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Antimicrobial Use and Farm Size in China's Shandong Province

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1. Introduction

Antimicrobial resistance poses a threat to public health across the world (Ferri et al. 2017). In addition to the use of antimicrobial drugs in humans, misuse of these in animal production is a main driver behind the emerging public health crisis of resistance (Sarmah, Meyer, and Boxall 2006; Landers et al. 2012; Holmes et al. 2016; Holman and Chénier 2015). Zhu et al. (2013) find that unmonitored use of antimicrobial drugs in livestock leads to the emergence and release of resistant genes into the environment. The association between antimicrobial use and resistance has been documented in both poultry and pig farms (Amaechi 2014).

Livestock products containing drug-resistant pathogens can pose considerable health risks to the health of consumers (Holmberg et al. 1984, White et al. 2001). Drug-resistant bacteria can also spread between animal species and to farm workers (Marshall et al. 1990), and have been found in soil, air and water near intensive livestock operations, though the extent to which this is a prominent pathway for transmission to humans remains unclear (Gibbs et al. 2006, Hong et al. 2013, Udikovic-Kolic et al. 2014). In addition to the public health effects, the presence of antimicrobial-resistant bacteria in the environment creates an ongoing need for higher volumes of new, more effective drugs for livestock production over the long term, reducing profitability in the sector. While the use of antimicrobials in livestock has historically been concentrated in highly industrialized countries, usage is rapidly increasing in low and middle-income countries (Van Boeckel, 2015). Understanding patterns and drivers of antibiotic use in settings with low regulatory enforcement capacity is thus critical for addressing the global challenge of emerging antibiotic resistance.

In this paper, we examine antibiotic use in the Chinese hog farming sector. China warrants special attention for several reasons. First, China is both the largest producer and the largest consumer of antibiotics in the world (Zhu et al. 2013). Second, it leads the world in use of antimicrobial drugs in livestock (Van Boeckel et al. 2015). Third, several studies have shown higher levels of antibiotic resistance in China than in other countries (Zhang et al. 2006; Hu et al. 2014; Hvistendahl 2012). Finally, the combination of high rates of antibiotic use and weak regulatory enforcement make China an ideal setting in which to examine the drivers of antimicrobial use in livestock production.

The use of antimicrobials both for treatment of disease in animals and growth promotion is largely unmonitored in China. High rates of use are evident in the concentrations of antibiotic residues commonly detected in animal manure (Qiao et al. 2012). In a 2007 survey, it was estimated that nearly half of the 210,000 tons of antibiotics produced in the country were used in animal feed (Hvistendahl 2012). Another study found that microbes sampled from the digestive tracts of people in China were dominated by genes resistant to tetracycline, which in China is mostly used in animal feed (Hvistendahl 2012; Hu et al. 2014). In 2016, the Chinese government issued a national action plan to contain antimicrobial resistance. The strategy included discontinuation of the use of antibiotics as animal growth promoters as a goal (Xiao 2017), suggesting official recognition that this practice was prevalent.

We focus on the hog farming sector for two reasons. First, pork is the main type of meat consumed in China. Both production and consumption of pork in China account for more than half of the total volume in the world (USDA 2019; OECD n.d.). Second, antimicrobial drugs are widely used in hog production in China (Krishnasamy, Otte, and Silbergeld 2015). While China has issued a series of regulations for antimicrobial use in the livestock industry since 2001, enforcement of these is not strict (Ying et al.

2017). Lin et al. (2010) sampled 485 pork products from supermarkets and restaurants in Guangzhou and found that only 76% met the standard for antibiotic residues.

Using farm-level survey data from Shandong, China, we investigate the relationship between antibiotic use and farm size. We find that larger farms tend to use more biological security measures such as segregation of animals and cleaning, and use more vaccines on average. Medium-sized farms are the most likely to use any antibiotics, and also administer the highest dosages on average. As the Chinse hog farming industry is undergoing a transition from small- to large-scale farming, our findings have implications for food policy and antibiotic regulations in China and other transitioning economies where livestock production is intensifying.

We contribute to an emerging literature that relates antimicrobial use and resistance to farm size. A positive association between farm size and the use of antimicrobials in hog production, both in terms of the frequency and the average daily dosages, has been reported in settings as diverse as Nigeria (Amaechi 2014) and the Netherlands (Fels-Klerx et al. 2011). Similarly, an earlier study found that hog farms in the U.S. with at least 50 animals were more likely to use off-label feed additives than were smaller farms (Dewey et al. 1997). Levels of antimicrobial resistance, including multidrug-resistance, were also found to be higher in medium-scale farms than small farms, where medium-scale farms were defined as farms with 100-500 hogs and small-scale farms less than 20 hogs (Ström et al. 2017). Our results are consistent with these previous findings in terms of the positive relationship between antimicrobial use and farm size when farms of up to 500 hogs are considered. However, we find that usage is lower in the largest farms.

Why do farms in this intermediate range use more antibiotics? A potential explanation is that this is a response to greater disease pressure arising from the concentration of a larger number of animals. A positive association between disease prevalence and farm size has been reported in many settings, including Sweden (Österberg et al. 2006), Belgium (Hautekiet et al. 2008) and Spain (García-Feliz et al. 2009). However, once farms reach a certain size, farms appear to reach an economy of scale in veterinary services and investment in biosecurity infrastructure. This enables a more sophisticated approach to disease management, with increased reliance on vaccines and biosecurity measures, and lower use of prophylactic antibiotics.

