weaners_{it}$, and $finishers_{it}$ represent the number of animals on farm $i$ in year $t$, converted to "stock units" (average of farms' beginning and ending stock of the respective animal categories, according to FADN data).

Second, we used a logistic regression model in which the farm's probability (represented by an odds ratio, OR) of exceeding a given threshold (given by the fraction $\mu$ of the yellow card limit) was described as a linear function of a set of risk factors:

$$\log\left(OR_{it}\right) = \log\left(\frac{P\left(y_{it}/\overline{y_{it}} \geq \mu | x, \alpha\right)}{P\left(y_{it}/\overline{y_{it}} < \mu x, \alpha\right)}\right) = \alpha_0 + \sum_j \alpha_j \cdot x_{ijt} + \varepsilon_{it}. \tag{3}$$

Here, the $\alpha$-parameters represent how much the probability of exceeding an antimicrobial use of $\mu \cdot \overline{y_{it}}$ increases if the respective risk factors $x_j$ increase by 1 unit, expressed as changes in the logarithm of the odds ratio. The effect of changes in the $x_j$ variable on the probability of exceeding the $\mu$ threshold can then be estimated as $\alpha_j \cdot \bar{P}/(1-\bar{P})$, where $\bar{P}$ represents the average probability of exceeding the threshold at baseline. For example, if $\mu = 0.75$, then the expression gives the probability of exceeding 75% of the yellow card limit changes with a 1-unit increment in risk factor $x_j$.

Previous studies of potential risk factors for high antimicrobial use in pig production include van der Fels-Klerx et al. (2011), van Rennings et al. (2015), and Postma et al. (2016). All three studies found an effect of farm or herd size, but van der Fels-Klerx et al. also found that production system and regional livestock density significantly influenced antimicrobial use. Van Rennings et al. found a "veterinarian effect" on the use, and Postma et al. found that biosecurity factors had a significant influence on antimicrobial use. In addition to these risk factors from the literature, we also hypothesized that stocking density in the pig houses played a role for infection pressure and hence for the need for antimicrobial treatment, especially for sow farms. This stocking density depended on pig house quality (age) because many older houses were not dimensioned for the current productivity level (weaned piglets per sow). In order to include the potential pig house age effect on the risk of high antimicrobial use, we constructed a house quality index variable as the ratio between the houses' recorded value (according to the farm accounts) and a calculated value of up-to-date pig houses, based on calculations from the Danish Pig Research Centre SEGES (Udesen, 2018): In 2017/2018, the current housing investment cost was estimated to be €2,550 per sow, €240 per weaner space (until 30 kg weight), and €460 per finisher space (above 30 kg weight), which were projected to previous years assuming a 2% annual growth rate in these investment costs. The calculated value of up-to-date pig buildings was estimated as $\sum_{age\ groups} animal\ stock \cdot housing\ investment\ per\ animal\ space$. It should be noted that this indicator is subject to some uncertainty, as the recorded value in the accounts could include other buildings than pig houses, and no adjustment was made for rented buildings in the estimation.

In the present analysis, we chose to focus on the following set of potential risk factors: age of the farm (since establishment), age of the farm manager, size of the herd (number of livestock units),[1] 7-kg piglets' share of the farm's total pig output, 30-kg pigs' share of farm's total pig output, finisher pigs' share of farms' total pig output, whether the farm was organic, index for quality of pig houses, and region. The risk factor analysis yielded a categorization of pig farms in high- and low-using farms in the sense that high-using farms had a statistically expected antimicrobial use that was relatively close to (or above) the maximum limit.

### Econometric Analysis of Relationship between Antimicrobial Use and Economic Performance

The study of antimicrobial use's influence on farms' economic results was done by econometric analysis, based on data for pig farms' production, costs, and antimicrobial use, and taking into account whether farms were "high users" or not. In particular, assuming profit-maximizing behavior, producers' behavior was represented by a constrained profit function, which depended on the prices of outputs (piglets, finishers, or other pigs), the prices of variable inputs (e.g., feeds, salaries), the farms' endowments of fixed inputs (e.g., buildings), various structural factors that might affect the possibilities for economic optimization (e.g., farm size, type of production), the use of antimicrobials, and the farm's technological stage (represented by the above-mentioned index of building quality). Based on such a profit function, it was possible to derive indicators on the producer's economic behavior (e.g., the price sensitivity of input demand) or the degree to which various constraints affected the farm's economic optimization—represented by shadow prices.

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[1] The definition of livestock units (LU) is based on EU's Farm Accounts Statistics Network (FADN): (1 sow $\sim$ 0.5 LU, 1 weaner $\sim$ 0.027 LU, 1 finisher pig or young sow $\sim$ 0.3 LU (https://ec.europa.eu/agriculture/rica/pdf/site_en.pdf, p. 63)

As a point of departure, producers with antimicrobial use clearly below the yellow card limit were assumed to consider antimicrobials as a variable input that could be optimized based on the price conditions. *A priori*, it was thus expected that the shadow price of antimicrobials would be limited for these farms; that is, the possible output gains from using an extra dose would be outweighed by additional costs of using this additional dose. In contrast, farms with an antimicrobial use close to the limit would have to consider antimicrobials as a fixed input, which they could not optimize (if optimization would mean higher use). The profit function for these farms depended on the allowed quota of antimicrobials, and it would be possible to derive a nonnegative shadow price for this quantity. In this case, the shadow price represents the economic value for the farmer (in terms of increased output or reduced costs), if they could use an additional dose.