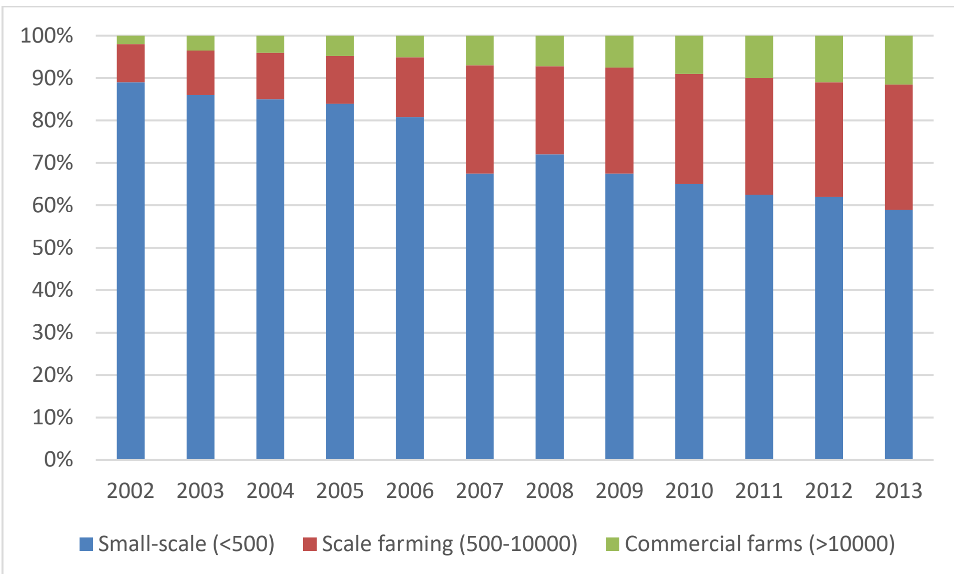
3. Data and Descriptive Statistics

2.1 Sample composition

We surveyed 934 hog-raising households in a County of Shandong province in China in January 2016.[1] Shandong province is among the top five largest hog producing provinces in China, and the study county is a major hog producing county in Shandong province.[2]

Figure 1 shows the increase over time in the proportion of hogs produced on large-scale farms in China over time, with farm size defined based on the number of hogs produced each year.

Figure 1: Transitioning into scale farming in Chinese hog production, 2002-2013



Source: Department of Livestock Production, Ministry of Agriculture of China

Despite this, the vast majority of hog farms in China remain small. Table 1 presents the number of farms in each size group during 2011-2014 in China based on data from the China Livestock Statistical Yearbook. Size groups are defined as in Figure 1. In 2014, 95% of hog farms in China produced fewer than 49 hogs per year, and an additional 3% of hog farms produced 50-99 hogs per year.

1 We attempted to survey all hog-raising households in this county. In practice, a small number of households which we failed to access after two attempted visits were excluded from the sample.

2 The original sample size was 944 hog farms. We dropped 10 farms for which the summation of the following three numbers is zero: the number of hogs produced in 2015, hogs in stock at the end of the calendar year 2015 and the number of hog deaths during 2015.

Table 1: Number of hog farms by size category (national statistics)

Farm size (hog prod'n)	1-49	50-99	100-499	500-999	1,000-2,999	3000+	Total
2011	55,129,498	1,724,703	782,338	157,036	58,180	22,587	57,874,342
	95.3%	3.0%	1.4%	0.3%	0.1%	0.0%	100%
2012	51,898,933	1,726,108	817,834	167,762	63,509	24,286	54,698,432
	94.9%	3.2%	1.5%	0.3%	0.1%	0.0%	100%
2013	49,402,542	1,619,877	827,262	175,652	65,369	25,261	52,115,963
	94.8%	3.1%	1.6%	0.3%	0.1%	0.0%	100%
2014	46,889,657	1,571,123	810,448	175,213	66,466	25,728	49,538,635
	94.7%	3.2%	1.6%	0.4%	0.1%	0.1%	100%

Source: China Livestock Statistical Yearbook

Panel A of Table 2 replicates Table 1 using survey data, and shows that over 50% of the farms in our sample raised more than 50 hogs in both 2014 and 2015, compared to 5% in the national statistics. Similarly, 4% of the farmers surveyed produced over 500 hogs in 2015, while the proportion of hog farmers producing this many hogs according to national statistics was 0.6%.[3]

[3] Our definition of farm size, described in the following sub-section, includes the number of hog deaths, whereas national statistics include only hogs produced. Excluding these does not greatly affect the distribution of farm size in our data, as hog deaths constitute a small share of total hogs (Table 4).

Table 2: Number of sampled hog farms and hog production by size category (survey data)

Farm size (hog prod'n + deaths):		1-49	50-99	100-499	500-2999	Total
Panel A: Number of farms						
2014	number	356	146	234	20	756
	%	47%	19%	31%	3%	100%
2015	number	428	183	287	36	934
	%	46%	20%	31%	4%	100%
Panel B: Total hog production						
2014	number	8,734	9,979	48,187	16,193	83,093
	%	11%	12%	58%	19%	100%
2015	number	10,276	12,968	63,138	35,502	121,884
	%	8%	11%	52%	29%	100%

Source: Survey data, Shandong, 2014-2015

However, due to challenges recruiting very large farms into the study, these are under-represented in our data. Panel B of Table 2 presents the share of total hog production among surveyed farmers by farm size. Of all the hogs produced by farmers in the sample in 2015, 29% were produced on farms in the largest size category, whereas according to China Livestock Statistical Yearbook, this figure was approximately 41% nationwide in 2013 (Figure 1).