For the econometric analysis, we decomposed the profit function into a revenue function, which depended on the output prices and various structural variables, and a cost function, which depended on the input prices and also on various structural variables. For the cost function, we furthermore estimated both a variable cost function (considering capital and farmer's own labor input as fixed) and a total cost function (considering all inputs as variable), representing the short run and the long run, respectively. The econometric estimations of revenue and cost functions were conducted for the group of pig farms as a whole as well as for three subcategories of farms: specialized sow/piglet production, specialized finisher pig production, and integrated piglet/finisher production. For the present purpose, these estimated functions were used to derive short- and long-run shadow prices of antibiotic antimicrobial doses for the respective farm groups.[2]

The transcendental logarithmic (translog) functional form was used to approximate both the revenue function and the cost functions. The translog functional form yields the opportunity to consider farms' adaptations to changed economic conditions (prices and other explanatory variables) from year to year. For the revenue function, the translog specification had the mathematical form

$$\begin{aligned}\ln\frac{R}{p_N} = {} & \alpha_0 + \sum_{i=1}^{N-1}\alpha_i\cdot\ln\frac{p_i}{p_N} + 1/2\cdot\sum_{i=1}^{N-1}\sum_{j=1}^{N-1}\alpha_{ij}\cdot\ln\frac{p_i}{p_N}\cdot\ln\frac{p_j}{p_N} \\ & + \sum_h\beta_h\cdot z_h + 1/2\cdot\sum_h\sum_g\beta_{hg}\cdot z_h\cdot z_g + \sum_{i=1}^{N-1}\sum_h\delta_{ih}\cdot\ln\frac{p_i}{p_N}\cdot z_h.\end{aligned} \tag{4}$$

Here, $R$ represents the total revenue from the farm's pig activities, the $p$ variables represent sales price for different categories of pigs, and the $z$ variables represent other variables that could influence the revenues (e.g., use of antimicrobials, herd size, production system, or equipment endowment). Letting the $z_{AB}$ variable represent antimicrobial input, the marginal effect of this antimicrobial input on revenue could be derived from this function as

$$\lambda_{AB}^{R} = \frac{\partial R}{\partial z_{AB}} = \frac{R}{z_{AB}}\cdot\left(\beta_{AB} + \sum\nolimits_g\beta_{hg}\cdot z_g + \sum_{i=1}^{N-1}\delta_{iAB}\cdot\ln\frac{p_i}{p_N}\right). \tag{5}$$

This expression thus represents the expected additional sales revenue if the antimicrobial input increased by one standard unit dose.

In addition to the antimicrobial use, the revenues were assumed to depend on the farm's technological stage (represented by the above-mentioned index for quality of buildings and by the endowment of equipment), the farm size (number of livestock units) and the category of pig farming (piglet, finisher, or integrated farming) on the farm.

In addition to increasing the output per pig space through reduced piglet mortality or shortened periods with reduced weight gain, the value for pig farms of using antimicrobials also consists of

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[2] The number of antimicrobial standard unit doses, as reported in the VETSTAT database, was used as a measure of the antimicrobial input on the farms because the number of doses is the target for the yellow card regulation scheme. The number of doses constitutes a comparable measure of antimicrobial treatment intensity across animal age classes and active substances.

possible cost impacts because handling of disease problems can be an alternative to other and more costly on-farm measures. Such cost implications were captured by estimating cost functions. As mentioned, we considered both short- and long-run perspectives on costs. Variable costs, $V$, (i.e., costs that can be adjusted in the short run) include feeds, veterinary services (excluding medicine), other services, and salaries to hired labor. Corresponding to the revenue side, we used a translog functional form, with prices of variable inputs as explanatory variables, together with a set of other explanatory variables that also to some extent differed from the revenue function (e.g., with inclusion of an equipment intensity variable as a proxy for the farm's technological level). Total costs, $C$, included the variable costs plus capital input and the owner family's own labor input. The model for total costs reflects the farms' cost adjustments in the long run, including investments, depreciation of invested capital, or adjustments of own labor input on the farm.

As an analog to equation (5), the marginal effect of one antimicrobial dose on the costs could be derived, representing the extra cost to the farm, if one additional dose of antimicrobial could be used. If the effect is positive, it implies an additional cost per pig space, whereas a negative effect implies a cost reduction. From the two cost functions, we derived expressions for marginal effects of antimicrobial use on variable costs, $\lambda_{AB}^{V}$, and total costs, $\lambda_{AB}^{C}$, respectively. Subsequently, the short- and long-run shadow prices of antimicrobial use could be calculated as $\lambda_{AB}^{R} - \lambda_{AB}^{V}$ and $\lambda_{AB}^{R} - \lambda_{AB}^{C}$, respectively.

In the econometric estimation, there was a risk of simultaneity bias because antimicrobial input is a decision variable in the farm's maximization of profit, but at the same time, both the need for antimicrobials and the economic performance could be affected by exogenous influences, such as disease outbreaks. In order to account for extraordinary fluctuations in antimicrobial use due to such influences, the model was identified based on the assumption that minor year-to-year variations in a farm's antimicrobial use per livestock unit reflected the farm's normal economic optimization under "normal" disease conditions, whereas years with larger peaks in antimicrobial use represented extraordinary disease events. Hence, the econometric model included a proxy dummy variable, which assumed the value of 1 in years in which antimicrobial use was more than 20% higher than the farm's statistically expected use, and 0 otherwise.

Besides risk of simultaneity bias, endogeneity caused by reverse causality could be present if the economic performance of pig farms influences antimicrobial use. Low economic performance could deter or restrain farmers from using antimicrobials due to liquidity issues, where diseases are improperly diagnosed or not enough antimicrobials are bought. Due to Danish legislation, a veterinarian must inspect the herd at intervals of no more than 35 days, and this suggests that the risk of underdiagnosis and undertreatment of infections is low. Further, the Danish financial infrastructure—in which banks are an integrated part of the financial structure—ensures that farmers normally have the capital capacity to buy the "optimal" quantity of antimicrobials. Another effect of reverse causality could be that farmers with poor economic performance do not have the liquidity to invest in modern and optimally sized farrowing and weaner sections and hence are more exposed to disease risk. In the econometric analysis, the latter reverse causality has been dealt with by introducing the index for quality of buildings (see above).

Finally, we included a year fixed effect to account for general year-to-year fluctuations (e.g., genetic development). All farm-level variables (revenues, costs, equipment, number of antimicrobial doses) were scaled to be expressed per livestock unit.