2.2 Definition of farm size

Farmers were asked to recall hog production practices in 2015 and outcomes in both 2015 and 2014, including the number of hogs produced and the number of hog deaths over the course of the year. We use the sum of these values as our definition of farm size.[4]

Because we observe disease management practices in 2015, our main results are based on 2015 farm size. However, we note that this measure of farm size is simultaneously determined with disease management practices, leading to the potential for reverse causality in the regression models presented below. As a robustness check, we therefore include in Appendix B results from the same models but using the 2014 farm size variable. The correlation coefficient between farm size in 2014 and 2015 is 0.81.

4 Hog sales peak in advance of the Chinese New Year celebration, in late January or early February, and farmers typically begin counting annual production after this date. For this reason, we define 2015 farm size as the sum of 2015 production, 2015 deaths, and stocks at the time of the survey in January 2016. For 2014, farm size is defined as 2014 production (New Year to New Year) plus hog deaths.

2.3 Hog breeds by farm size

Farmers were asked how many hogs of each breed they raised. Breeds include local hogs, hybrid local hogs, hybrid foreign hogs, triple local hogs and triple foreign hogs. Triple breeds are generally considered more resistant to disease but less productive than local and hybrid breeds.

In almost all cases (96%) farmers only raised one breed of hogs. As shown in Table 3, 24.7% of the farms surveyed raised local hogs, 27.6% raised hybrid local hogs, 23.3% raised hybrid foreign hogs, 18.6% raised triple local hogs and 5.8% raised triple foreign hogs. These percentages vary by farm size, with smaller-scale farms raising more pure local breeds and fewer triple breeds relative to larger-scale farms.

Table 3: Proportion of hogs in stock by breed and farm size category

Farm size (2015 hog prod'n + deaths)	1-49	50-99	100-499	500-2,999	Total
Local pure	0.269	0.280	0.224	0.101	0.247
Hybrid local	0.297	0.274	0.261	0.233	0.276
Hybrid foreign	0.255	0.231	0.218	0.194	0.233
Triple local	0.142	0.179	0.217	0.319	0.186
Triple foreign	0.037	0.037	0.080	0.153	0.058
Total	1.000	1.000	1.000	1.000	1.000

This pattern could be explained by the fact that triple breeds are less disease resistant than local pure and hybrid breeds (Liu, Chen and Hill 2019). Small farmers are less equipped to cope with income shocks, which may lead to greater risk aversion and thus avoidance of riskier triple breeds. Differences in breed composition by farm size may contribute to differences in farms' needs for disease management through biosecurity, vaccination, and antimicrobial use.

2.4 Disease prevalence, hog mortality, and disease management by farm size

We next present data on disease prevalence, hog mortality, antibiotic use, biosecurity measures and vaccine use. Panel A of Table 4 shows disease prevalence and death rates by farm size. As enteritis and lung disease (pleuropneumonia and asthma) are the two most common types of hog disease, farmers were asked whether any hog in the farm had been affected by these problems in 2015. Overall, 87.5% of farmers reported that their hogs had been affected by either enteritis or lung disease, with 51.1% reporting lung problems and 82% reporting enteritis. We observe an upward trend in the prevalence of lung disease as farm size increases, while enteritis is constant over farm size.

The death rate is constructed as the number of hog deaths in 2015 divided by the total number of hogs produced (including end of year stocks). The death rate is decreasing in farm size, with the smallest farms reporting 5.5% compared to a rate of 2.5% reported by the largest farms.

Panel B of Table 4 presents antibiotic use by farm size. Capturing detailed information on antibiotic use through surveys is challenging for three reasons. First, farmers use many different types and formulations of antibiotic drugs and may not be able to recall the amount of active ingredient administered. Second, unit costs may vary based on purchase volume, making imputation of usage from total expenditure problematic, especially when analyzing the relationship between use and farm size. Finally, small farmers often rely on veterinarians to administer antibiotics and cannot distinguish the cost of medicine from the labor cost. To overcome these challenges, we use three questions to capture antibiotic use: i) when hogs get sick, what dosage of antibiotics (how many times the recommended dosage) do you use? ii) if some hogs in your farm get sick, do you use antibiotics preventatively on the hogs that are not sick? iii) if no hogs in your farm get sick, do you use antibiotics preventively on the hogs? Based on the three questions, we generate three variables: dosage of antibiotic use,[5] whether antibiotics are used preventively if some hogs are infected, and whether antibiotics are used preventively if no hogs are infected.

5 Dosage of antibiotic use is defined on the subsample of farms where some hogs had disease. We also dropped the farmers who answered "don't know" from the sample. For these two reasons, the sample size is reduced for this outcome variable.

Table 4: Outcome variables by farm size (2015 hog numbers)

Farm size	N	1-49	50-99	100-499	500-2999	Total
Panel A: disease						
=1 if affected by enteritis or lung disease	934	0.841	0.896	0.902	0.944	0.875
=1 if affected by lung disease	934	0.409	0.536	0.631	0.639	0.511
=1 if affected by enteritis	934	0.801	0.842	0.833	0.833	0.820
Death rate 2015 = death / production + deaths	934	0.055	0.054	0.051	0.025	0.053
Panel B: antibiotic use						
dosage of antibiotic use (times)	766	1.282	1.391	1.369	1.314	1.336
=1 if use antibiotics preventively when some hogs are infected	926	0.603	0.624	0.703	0.611	0.638
=1 if use antibiotics preventively when no hogs are infected	929	0.338	0.381	0.493	0.361	0.395
Panel C: biosecurity measures						
Capital-intensive biosecurity investment	934	0.269	0.339	0.457	0.537	0.351
Behavioral biosecurity investment	934	0.555	0.624	0.677	0.681	0.611
Total biosecurity investment	934	0.437	0.506	0.585	0.621	0.503
Biosecurity index	825	-0.968	0.007	1.322	2.400	0.010
Panel D: vaccine use						
Number of free vaccines used	934	1.210	1.683	1.969	1.750	1.557
Number of purchased vaccine used	934	1.839	2.044	2.540	2.833	2.133
Total number of vaccines used	934	2.832	3.355	4.017	3.972	3.343

Note: Dosage of antibiotic use is defined on the subsample of farms where some hogs had disease. Biosecurity Component is the common component derived from principal component analysis.

As shown in Panel B of Table 4, overall 63.8% of farms use antibiotics preventively when some hogs are infected and 39.5% of farms use antibiotics for preventive reasons even when no hogs are infected. Antibiotic dosage and both types of preventive use are highest among farmers that produce between 50 and 499 hogs.

Panel C of Table 4 presents data on the biosecurity measures taken by farms. The survey included 27 yes/no questions on farm biosecurity, including segregation of animals, cleaning, temperature control, and record-keeping. Depending on whether the biosecurity measure is more capital intensive (such as air-conditioning and heating systems in hog pens) or more behavioral (such as changing clothes before entering hog pens), we classify these into two groups: capital- and behavior- intensive biosecurity measures. The former group includes 12 measures, and the latter 15 measures (Table A.1 in the Appendix lists the elements included in each group). We construct the variable "capital-intensive biosecurity investment" for each farm by dividing the number of capital-intensive biosecurity measures taken by 12. Likewise, we construct the variable "behavioral biosecurity investment" by dividing the number of behavioral biosecurity measures taken by 15. In addition, we construct two aggregate biosecurity variables. First, the variable "total biosecurity investment" is equal to the total number of biosecurity measures divided by 27. Second, we collapse the 27 biosecurity measures into a single variable using principle components analysis.[6] Because some biosecurity measures have missing values, the common non-missing component only has 834 observations.

As shown in Panel C of Table 4, farms take an average of 13.6 (=0.503 * 27) biosecurity measures, of which 4.2 (=12*0.351) are capital-intensive and 9.2 (=0.611*15) are primarily behavioral. Comparing across columns, we see the pattern that larger farms take more biosecurity measures than small farms.

Lastly, panel D of Table 4 presents vaccine use by farm size. In China, the government provides free hog vaccination, including for foot and mouth disease, swine flu, and highly pathogenic porcine reproductive and respiratory syndrome (PRRS). As free vaccines are limited in terms of both supply and variety, most farmers purchase additional vaccines. In our sample, 64% of farms used one or more vaccines obtained for free from the government. Of these, 77% purchased at least one additional vaccine from the market. In addition, 31% of farmers only used purchased vaccines.

During the survey, each farmer was shown a list of vaccines, from which they selected a subset of vaccines that were used in their farms during the previous year. We measure vaccine use by the number of free, purchased, and total vaccines used.

Overall, farms use 1.6 types of free vaccines on average, although three different free vaccines were available. The average number of purchased vaccines was 2.1, and the total number of vaccines used was 3.3.[7] Medium-scale farms (100-500 hogs) were more likely to use free vaccines than either small or larger farms, and also used the largest number of vaccines on average. The use of purchased vaccines, on the other hand, is positively correlated with farm size, perhaps due to greater access to resources among larger farms.

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6 Principal components analysis a statistical procedure that converts a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables (principal components). The first principal component is that which accounts for the largest share of variability in the data. We use the first principal component of the 27 biosecurity variables as an index of investment in biosecurity.

7 Some farmers used both free and purchased vaccines against a given disease.

2.5 Covariates

In addition to farm size, previous literature has found that educational attainment is negatively associated with use of antimicrobials (Amaechi 2014). Other determinants of antibiotic use may include risk preferences, which in turn may be correlated with household income (e.g. Liu and Huang 2013; Liu 2012). These and other factors determining the use of antibiotics, vaccination, and biosecurity measures are likely to be correlated with farm size. In the following section, we attempt to isolate the influence of farm size on these outcomes through the use of multiple regression analysis.

We control for the age, years of schooling, years of experience raising hogs, and risk aversion level[8] of the farm manager, as well as the total household income. Summary statistics for these variables are shown in Appendix Table A.2.

4. Empirical Specifications

We use two empirical specifications to estimate the relationship between farm size and three groups of outcomes: use of biosecurity measures, vaccination, and antibiotic use,

First, we regress outcome variables on group size indicators, controlling for covariates using the following empirical specification:

$$y_i = \beta_0 + \sum_{k=2}^{4} \beta_k D_i^k + \gamma X_i + \epsilon_i, \qquad (1)$$

where D_i^k is an indicator equal to 1 if farm *i* belongs to size group k (k= 2, 3 and 4). Size group 1 has less than 50 hogs; size group 2 has 50-99 hogs; size group 3 has 100-499 hogs; size group 4 has more than 500 hogs.[9] Coefficients on group size indicators represent the difference between each size group and the comparison group of fewer than 50 hogs. y_i denotes the outcome variable, and X_i represents the control variables described above.

Second, to test for nonlinearity in the relationship between each of the outcome variables and farm size, we apply the following quadratic specification.

$$y_i = \alpha_0 + \alpha_1 S_i + \alpha_2 S_i^2 + \gamma' X_i + \mu_i, \qquad (2)$$

8 Risk aversion is coded as a binary indicator equal to one if the sigma Binswanger score is greater than 7.

9 The same thresholds are used when using the measurements “2014 hog numbers” and “hog production in 2015”. When using hog pen areas as the measurement of farm size, the thresholds are respectively the 25th, 50th and 75th percentiles of the distribution of hog pen areas.

where S_i represents the natural logarithm of farm size, and the other variables are the same as in equation (1).