### Categorization of Low- and High-Use Pig Farms

To distinguish between low- and high-use pig farms, we conducted a fixed-effects linear regression regarding the influence of the potential risk factors on the farm-level ratio between actual antimicrobial use and maximum limit. Most of the estimated coefficients were statistically significant and suggested that antimicrobial use was increasing with herd size, whereas farmer age and organic production tended to reduce the consumption. The estimated farm-specific intercept

**Table 2. Structural Risk Factors for Farms with Systematically High Antimicrobial Use**

| | Linear Regression Parameter | Logistic Regression Parameter |
|---|---|---|
| Age of farm owner | $-0.0015^{**}$ | $-0.0002$ |
| Number of permanent employees | $0.0098^{***}$ | $0.0002$ |
| Number of pig livestock units | $0.00002^{*}$ | $0.0000$ |
| Organic | $-0.2315^{***}$ | $-0.0195^{***}$ |
| Year of farm establishment | $0.0018^{***}$ | $0.0001$ |
| Piglet farm | $0.0334^{*}$ | $0.0030$ |
| Finisher farm | $-0.0727^{***}$ | $-0.0046^{*}$ |
| Index for quality of buildings | $-0.0308^{**}$ | $0.0018^{***}$ |
| Capital region | $-0.0334$ | $-0.0092$ |
| Sealand region | $-0.0252$ | $-0.0021$ |
| Funen district | $0.0073$ | $-0.0029$ |
| South Jutland district | $-0.0085$ | $-0.0040$ |
| West Jutland district | $0.0187$ | $0.0005$ |
| East Jutland district | $-0.0222$ | $0.0014$ |
| Intercept | $-30,780^{**}$ | $-0.3086$ |

*Notes:* Single, double, and triple asterisks (*, **, ***) indicate significance at the 5%, 1% and 0.1% level, respectively. Estimated coefficients from regression of fixed-effect parameters from linear and logistic fixed-effects regression models on relevant structural variables.

terms in the fixed-effects model represented systematic differences in the antimicrobial use across farms. By regressing these farm-specific intercept estimates on a set of structural variables, it was possible to discern a "systematic" relationship between farms' antimicrobial use level and these structural variables. Results from this regression showed that a systematically high level of antimicrobial use was positively associated with farm size (both in terms of herd size and number of employees) and negatively associated with farmer age and the number of years since farm establishment. Results of this regression of farm-specific intercepts on structural variables are presented in the "linear regression" column in Table 2. Farms with a relatively high share of finisher pigs tended to have lower use (relative to the norm). No systematic regional differences were identified in the regression.

As a supplement, logistic regressions were conducted to determine risk factors that influence the farms' probability of exceeding a given threshold for antimicrobial use (75% of the maximum limit). As in the linear regression, a farm-specific intercept term (fixed effect) was included in the logistic regression to represent systematic differences across farms. General year-to-year variation seemed to contribute significantly to variations in the probability of exceeding the thresholds, and variations in the sales share of weaner pigs also had a significant influence on the probability. The estimated farm-level intercepts from the logistic regression were regressed on various structural variables for the farms, to disclose explanatory factors behind the systematic differences among farms, shown in the "logistic regression" column in Table 2. These regression results showed—fairly consistent with the results for the intercepts from the linear regression model—that the risk of exceeding the threshold depended positively on farm size and negatively on the age of the farmer or the farm, and the risk tended to be lower for organic pig farms and for farms specializing in finisher pigs (Table 2, last column).

Three thresholds were considered in the logistic regression model: 50%, 75%, and 90% of the maximum limit, to check the sensitivity of the results to this threshold. The findings were quite robust to the choice of threshold in the regression.

The vast majority (around three quarters) of variation in farms' antimicrobial use could be ascribed to systematic differences among farms. These systematic differences could be associated to some extent with structural and observable characteristics (e.g., farm size, composition of production activities, organic status) but also to nonobservable characteristics (e.g., various aspects of farm management, hygiene).

Based on the identified differences among farms' systematic levels of antimicrobial use from the two regressions, high-use farms could be identified as those with a systematically high antimicrobial use (in the upper quartile of the distribution of these intercepts) in either case. These high-use farms tended to be characterized by owners that were 2–3 years younger than those of low-use farms, larger (10% larger in terms of livestock units and 20%–30% larger in terms of employees), more oriented toward piglet production, and with less-modern production facilities. These differences were fairly consistent, irrespective of whether the distinction between low- and high-use farms was based on linear or logistic regression approach.

## Results

We conducted econometric analyses of the translog revenue and cost functions for pig farms. Hence, the analyses distinguished between the influence of antimicrobials on the output as well as on the input side, adjusting for factors that could interfere with this influence, including structural factors, indicators of technological status of the farm, and whether the farm is a high or low user of antimicrobials in production (reflected in the interaction term between "high" and the number of doses per livestock unit). A disease outbreak dummy variable distinguishing between "ordinary" and "extraordinary" variations in need for antimicrobials was also included in the regressions. Results of the econometric estimations for the revenue function, the variable cost function, and the total cost function per livestock unit, respectively, are shown in Tables S1–S3 in the Online Supplement (see www.jareonline.org). A few comments should be associated with some of the estimated coefficients, which have direct importance for the calculation of shadow prices for pig farms' antimicrobial use.

As regards the revenue function (Online Supplement Table S1), the results for "all pig farms" show that the statistical model is capable of explaining 30% of the variation in the dependent variable. A considerable share of the estimated coefficients are statistically significant. The coefficient of antimicrobial use per livestock unit was negative (but insignificant), whereas the coefficient of the squared antimicrobial input was positive. The revenue effect of an extra dose depended on the combination of these coefficients, and the positive sign on the squared antimicrobial input implied that the marginal revenue effect of antimicrobial use was an increasing function of the antimicrobial input. The pattern in the estimated coefficients was fairly consistent across types of pig farming—however, there was some variation as regards statistical significance and sign of some of the coefficients. Whether the farm is categorized as high use or low use (reflected in the *High* dummy variable, which equals 1 for high-use farms and 0 otherwise) influences the revenue function through the $High \times \log(Doses/LU)$ interaction term, and the estimated coefficients suggest that high-use farms obtain a lower revenue effect from additional antimicrobial doses than low-use farms, which would be consistent with a diminishing marginal productivity of antimicrobials.