5. Results

Tables 5 through 7 present the main results, based on farm size in 2015. Table 5 shows the association between farm size and biosecurity measures. We report results for four outcome variables: the biosecurity index equal to the first principal component of the 27 biosecurity variables (columns 1 and 2), capital-intensive biosecurity (columns 3 and 4), behavioral biosecurity (columns 5 and 6), and total biosecurity (columns 7 and 8), from equations (1) and (2), respectively. Larger farms generally use a larger number of biosecurity measures, both in terms of the PCA-derived biosecurity index and the average number of biosecurity measures implemented (columns 1 and 7). The pattern of biosecurity investment differs for capital-intensive versus behaviorally intensive measures. Use of capital intensive biosecurity measures increases at an increasing rate as farm size increases (column 4). In contrast, the relationship between farm size and behaviorally intensive biosecurity measures is fairly constant (column 6). Overall, the estimation results are consistent with the descriptive statistics in Panel C of Table 5: over the observed range of farm sizes, behavioral and capital biosecurity investment and the overall use of biosecurity measures all increase with farm size.

Table 5: Main results: Biosecurity investment and farm size (measured by 2015 hog numbers)

	Biosecurity index		Capital-intensive biosecurity		Behavioral biosecurity		Total biosecurity	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Size 2 [50, 99]	0.442***		0.029*		0.034**		0.032**	
	(0.168)		(0.016)		(0.014)		(0.013)	
Size 3 [100,499]	1.207***		0.098***		0.054***		0.073***	
	(0.196)		(0.018)		(0.016)		(0.014)	
Size 4, 500+	1.853***		0.139***		0.045		0.087***	
	(0.394)		(0.035)		(0.030)		(0.027)	
Log (size)		0.118		0.004		0.054***		0.032*
		(0.237)		(0.022)		(0.020)		(0.018)
Square of log(size)		0.058**		0.005**		-0.003		0.001
		(0.028)		(0.003)		(0.002)		(0.002)
Age of manager	0.019	0.025	0.004	0.005	0.003	0.004	0.003	0.004
	(0.049)	(0.048)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
(Square) age of mnger	-0.017	-0.022	-0.003	-0.004	-0.002	-0.003	-0.003	-0.003
	(0.047)	(0.047)	(0.004)	(0.004)	(0.004)	(0.004)	(0.003)	(0.003)
Years raising hogs	0.005	0.005	0.000	0.000	0.000	0.000	0.000	0.000
	(0.008)	(0.008)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Sch years of manager	0.093***	0.089***	0.008***	0.008***	0.008***	0.007***	0.008***	0.008***
	(0.019)	(0.019)	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)
log HH income	0.501***	0.363***	0.044***	0.032***	0.028***	0.019**	0.035***	0.024***
	(0.085)	(0.089)	(0.008)	(0.008)	(0.007)	(0.007)	(0.006)	(0.007)
If sigma Binswanger > 7	-0.101	-0.105	-0.016	-0.015	0.004	0.005	-0.004	-0.004
	(0.128)	(0.126)	(0.012)	(0.012)	(0.010)	(0.010)	(0.009)	(0.009)
Constant	-7.466***	-7.011***	-0.371***	-0.320**	0.095	0.044	-0.113	-0.118
	(1.476)	(1.494)	(0.136)	(0.137)	(0.119)	(0.121)	(0.108)	(0.109)
N	816	816	924	924	924	924	924	924
R squared	0.31	0.33	0.26	0.28	0.15	0.16	0.25	0.27
Size 2 = Size 3 (p val.)	0.00		0.00		0.20		0.00	
Size 3 = Size 4 (p val.)	0.07		0.18		0.72		0.58	

Note: Biosecurity index is derived from the first component of the 27 binary biosecurity measure variables, Capital-intensive biosecurity = the number of capital-intensive biosecurity measures / 12; Behavioral biosecurity = the number of behavioral-intensive biosecurity measures / 15; Total biosecurity = the total number of biosecurity measures / 27.

Table 6 shows the association between vaccine use and farm size. Column 1 and 2 show that medium-sized farms [50-500] use more free vaccines than small farms. Both specifications suggest that use is lower among the largest farms, though this nonlinearity is not statistically significant. As for using purchased vaccines, results in Column 3 show that the number of purchased vaccines increases monotonically with farm size. No significant relationship between farm size and use of purchased vaccines is observed in the quadratic specification (Column 4). Farms with 100-499 hogs use the most vaccines overall, although again no significant nonlinearity is observed (Column 5 and 6). These results are also consistent with descriptive statistics from panel D in Table 4.

Table 6: Main results: Vaccine use and farm size (measured by 2015 hog numbers)