Estimation results for the translog variable cost function are displayed in Online Supplement Table S2 and for the total cost function in Online Supplement Table S3. For all four pig farm categories, the explanatory power of the two cost functions is higher than for the revenue function, which makes sense as the revenue side in pig production has a more substantial stochastic component than the cost side in terms of both within-year price fluctuations and health-related output fluctuations. In the short-run cost function, antimicrobial use interacts with price variables as well as with other explanatory variables, and some of these interaction terms contribute in a way that is statistically significant, suggesting some substitutability between antimicrobials and the variable inputs. Also, the antimicrobial input and the squared antimicrobial input contribute significantly.

For high-use farms with piglet production, an additional antimicrobial dose tends to reduce the costs more than for low-use farms.

The antimicrobial input and the squared antimicrobial input also contributed significantly to the cost functions. Herd size and index for quality of buildings contributed negatively to the costs, again suggesting that larger and more up-to-date buildings implied more cost-effective production.

The constructed variable for quality of buildings occurred in two terms of the variable cost function—directly, and in interaction with the number of antimicrobial doses—and the effect of this variable-on-variable cost was given by the sum of these two effects. A positive coefficient on the interaction term meant that the cost-reducing effect of an additional dose of antimicrobial in the short run was smaller for farms with a high quality of buildings than for farms with older buildings. Whether the farm was low use or high use did not seem to significantly influence the level for variable costs. The mechanisms reflected in the estimated total cost function—representing long-run behavior—were quite similar to those in the short run.

As outlined in the methodology section, expressions for the marginal effect of antimicrobial use on revenue and costs, respectively, can be derived from the revenue and cost functions. Table 3 displays mean values for the calculated effects of antimicrobial doses on revenues, costs, and profitability for low- and high-use pig farms—as a whole and distinguished according to main production type. These values represent the impact of one additional standard unit dose of antimicrobial, and this was presumed to represent the economic loss to the farmers if their access to antimicrobials were reduced by one dose. Subtracting the change in variable costs from the change in revenue yielded an estimate of the change in gross margin, which could be interpreted as the short-run shadow price of antimicrobial input. Similarly, the long-run shadow price could be calculated by subtracting the change in total costs from the change in revenue. Hence, the long-run shadow price represented the net value to the farmers of an antimicrobial dose, accounting for adjustments in both variable and fixed costs.

The results in Table 3 show that one additional unit dose of antimicrobial yielded an average increased sales revenue of 7.76 euro cents on low-use farms and 2.71 cents on high-use farms (on average, €1 $\sim$ US$1.25 for the considered period). These improvements most likely occurred due to reduced piglet mortality and increased average weight gain due to better disease treatment with antimicrobials. On high-use farms, an additional dose led to increased variable costs of 0.97 cents and increased total costs of 1.58 cents. Part of these additional costs were probably related to increased feed use due to improved weight gain when the animals were free from disease. These effects implied an average short-run shadow price of 4.01 cents and 1.75 cents per antimicrobial unit dose for low- and high-use farms, respectively, and an average long-run shadow price of 1.02 and 1.14 cents for the two categories of pig farms. An average long-run shadow price of 1.14 cents per standard unit dose on high-use farms is equivalent to a marginal change in production cost of 8 cents per 7-kg piglet produced, 17 cents per 30-kg pig, or 57 cents per finisher pig, if restriction means one day less with antimicrobial treatment.

Corresponding results for subcategories of pig farms are displayed in the remaining columns of Table 3. These results show that marginal antimicrobial use in particular affects the revenues on sow farms, probably because antimicrobial use contributes to reduce piglet mortality and shortens the periods with low weight gain, due to—for example—weaning diarrhea. Positive revenue effects of antimicrobial use were also found for other types of pig farms, but smaller than those for the sow farms. However, the results also showed that increased antimicrobial use increased the costs, mainly on pig farms with currently low antimicrobial use. Overall, the results showed a positive shadow price of antimicrobials on farms with piglet production (sow farms and integrated pig farms) and especially on those sow farms with currently high antimicrobial use. These were the farms that would be economically affected the most if access to antimicrobials were restricted further.

Combining the estimated parameters from the econometric analyses with farm-level data, it was possible to calculate the shadow price of antimicrobials for each individual farm. Figure 1 illustrates

**Table 3. Average Economic Value of One Additional Antimicrobial Dose on Different Pig Farm Groups**

| | All Pig Farms | | Sow Farms | | Finisher Farms | | Integrated Pig Farms | |
|---|---|---|---|---|---|---|---|---|
| | Low-Use | High-Use | Low-Use | High-Use | Low-Use | High-Use | Low-Use | High-Use |
| Euro cents per standard unit dose | | | | | | | | |
| Changed sales revenue | 7.76 | 2.71 | 8.26 | 1.82 | 3.69 | 1.32 | 1.37 | 0.90 |
| Changed variable cost | 3.75 | 0.97 | 1.97 | 0.08 | 2.96 | 0.87 | −2.25 | −1.33 |
| Changed gross margin | 4.01 | 1.75 | 6.29 | 1.73 | 0.73 | 0.45 | 3.62 | 2.22 |
| Changed total cost | 6.74 | 1.58 | 1.37 | −0.10 | 3.55 | 0.99 | −1.87 | −2.26 |
| Changed profit | 1.02 | 1.14 | 6.89 | 1.92 | 0.13 | 0.33 | 3.24 | 3.16 |
| Euro cents per 7-kg piglet | | | | | | | | |
| Changed gross margin | 27 | 12 | 42 | 12 | | | 24 | 15 |
| Changed profit | 7 | 8 | 46 | 13 | | | 22 | 21 |
| Euro cents per 30-kg pig | | | | | | | | |
| Changed gross margin | 60 | 26 | 94 | 26 | | | 54 | 33 |
| Changed profit | 15 | 17 | 103 | 29 | | | 49 | 47 |
| Euro cents per finisher pig | | | | | | | | |
| Changed gross margin | 200 | 87 | | | 36 | 22 | 181 | 111 |
| Changed profit | 51 | 57 | | | 7 | 16 | 162 | 158 |