	# of free vaccines used		# vaccines purchased		total vaccines used	
	(1)	(2)	(3)	(4)	(5)	(6)
Size 2 [50, 99]	0.398***		0.039		0.324**	
	(0.118)		(0.151)		(0.137)	
Size 3 [100,499]	0.537***		0.382**		0.758***	
	(0.134)		(0.172)		(0.156)	
Size 4, 500+	0.218		0.543*		0.529*	
	(0.257)		(0.329)		(0.299)	
Log (size)		0.510***		-0.107		0.332*
		(0.167)		(0.214)		(0.195)
Square of log(size)		-0.032		0.028		-0.005
		(0.020)		(0.025)		(0.023)
Age of manager	0.062*	0.071**	-0.023	-0.024	0.033	0.039
	(0.033)	(0.033)	(0.043)	(0.043)	(0.039)	(0.039)
(Square) age of mnger	-0.041	-0.050	0.000	0.002	-0.036	-0.042
	(0.032)	(0.032)	(0.042)	(0.041)	(0.038)	(0.038)
Years raising hogs	-0.003	-0.003	0.007	0.007	0.005	0.005
	(0.005)	(0.005)	(0.007)	(0.007)	(0.006)	(0.006)
Sch years of manager	0.043***	0.041***	0.008	0.009	0.047***	0.046***
	(0.013)	(0.013)	(0.017)	(0.017)	(0.015)	(0.015)
log HH income	0.152***	0.076	0.091	0.102	0.180***	0.137*
	(0.059)	(0.062)	(0.075)	(0.079)	(0.068)	(0.072)
If sigma Binswanger > 7	0.108	0.118	-0.233**	-0.238**	-0.099	-0.096
	(0.087)	(0.086)	(0.111)	(0.111)	(0.101)	(0.101)
Constant	-2.841***	-3.429***	2.128	2.094	-0.071	-0.668
	(1.012)	(1.029)	(1.294)	(1.323)	(1.178)	(1.204)
N	924	924	924	924	924	924
R squared	0.10	0.11	0.07	0.07	0.14	0.14
Size 2 = Size 3 (p val.)	0.29		0.04		0.00	
Size 3 = Size 4 (p val.)	0.16		0.58		0.38	

Table 7 shows the relationship between antibiotic use and farm size. Despite higher disease prevalence in the largest farms (Table 3), we observe the heaviest use of antibiotics in those of intermediate scale. While none of the coefficients on the farm size indicators are significantly associated with dosage of treated animals, there is a concave relationship between log farm size

Table 7: Main results: Antibiotic use and farm size (measured by 2015 hog numbers)

	Antibiotic dosage (times the recommended dose)		Use antibiotics preventively when some hogs are sick		Use antibiotics when no hogs are sick	
	(1)	(2)	(3)	(4)	(5)	(6)
Size 2 [50, 99]	0.073		0.011		0.012	
	(0.052)		(0.046)		(0.046)	
Size 3 [100,499]	-0.016		0.088*		0.089*	
	(0.057)		(0.052)		(0.052)	
Size 4, 500+	-0.133		-0.002		-0.062	
	(0.106)		(0.099)		(0.100)	
Log (size)		0.231***		0.135**		0.044
		(0.076)		(0.065)		(0.066)
Square of log(size)		-0.028***		-0.014*		-0.002
		(0.009)		(0.008)		(0.008)
Age of manager	-0.020	-0.019	0.013	0.012	0.013	0.014
	(0.014)	(0.014)	(0.013)	(0.013)	(0.013)	(0.013)
(Square) age of mnger	0.022	0.021	-0.016	-0.015	-0.013	-0.014
	(0.014)	(0.014)	(0.012)	(0.012)	(0.013)	(0.013)
Years raising hogs	0.004*	0.004*	0.002	0.003	0.001	0.000
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Sch years of manager	0.017***	0.016***	0.006	0.006	0.006	0.005
	(0.006)	(0.006)	(0.005)	(0.005)	(0.005)	(0.005)
log HH income	0.051**	0.043	-0.015	-0.010	0.031	0.023
	(0.025)	(0.027)	(0.023)	(0.024)	(0.023)	(0.024)
If sigma Binswanger > 7	-0.064*	-0.062*	-0.027	-0.027	0.040	0.042
	(0.037)	(0.037)	(0.034)	(0.033)	(0.034)	(0.034)
Constant	1.033**	0.669	0.518	0.203	-0.366	-0.413
	(0.428)	(0.436)	(0.389)	(0.398)	(0.395)	(0.405)
N	759	759	916	916	920	920
R squared	0.04	0.04	0.02	0.02	0.03	0.02
Size 2 = Size 3 (p val.)	0.11		0.12		0.13	
Size 3 = Size 4 (p val.)	0.20		0.29		0.08	

and dosage (Column 2), with a turning point of 61 hogs. This inverse U-shaped relationship between antibiotics use and farm sizes is also seen in the quadratic regression relating prophylactic use when some animals are sick (Column 4). The turning point of this nonlinearity is 124 hogs. The alternative specification for this outcome also shows higher use among farms in the range of 100 and 499 hogs ($p<0.1$, Column 3). Prophylactic use in the absence of any diseased hogs is also more common in this range of farm size compared to either the smallest, or the largest farms ($p<0.1$, Column 5), though in this case farm size is not associated with the outcome in the quadratic specification (Column 6).

Overall, consistent with the descriptive statistics from Table 5, the dosage of antibiotic use and the use for preventive reasons (whether with some hogs infected or not) are all highest among the farms with 50-499 hogs.

6. Robustness Checks

We repeat the analysis shown in Tables 6 through 8 using hog numbers in 2014. Results are in the Appendix B. Consistent with main results, the estimates show that larger farms use a larger number of biosecurity measures on average and that farms with 50-499 hogs use more vaccines than smaller farms. Again, both linear and quadratic regression results suggest an inverse U-shaped relationship between antibiotic use and farm size: the use of antibiotics first increases and then decreases with farm size. In other words, medium-sized farms have both the highest rates of prophylactic use and use the highest doses of antibiotics.

7. Discussion and Conclusion

Based on a survey of 934 hog farmers in Shandong province of China, we investigate the relationship between antibiotic use and farm size. We find an inverse U-shape relationship between farm size and antibiotic use. Farms with 50-499 hogs are the heaviest users of antibiotics compared to farms with less than 50 hogs and those with over 500 hogs, in terms of both prophylactic use and dosage.

Larger farms tend to use more vaccines, especially purchased vaccines, and to make use of biosecurity measures. The use of capital-intensive biosecurity measures is increasing in farm size at an increasing rate.

The Chinese hog farming sector is transitioning from small-scale to large-scale farming, following the international trend of structural transformation. The Chinse government has issued many policies promoting this transition, such as subsidies for medium-sized farms. However, regulations related to the hog production processes, in particular antibiotic use, are not well enforced, to the extent that these exist, are not well enforced. Our results suggest a need for the enforcement of such regulations.

Our findings also suggest that larger farms find it cost-effective to invest in alternatives to prophylactic use of antimicrobials, such as vaccines and biosecurity. The lower use of antimicrobials by the largest farms indicates a case for promoting these alternative disease management

Appendix A

Table A.1 Investment in Biosecurity measures

	N	Average	min	max
Capital intensive biosecurity investment				
Is the pig farm enclosed within a fence and lockable gate?	934	64.5%	0	1
Is the pig farm enclosed with bird-proof net?	933	27.1%	0	1
Is the pig farm enclosed with a specialized loading and unloading area?	933	41.5%	0	1
Is the pig farm equipped with water cannons？	934	30.2%	0	1
Do you have washing vehicle?	932	8.7%	0	1
Is the hog excrement being specially cleaned up, such as using the methane tank or fermentation bed?	933	34.3%	0	1
Do you have disinfecting vehicles？	933	6.1%	0	1
Are the facilities and tools (such as shovel and brushes) shared across hog production areas?	932	56.9%	0	1
Is the pig farm equipped with cooling system?	934	32.1%	0	1
Is the pig farm equipped with heating system?	931	24.3%	0	1
Is the pig farm equipped with ventilation facilities?	933	22.5%	0	1
Do different section/areas use different veterinary tools (such as pinhead)?	925	73.3%	0	1
Behavioral biosecurity investment				
Are piglets produced in your own farms (rather than purchased)?	932	84.4%	0	1
Did you produce the piglets using artificial insemination？	910	75.3%	0	1
Are nonworkers allowed to enter the hog farm?	933	74.0%	0	1
Are professional clothes and shoes required when working in the hog farm?	933	73.3%	0	1
Is there a specialized area for showering, changing clothes and shoes in the hog farm?	932	35.3%	0	1
Is the farm able to effectively stop rodents from entering it?	934	28.5%	0	1
Are your farm workers likely to also work with hogs in other hog farms?	931	78.6%	0	1
Do you use herd boar from other hog farms to produce piglets?	874	35.1%	0	1
Do you often clean the hog pen?	932	87.6%	0	1
Do you disinfect the hog farm?	932	85.0%	0	1
Do you sterilize the manure tank?	918	34.1%	0	1
Is there a specialized disinfecting area for shoes?	934	21.0%	0	1
Do hogs take anthelmintic to scour the parasite?	933	94.4%	0	1
Do you have disease record for the hogs?	934	9.9%	0	1
Are there any other animals raised around the pig farm? Such as sheep, horse, cow and poultry?	932	70.6%	0	1

Table A.2 Summary statistics of covariates

	N	Average	min	max
Age of the farm manager	934	50.98	23	76
years that you raised hogs	932	10.78	1	51
years of schooling of the manager	933	7.48	0	16
total household income	934	173,946	1,000	3,720,610
Risk Averse (sigma Binswanger>7)	927	0.63	0	1

Appendix B. Robustness checks

Table B.1 Biosecurity investment and farm size (measured by 2014 hog numbers)

	Biosecurity index		Capital-intensive biosecurity		Behavioral biosecurity		**Total biosecurity**	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Size 2 [50, 99]	0.334*		0.025		0.027*		0.027*	
	(0.193)		(0.018)		(0.015)		(0.014)	
Size 3 [100,499]	1.078***		0.075***		0.043**		0.057***	
	(0.218)		(0.020)		(0.017)		(0.016)	
Size 4, 500+	2.524***		0.218***		0.123***		0.166***	
	(0.528)		(0.046)		(0.040)		(0.037)	
Log(size)		-0.053		-0.024		0.049**		0.016
		(0.301)		(0.028)		(0.024)		(0.022)
Square of log(size)		0.079**		0.009**		-0.003		0.002
		(0.038)		(0.003)		(0.003)		(0.003)
Age of manager	0.068	0.060	0.007	0.006	0.005	0.005	0.006	0.006
	(0.056)	(0.055)	(0.005)	(0.005)	(0.004)	(0.004)	(0.004)	(0.004)
(Square) age of mnger	-0.066	-0.058	-0.006	-0.006	-0.005	-0.004	-0.005	-0.005
	(0.054)	(0.054)	(0.005)	(0.005)	(0.004)	(0.004)	(0.004)	(0.004)
Years raising hogs	0.007	0.007	0.000	0.000	0.000	0.000	0.000	0.000
	(0.009)	(0.009)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Sch years of manager	0.092***	0.089***	0.009***	0.008***	0.007***	0.007***	0.008***	0.008***
	(0.023)	(0.023)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
log HH income	0.498***	0.391***	0.046***	0.035***	0.025***	0.022***	0.035***	0.028***
	(0.100)	(0.105)	(0.009)	(0.010)	(0.008)	(0.008)	(0.007)	(0.008)
If sigma Binswanger > 7	-0.211	-0.181	-0.024*	-0.020	-0.003	-0.001	-0.012	-0.009
	(0.147)	(0.146)	(0.013)	(0.013)	(0.011)	(0.011)	(0.011)	(0.010)
Constant	-8.337***	-7.617***	-0.441***	-0.320*	0.087	0.013	-0.148	-0.136
	(1.685)	(1.782)	(0.154)	(0.163)	(0.132)	(0.141)	(0.122)	(0.129)
N	649	649	742	742	742	742	742	742
Turning point		0.3355		1.3		8.2		-4
Turning point		1.4		3.8		3522		0
R square	0.30	0.31	0.26	0.26	0.13	0.14	0.24	0.25
Size 2 = Size 3 (p val.)	0.00				0.37		0.06	
Size 3 = Size 4 (p val.)	0.00				0.02		0.00	