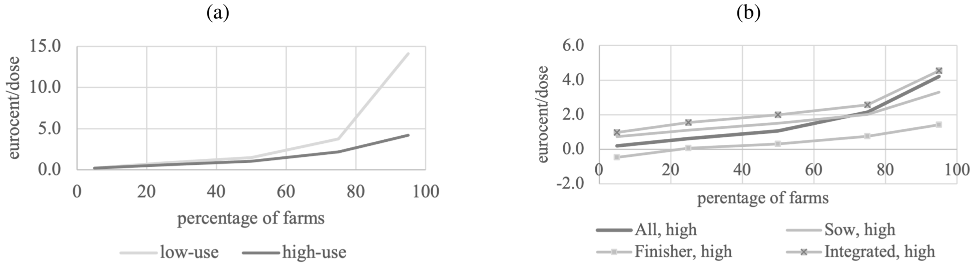

**Figure 1. Distribution of Short-Run Shadow Price of an Antimicrobial Dose across Pig Farms**

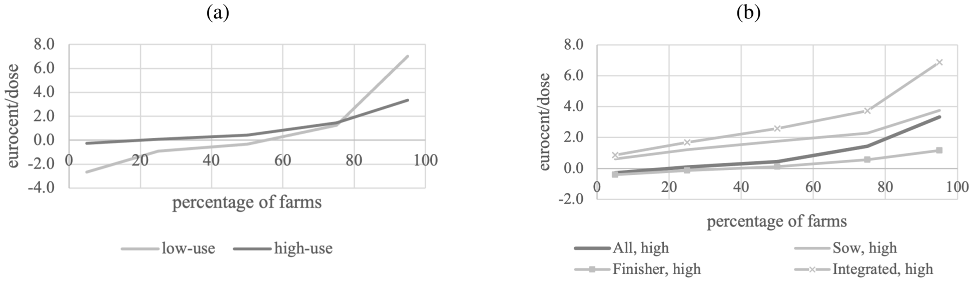

**Figure 2. Distribution of Long-Run Shadow Price of an Antimicrobial Dose across Pig Farms**

the distribution of the short-run shadow price across farms, distinguished by categories, where farms in a given category have been ranked according to estimated antimicrobial shadow price. Thus, a given curve (such as "high-use" in the left panel) displays the shadow price for—for example—the 40th or 80th percentiles of the farms in that category. Correspondingly, Figure 2 shows the distribution of the long-run shadow price of antimicrobials for the same categories of pig farms.

Considering Figure 1 in light of the results presented in Table 3, there appears to be a substantial difference between the mean and the median values for the shadow price of antimicrobials, as the mean was affected by relatively few "extreme" values in the tails of the distribution. Median values for the short-run shadow price were 1.5 and 1.1 cents per unit dose for low- and high-use farms, respectively. The distributions of short-run shadow prices appeared to be quite similar for low- and high-use farms. In the upper end of the distribution (those farms with a high shadow price of antimicrobials), estimates in the range of 2–4 cents per unit dose could be found for both high- and low-use farms. The right panel of Figure 1 shows the distribution of short-run shadow prices for different types of pig farming and demonstrates that shadow prices tended to be systematically higher on piglet producing farms (sow farms and integrated pig farms), and that some of these farms faced short-run shadow prices up to 5 euro cents per standard unit dose. In contrast, the shadow price of antimicrobials for finisher farms appeared to be consistently close to 0, suggesting that the quantitative constraints implied by the yellow card scheme were not binding on specialized finisher farms.

In the longer run, where farms' ability to make adjustments to—for example—capital inputs were considered, the pattern suggested that the yellow card scheme was more binding on high-use farms than on low-use farms. The level of the long-run shadow price was lower than the short-run shadow prices for both categories of pig farms. Hence, the median long-run shadow price was negative for low-use pig farms, whereas the 90% decile was around 5 and 3 cents per dose for low- and high-use farms, respectively. It is worthy of notice that a share of the low-use farms had a clearly negative long-run shadow price, which was also related to the relatively large impact of antimicrobials on long-run costs in Table 3 for these farms. A possible explanation for this could be that a share of these low-use farms had very low antimicrobial use and hence also a relatively limited

**Figure 3. Temporal Development in the Median Shadow Price of Antimicrobials in Pig Production, 2008–2016**

focus on optimizing their use of antimicrobials. The right panel of Figure 2 mirrors the right part of Figure 1 in the sense that farms with piglet production had systematically higher shadow prices than farms specializing in finisher pig production.

The econometric analyses were conducted on a dataset spanning the period of 9 years, and the displayed results represent this period as a whole. However, it is relevant to assess the temporal development in the shadow prices, and thereby the order of magnitude for the shadow price in the most recent years (e.g., in connection with setting new reduction targets for antimicrobial use). Figure 3 shows the development in the median short- and long-run shadow price of antimicrobials for the years 2009–2016.

The displayed results show that both short- and long-run shadow prices of an antimicrobial dose increased during the first years after the introduction of the yellow card scheme in 2011. Since 2014, the level—as represented by the median value—seems to have stabilized on a level just around 1.50 euro cents per standard unit dose in the short run and around 0 in the long run. We could interpret the long-run shadow price to mean that for the median farm, there was no net profit connected with the use of an additional dose when accounting for the farm's ability to adjust all inputs. As suggested by Figures 1 and 2, there may still be a fraction of pig farms with a positive long-run shadow price on antimicrobials. This fraction of farms could be expected to be affected economically if the access to antimicrobials were restricted further. The right part of Figure 3 suggests that these farms could mainly be expected to be found among piglet producers—both specialized sow farms and integrated pig farms.

The robustness of these findings was checked using two types of sensitivity analyses. First, whereas the presented calculations of shadow prices were based on the predicted number of antimicrobial doses (based on the risk factor models described previously), corresponding calculations were made in which the calculation of shadow prices was based on observed antimicrobial use instead of predicted use. Generally, the results were very close to those presented above. Second, the risk factor analysis described above developed two alternative criteria to distinguish high- from low-use farms: a criterion based on farms use of antimicrobials per animal, and a criterion based on estimated probability of exceeding 75% of the maximum allowed use. The former criterion was used for the analyses presented above, but re-estimating the models using the latter criterion did not alter the findings to any considerable extent. Finally, an alternative specification of the revenue and costs functions using a reduced form regression yielded results fairly consistent with those presented.