Note: Biosecurity index is derived from the first component of the 27 binary biosecurity measure variables, Capital-intensive biosecurity = the number of capital-intensive biosecurity measures / 12; Behavioral biosecurity = the number of behavioral-intensive biosecurity measures / 15; Total biosecurity = the total number of biosecurity measures / 27.

Table B.2: Vaccine use and farm size (measured by 2014 hog numbers)

	# free vaccines used		# vaccines purchased		Total vaccines used	
	(1)	(2)	(3)	(4)	(5)	(6)
Size 2 [50, 99]	0.241*		0.144		0.343**	
	(0.131)		(0.170)		(0.154)	
Size 3 [100,499]	0.261*		0.252		0.431**	
	(0.148)		(0.192)		(0.174)	
Size 4, 500+	-0.422		0.434		0.220	
	(0.339)		(0.441)		(0.400)	
Log(size)		0.630***		0.195		0.786***
		(0.206)		(0.268)		(0.241)
Square of log(size)		-0.058**		-0.006		-0.064**
		(0.025)		(0.033)		(0.030)
Age of manager	0.072*	0.073**	-0.023	-0.025	0.046	0.045
	(0.037)	(0.037)	(0.048)	(0.048)	(0.044)	(0.043)
(Square) age of mnger	-0.051	-0.052	0.000	0.002	-0.048	-0.047
	(0.036)	(0.036)	(0.047)	(0.047)	(0.043)	(0.042)
Years raising hogs	-0.002	-0.002	0.008	0.008	0.005	0.006
	(0.006)	(0.006)	(0.008)	(0.008)	(0.007)	(0.007)
Sch years of manager	0.053***	0.051***	0.007	0.006	0.056***	0.054***
	(0.015)	(0.015)	(0.020)	(0.020)	(0.018)	(0.018)
log HH income	0.241***	0.169**	0.158*	0.123	0.274***	0.192**
	(0.067)	(0.071)	(0.088)	(0.092)	(0.080)	(0.083)
If sigma Binswanger > 7	0.102	0.103	-0.167	-0.158	-0.063	-0.051
	(0.097)	(0.097)	(0.127)	(0.127)	(0.115)	(0.114)
Constant	-4.007***	-4.617***	1.357	1.233	-1.425	-2.295
	(1.126)	(1.199)	(1.465)	(1.562)	(1.328)	(1.405)
N	742	742	742	742	742	742
Turning point		5		16		6
Turning point		228		11,409,992		464
R squared	0.10	0.10	0.07	0.07	0.12	0.14
Size 2 = Size 3 (p val.)	0.89		0.57		0.60	
Size 3 = Size 4 (p val.)	0.02		0.64		0.55	

Table B.3: Antibiotic use and farm size (measured by 2014 hog numbers)

	Antibiotic dosage (times the recommended dose)		Use antibiotics preventively when some hogs are sick		Use antibiotics when no hogs are sick	
	(1)	(2)	(3)	(4)	(5)	(6)
Size 2 [50, 99]	-0.020		0.008		0.053	
	(0.056)		(0.050)		(0.051)	
Size 3 [100,499]	0.008		0.040		0.046	
	(0.062)		(0.057)		(0.058)	
Size 4, 500+	-0.168		0.019		-0.005	
	(0.137)		(0.130)		(0.133)	
Log (size)		0.178**		0.106		0.212***
		(0.086)		(0.079)		(0.081)
Square of log(size)		-0.023**		-0.010		-0.021**
		(0.011)		(0.010)		(0.010)
Age of manager	-0.012	-0.013	0.016	0.016	0.021	0.021
	(0.015)	(0.015)	(0.014)	(0.014)	(0.015)	(0.014)
(Square) age of mnger	0.014	0.015	-0.019	-0.019	-0.021	-0.021
	(0.015)	(0.015)	(0.014)	(0.014)	(0.014)	(0.014)
Years raising hogs	0.001	0.001	0.002	0.002	-0.001	-0.000
	(0.003)	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)
Sch years of manager	0.019***	0.019***	0.007	0.007	0.005	0.004
	(0.007)	(0.007)	(0.006)	(0.006)	(0.006)	(0.006)
log HH income	0.043	0.052*	-0.021	-0.025	0.033	0.015
	(0.029)	(0.031)	(0.026)	(0.027)	(0.027)	(0.028)
If sigma Binswanger > 7	-0.080*	-0.079*	-0.018	-0.016	0.039	0.042
	(0.041)	(0.041)	(0.038)	(0.037)	(0.038)	(0.038)
Constant	0.976**	0.551	0.508	0.328	-0.544	-0.807*
	(0.469)	(0.500)	(0.432)	(0.461)	(0.443)	(0.470)
N	620	620	737	737	739	739
Turning point		4		5		5
Turning point		48		200		156
R square	0.04	0.04	0.01	0.02	0.02	0.03
Size 2 = Size 3 (p val.)	0.64		0.56		0.91	
Size 3 = Size 4 (p val.)	0.14		0.85		0.66	

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