## Discussion

Relatively few studies are available with which to compare with the presented results. Van Asseldonk (2020) investigated the impacts of policy-determined restrictions on antimicrobial use in Dutch pig production and found a positive association between antimicrobial doses and both revenue and total costs (as in our study), but neither of the effects were statistically significant. In another recent study, Jensen and Belay (2019) attempted to estimate likely economic consequences for the Danish pig sector from reducing access to antimicrobials, based on findings from the literature. These analyses, which mainly reflected changes in revenues from changed piglet mortality and daily weight gain and with limited consideration of adjustment possibilities on the cost side, yielded somewhat higher estimated costs of reduced access.

In contrast, the present analysis also suggests some effects on costs, and this contributes to reduce the economic losses if farms were to reduce their use of antimicrobials. For example, reduced access to antimicrobials could incentivize farmers to change the feeding of weaner pigs (toward less protein-intensive feeds), to vaccinate, and to implement biosecurity measures in the short run, even if they would incur additional costs. In the longer run, farmers could be stimulated to consider future space needs and sectioning possibilities in pig houses when planning new investments. Typically, new pig houses are dimensioned based on a given productivity level, in terms of weaned piglets per sow. Consequently, many (older) farrowing stables are under-dimensioned because the number of piglets per sow has increased every year due to genetic progress. This leads to high stocking density as well as a tendency for farmers to wean piglets at a younger age, which in turn increases the infection pressure and the need for antimicrobial treatment. Less investment-intensive (but also less effective) solutions could include various ways to modify existing pig housing facilities to increase the share of farrowing space on the farms or to build low-cost houses or containers for additional farrowing pens. Moreover, sectioning of farrowing houses would enable emptying, cleaning, and disinfecting separate sections and hence improve hygiene and infection pressure in the stables; this is also a relevant option when constructing new buildings but may be less appropriate if the house is older and under-dimensioned. However, based on a number of previous studies and constant industry focus on securing the health of pigs, there does not seem to be a “quick fix” that can reduce the use of antimicrobials without imposing costs on the sector. At the farm level, the most appropriate solution will depend on the specific conditions on the individual farm.

The economic impact of antimicrobial use in production depended on price conditions. If sales prices for pigs are relatively high, the potential gains from securing the production through the use of antimicrobials will naturally also be relatively high, whereas high prices on feeds may imply that the economic gains from antimicrobial disease treatment become lower.

It is also important to be aware that the econometric analyses are based on data for a period during which the use of medical zinc for treatment of weaning diarrhea was allowed. In a future perspective, where this will not be the case in EU member states, estimates of pig farmers’ economic losses due to reduced access to antimicrobials are likely to be in the lower end.

## Conclusion

This study suggests that pig farmers’ access to antimicrobials represented an average economic value of around 1.7–4 euro cents per standard unit dose in the short run on both low- and high-use farms and 1.02–1.14 euro cents for low- and high-use farms, respectively, in the long run. On high-use pig farms, the long-run shadow price corresponded to 8 cents per 7-kg piglet, 17 cents per 30-kg pig, or 57 cents per finisher pig per day of antimicrobial treatment. The analyses also suggested a considerable heterogeneity in these losses, both within low- and high-use groups of pig farms. Hence, restrictions on the use of antimicrobials in pig production are likely to imply a loss in parts of the Danish pig sector—particularly within the production of piglets. The relatively low estimated value of antimicrobial doses in the long run—supported by farm economic calculus—suggests that some of the infectious disease problems in pig production may be reduced along with investments in new and more modern production facilities.

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# Online Supplement: How Valuable are Antimicrobials for Pig Production? An Econometric Analysis

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**Table S1. Econometric estimation results for translog revenue function (fixed effects model)**

| | All pig farms | | Specialised piglet farms | | Specialised finisher farms | | Integrated pig farms | |
|---|---|---|---|---|---|---|---|---|
| | **Coeff.** | **Std. Dev.** | **Coeff.** | **Std. Dev.** | **Coeff.** | **Std. Dev.** | **Coeff.** | **Std. Dev.** |
| Log(piglet price) | 40,980 | 15,902* | 116,288 | 37,805** | 30,775 | 26,050 | 119,163 | 19,596*** |
| Log(sow price) | −516,130 | 34,577*** | −86,107 | 32,509** | −11,854 | 23,954 | −111,838 | 17,761*** |
| Log(piglet price)$^2$ | 0.1673 | 0.5218 | 24,989 | 13,014 | −0.0306 | 0.8287 | 31,612 | 0.6460*** |
| Log(piglet price)* Log(sow price) | −40,904 | 11,207*** | −77,930 | 26,867** | −32,246 | 18,944 | −81,386 | 14,037*** |
| Log(LU) | −0.4615 | 0.0143*** | −0.7224 | 0.0317*** | −0.4571 | 0.0172*** | −0.2447 | 0.0223*** |
| Log(equipment/LU) | 0.0069 | 0.0019*** | 0.0060 | 0.0111 | 0.0067 | 0.0022** | 0.0067 | 0.0045 |
| Housing quality | −0.0751 | 0.0126*** | −0.0099 | 0.0431 | −0.1075 | 0.0164*** | −0.0817 | 0.0301** |
| Log(Doses/LU) | −0.0034 | 0.0035 | −0.0027 | 0.0132 | 0.0042 | 0.0041 | −0.0310 | 0.0166 |
| Log(Doses/LU)$^2$ | 0.0065 | 0.0012*** | 0.0062 | 0.0038 | 0.0017 | 0.0015 | 0.0070 | 0.0033* |
| High*Log(Doses/LU) | −0.0261 | 0.0046*** | −0.0382 | 0.0125** | −0.0156 | 0.0063* | 0.0134 | 0.0131 |
| Sales share 30kg pigs | 0.1981 | 0.0327*** | −0.2135 | 0.1571 | 0.2840 | 0.0494*** | 0.0886 | 0.0654 |
| Outbreak-proxy | 0.0150 | 0.0069* | 0.0077 | 0.0219 | 0.0297 | 0.0082*** | 0.0302 | 0.0115** |
| 2009 | 24,598 | 0.1701*** | −0.0188 | 0.0646 | −0.0876 | 0.0393* | 0.2131 | 0.0354*** |
| 2010 | 19,214 | 0.1333*** | −0.0054 | 0.0599 | −0.0662 | 0.0319* | 0.1703 | 0.0310*** |
| 2011 | 0.4454 | 0.0416*** | −0.1945 | 0.0506*** | −0.0999 | 0.0204*** | −0.1420 | 0.0264*** |
| 2012 | −0.7638 | 0.0508*** | −0.0974 | 0.0458* | −0.0146 | 0.0191 | −0.0950 | 0.0241*** |
| 2013 | −10,357 | 0.0698*** | −0.0503 | 0.0434 | 0.0045 | 0.0200 | −0.0940 | 0.0238*** |
| 2014 | 0.1924 | 0.0196*** | −0.0730 | 0.0361* | −0.0389 | 0.0131** | −0.0356 | 0.0194 |
| 2015 | 0.7881 | 0.0601*** | −0.0974 | 0.0376** | −0.0553 | 0.0191** | −0.0406 | 0.0206* |
| | | | | | | | | |
| $R^2$ | 0.3036 | | 0.7053 | | 0.2515 | | 0.2343 | |
| M.S.E. | 0.01311 | | 0.0144 | | 0.01474 | | 0.01191 | |
| $N$ | 4,133 | | 379 | | 3,027 | | 1,134 | |

*Notes:* Single, double, and triple asterisks (*, **, ***) indicate significance at the 5%, 1% and 0.1% level, respectively.

## Table S2. Econometric estimation results for variable cost function (fixed effects model)

| | All pig farms | | Specialised piglet farms | | Specialised finisher farms | | Integrated pig farms | |
|---|---|---|---|---|---|---|---|---|
| | **Coeff.** | **Std. Dev.** | **Coeff.** | **Std. Dev.** | **Coeff.** | **Std. Dev.** | **Coeff.** | **Std. Dev.** |
| Log(vet.price) | 86,610 | 0.5946$^{***}$ | 0.8974 | 0.3991$^{*}$ | 0.0836 | 0.1692 | 20,032 | 0.4200$^{***}$ |
| Log(wage rate) | 0.0773 | 0.0523 | 0.2502 | 0.2189 | 0.0648 | 0.0600 | −0.7724 | 0.2813$^{**}$ |
| Log(wage rate)$^2$ | 0.1111 | 0.0706 | 0.0982 | 0.1898 | 0.2062 | 0.0897$^{*}$ | −0.3054 | 0.1502$^{*}$ |
| Log(vet.price)* Log(wage rate) | −0.0394 | 0.1273 | 0.1446 | 0.3188 | −0.1215 | 0.1611 | 0.4055 | 0.2505 |
| Log(wage rate)*Sales share 30kg pigs | −0.0378 | 0.0376 | −0.1301 | 0.1081 | 0.1017 | 0.0861 | −0.1391 | 0.0856 |
| Log(vet.price)* Sales share 30kg pigs | 0.0732 | 0.0622 | −0.3809 | 0.2135 | −0.1225 | 0.1562 | −0.2247 | 0.1493 |
| Log(LU) | −0.4099 | 0.0120$^{***}$ | −0.5630 | 0.0238$^{***}$ | −0.4296 | 0.0145$^{***}$ | −0.5307 | 0.0183$^{***}$ |
| Log(equipment/LU) | 0.0070 | 0.0015$^{***}$ | 0.0128 | 0.0084 | 0.0075 | 0.0018$^{***}$ | 0.0079 | 0.0038$^{*}$ |
| Housing quality | −0.2343 | 0.0181$^{***}$ | 0.0012 | 0.0915 | −0.2489 | 0.0211$^{***}$ | 0.0232 | 0.3167 |
| Log(Doses/LU) | −0.0152 | 0.0043$^{***}$ | 0.0803 | 0.0487 | −0.0073 | 0.0053 | −0.1168 | 0.0366$^{**}$ |
| Log(Doses/LU)$^2$ | 0.0056 | 0.0010$^{***}$ | 0.0073 | 0.0030$^{*}$ | 0.0025 | 0.0013 | 0.0013 | 0.0029 |
| High*Log(Doses/LU) | −0.0072 | 0.0039 | −0.0377 | 0.0132$^{**}$ | −0.0005 | 0.0053 | −0.0242 | 0.0185 |
| Log(wage rate)*Log(Doses/LU) | −0.0069 | 0.0060 | −0.0133 | 0.0213 | −0.0127 | 0.0068 | 0.1248 | 0.0323$^{***}$ |
| Log(vet.price)*Log(Doses/LU) | 0.0632 | 0.0134$^{***}$ | −0.0199 | 0.0382 | 0.0620 | 0.0165$^{***}$ | −0.1901 | 0.0492$^{***}$ |
| Hous.qual.*Log(Doses/LU) | 0.0299 | 0.0021$^{***}$ | −0.0067 | 0.0115 | 0.0314 | 0.0025$^{***}$ | −0.0040 | 0.0374 |
| Sow farm*Log(Doses/LU) | −0.0150 | 0.0036$^{***}$ | −0.0950 | 0.0505 | −0.0260 | 0.0094$^{**}$ | 0.0874 | 0.0293$^{**}$ |
| Sales share 30 kg pigs | 0.1738 | 0.0402$^{***}$ | 10,186 | 0.4440$^{*}$ | 0.0483 | 0.0937 | −0.5459 | 0.2526$^{*}$ |
| Outbreak-proxy | 0.0175 | 0.0057$^{**}$ | 0.0279 | 0.0166 | 0.0319 | 0.0068$^{***}$ | 0.0210 | 0.0096$^{*}$ |
| 2009 | −21,375 | 0.1382$^{***}$ | −0.0195 | 0.0450 | −0.1118 | 0.0288$^{***}$ | −0.0351 | 0.0248 |
| 2010 | −25,734 | 0.1673$^{***}$ | −0.0353 | 0.0504 | −0.1157 | 0.0346$^{***}$ | −0.0264 | 0.0287 |
| 2011 | 15,460 | 0.1054$^{***}$ | −0.0051 | 0.0424 | −0.0007 | 0.0242 | −0.0104 | 0.0255 |
| 2012 | 18,371 | 0.1210$^{***}$ | 0.0171 | 0.0406 | 0.0613 | 0.0267$^{*}$ | 0.0136 | 0.0244 |
| 2013 | 23,433 | 0.1548$^{***}$ | 0.0484 | 0.0433 | 0.0745 | 0.0326$^{*}$ | 0.0068 | 0.0268 |
| 2014 | 10,615 | 0.0717$^{***}$ | 0.0458 | 0.0317 | 0.0137 | 0.0171 | 0.0080 | 0.0186 |
| 2015 | 0.5154 | 0.0367$^{***}$ | −0.0084 | 0.0266 | −0.0081 | 0.0114 | −0.0241 | 0.0152 |
| $R^2$ | 0.4317 | | 0.7226 | | 0.33 | | 0.4986 | |
| M.S.E. | 0.00858 | | 0.00786 | | 0.01002 | | 0.00813 | |
| $N$ | 4,133 | | 379 | | 3,027 | | 1,134 | |

*Notes:* Single, double, and triple asterisks (*, **, ***) indicate significance at the 5%, 1% and 0.1% level, respectively.

## Table S3. Econometric estimation results for total cost function (fixed effects model)

| | All pig farms | | Specialised piglet farms | | Specialised finisher farms | | Integrated pig farms | |
|---|---|---|---|---|---|---|---|---|
| | **Coeff.** | **Std. Dev.** | **Coeff.** | **Std. Dev.** | **Coeff.** | **Std. Dev.** | **Coeff.** | **Std. Dev.** |
| Log(vet.price) | 104,552 | 28,741*** | 11,147 | 0.5675 | 0.6062 | 0.4216 | 28,091 | 0.5470*** |
| Log(wage rate) | 0.0611 | 0.0505 | 0.3876 | 0.2088 | 0.0491 | 0.0578 | −12,803 | 0.2809*** |
| Log(capital price) | −25,532 | 29,811 | −0.3939 | 0.3787 | −0.2538 | 0.3292 | −0.2137 | 0.2904 |
| Log(wage rate)$^2$ | 0.0003 | 0.0633 | 0.0428 | 0.1742 | 0.0879 | 0.0787 | −0.3204 | 0.1481* |
| Log(vet.price)* Log(wage rate) | 0.1524 | 0.2704 | 0.2377 | 0.7023 | −0.1640 | 0.3337 | 0.8674 | 0.5503 |
| Log(capital price) *Log(wage rate) | −0.1440 | 0.2002 | −0.1287 | 0.5745 | 0.0516 | 0.2478 | −0.4435 | 0.4157 |
| Log(wage rate)*Sales sh. 30kg pigs | −0.0024 | 0.0336 | −0.0280 | 0.0956 | 0.1516 | 0.0758* | −0.1717 | 0.0849* |
| Log(vet.price)* Sales sh. 30kg pigs | −0.0144 | 0.0555 | −0.4552 | 0.1888* | −0.2266 | 0.1369 | −0.1010 | 0.1470 |
| Log(LU)Âă | −0.4990 | 0.0102*** | −0.6037 | 0.0199*** | −0.5228 | 0.0121*** | −0.5711 | 0.0178*** |
| Log(Doses/LU) | −0.0032 | 0.0036 | 0.0856 | 0.0421* | 0.0083 | 0.0042* | −0.1372 | 0.0256*** |
| Log(Doses/LU)$^2$ | 0.0054 | 0.0009*** | 0.0058 | 0.0025* | 0.0017 | 0.0011 | 0.0023 | 0.0028 |
| High*Log(Doses/LU) | −0.0124 | 0.0035*** | −0.0341 | 0.0081*** | −0.0038 | 0.0046 | −0.0291 | 0.0146* |
| Log(wage rate)*Log(Doses/LU) | 0.0013 | 0.0054 | −0.0339 | 0.0191 | −0.0065 | 0.0060 | 0.1952 | 0.0320*** |
| Log(vet.price)*Log(Doses/LU) | 0.0334 | 0.0118** | 0.0219 | 0.0313 | 0.0355 | 0.0143* | −0.2661 | 0.0486*** |
| Outbreak-proxy | 0.0158 | 0.0050** | 0.0157 | 0.0147 | 0.0310 | 0.0059*** | 0.0136 | 0.0094 |
| Sow farm*Log(Doses/LU) | −0.0068 | 0.0032* | −0.0904 | 0.0427* | −0.0124 | 0.0082 | 0.0735 | 0.0288* |
| Sales share 30 kg pigs | 0.1223 | 0.0359*** | 0.8720 | 0.3746* | −0.0173 | 0.0816 | −0.3894 | 0.2475 |
| 2009 | −19,846 | 0.1244*** | −0.1162 | 0.0453* | −0.1547 | 0.0330*** | −0.1090 | 0.0335** |
| 2010 | −22,916 | 0.1670*** | −0.1384 | 0.0469** | −0.1504 | 0.0339*** | −0.1116 | 0.0342** |
| 2011 | 10,732 | 0.3910** | −0.0229 | 0.0453 | −0.0152 | 0.0328 | −0.0120 | 0.0301 |
| 2012 | 13,487 | 0.3715*** | −0.0058 | 0.0402 | 0.0376 | 0.0310 | 0.0041 | 0.0268 |
| 2013 | 18,602 | 0.3142*** | 0.0339 | 0.0380 | 0.0504 | 0.0296 | 0.0064 | 0.0263 |
| 2014 | 0.9593 | 0.0640*** | 0.0588 | 0.0284* | 0.0252 | 0.0175 | 0.0366 | 0.0207 |
| 2015 | 0.4642 | 0.0328*** | −0.0006 | 0.0228 | −0.0023 | 0.0110 | −0.0125 | 0.0157 |
| $R^2$ | 0.532 | | 0.791 | | 0.457 | | 0.531 | |
| M.S.E. | 0.0068 | | 0.0061 | | 0.0077 | | 0.008 | |
| *N* | 4,133 | | 379 | | 3,027 | | 1,134 | |

*Notes:* Single, double, and triple asterisks (*, **, ***) indicate significance at the 5%, 1% and 0.1% level, respectively.