



Economic analysis of biosecurity adoption in dairy farming: evidence from Ireland

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Abstract

Given the significant negative impact of livestock disease outbreaks on animal and public health, preventing disease spread through biosecurity practices is important. In this study, we used a nationally representative dataset that included information on biosecurity practices of almost 300 Irish dairy farmers. We applied parametric and nonparametric estimation methods to assess the economic implications of adopting the following biosecurity measures: vaccination, bulk tank milk testing for diseases, and not pooling colostrum. We found mixed evidence of biosecurity practices on economic outcomes, measured as gross margins per cow. Specifically, we found that vaccination and testing bulk tank milk for diseases were significantly associated with better economic outcomes for dairy farms. However, we found no significant association with the economic performance of not pooling colostrum from more than one animal. Our findings have important policy implications required for targeting support for the adoption of biosecurity practices in dairy herds.

Lay Summary

Given the significant negative impact of livestock disease outbreaks on animal and public health, preventing disease spread through biosecurity practices is important. In this article, we assessed the economic implications of the adoption of biosecurity practices on Irish dairy farms. Specifically, we studied vaccination, testing bulk tank milk for diseases, and not pooling colostrum from more than one animal. Our analysis is based on a dataset of almost 300 dairy farmers that included information on the adoption of these practices combined with detailed information on the farm's economic performance. Our findings support the adoption of biosecurity measures. Specifically, we found that vaccination and testing bulk tank milk for diseases are significantly associated with economic benefits resulting in higher gross margins per cow, while our results do not provide a positive association on farm economic performance of not pooling colostrum. However, not pooling colostrum from more than one animal as a biosecurity practice is not negatively associated with economic outcomes of farms. Our results are important from a policy perspective to support increased adoption of biosecurity practices among livestock farmers globally.

Key words: biomanagement, biosecurity, dairy farming, farm economic performance

Abbreviations: AHI, Animal Health Ireland; ATT, average treatment effect on the treated; BVD, bovine viral diarrhoea; BTB, bovine tuberculosis; DAFM, department of agriculture, food and the marine; DiD, difference-in-difference; FADN, farm accountancy data network; GM, gross margin; GPS, generalized propensity score; IBR, infectious bovine rhinotracheitis; IPWRA, inverse-probability-weighted regression adjustment; IV, instrumental variable; MAP, mycobacterium avium paratuberculosis; MNL, multinomial logit; NFS, national farm survey; OLS, ordinary least square; POM, potential outcome means; PSM, propensity score matching; SCC, somatic cell count; TE, treatment effect

Introduction

Maintaining good animal health is important for farm businesses; and livestock disease outbreaks can have considerable economic consequences affecting trade, food prices, and public health (Hennessy and Wolf, 2018). Government control efforts, such as government-mandated testing, herd movement restrictions, and culling of reactor animals to eliminate diseases, are often a last resort, which is cost-effective (Schaefer et al., 2021). Specifically, Schaefer et al. (2021) showed that government control efforts on bovine tuberculosis (BTB) generated a positive external value for the British beef sector. Thus, implementing farm-specific biosecurity plans can help to mitigate disease spread in the first place, and as such avoid 'last resort' measures. However, at the farm level, dis-

ease control efforts are often associated with additional costs. And farmers may not always be fully aware of subclinical animal diseases (Hennessy and Wolf, 2018). This underlines the importance of promoting biosecurity practices on farms.

Biosecurity consists of bioexclusion and biocontainment practices. Bioexclusion encompasses management practices to prevent infectious pathogens entering the farm, such as maintaining a closed herd and testing and quarantining bought-in livestock, while biocontainment practices (e.g., vaccination, accommodating livestock by age cohort) prevent the intra-farm or intraherd transmission of diseases. Despite their vital importance, there is ample evidence that adoption of biosecurity practices, such as not pooling colostrum, testing, and maintaining a closed herd, etc. on farms is low (e.g., Brennan

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and Christley, 2012; Sayers et al., 2013; Shortall et al., 2016; Emanuelson et al., 2018; Mee, 2020; McCarthy et al., 2021a). Given that biosecurity measures may reduce profit (Belay and Jensen, 2021), from an economic perspective at least, a low adoption rate of biosecurity practices is not surprising. Nevertheless, some farmers believe biosecurity measures to be effective and adopt biosecurity measures to prevent the spread of a disease and to improve animal health and welfare (Denis-Robichaud et al., 2019).

There is a general consensus in the literature that disease prevention is associated with both costs and benefits for the farmer (Jarvis and Valdes-Donoso, 2018), which makes promoting biosecurity practices with farmers more challenging when compared to new practices with clear proven economic benefits. While animal diseases lead to economic losses, prevention of diseases through biosecurity measures such as vaccination, closed herds, testing of new animals and so forth, generate additional costs and hence can reduce farm profit (Jarvis and Valdes-Donoso, 2018; Belay and Jensen, 2021). At the farm level, the farmer's own assessment of the perceived benefits and costs of implementing biosecurity measures will likely depend on the farmer's general aptitude for risk and expected probability that a disease will enter or break out in the herd. Nevertheless, despite initial costs of implementing biosecurity measures, disease prevention can lead to healthier animals, which are more productive and derive higher profit (McInerney, 1996; Bennett, 2003; MacDonald and Wang, 2011; Stott et al., 2012). Therefore, the economic implications of adopting biosecurity measures are uncertain ex-ante, justifying the need for further empirical analysis.

In Ireland, maintaining good biosecurity practices on dairy farms has become particularly relevant given the expansion of the national dairy herd following the 2015 abolition of milk quotas across the EU. The national dairy herd in Ireland has increased by over 40% over the last decade (CSO, 2020), and the vast majority of herd expansion was due to existing dairy farmers increasing their herd size. For example, in 2010, just over 10% of farms had more than 100 cows, while this figure had increased to 23% in 2018 (Teagasc, 2019). This significant expansion in average herd sizes has also increased fears around diseases entering dairy farms (McCarthy et al., 2021a), and intraherd transmission of infections, which can have detrimental effects not only on the welfare and health of the animals but also on public health, e.g., bovine tuberculosis, paratuberculosis, bovine viral diarrhoea, and salmonellosis. Despite this, the adoption of biosecurity measures on Irish dairy farms is ad hoc; there are mandated (by legislation) biosecurity measures for some pathogen-specific diseases (a single pathogen causes the disease), e.g., bovine viral diarrhoea (BVD), but voluntary adoption of biosecurity practices for other pathogen-specific diseases, e.g., cryptosporidiosis. For some nonpathogen-specific diseases (more than one pathogen may cause the disease), e.g., mastitis, biosecurity practices are widely adopted, while for other nonpathogen-specific diseases, e.g., calf diarrhoea, biosecurity measures are variably adopted (Mee, 2020). Additionally, some bioexclusion measures are mandated, e.g., premovement testing for bovine tuberculosis but others are not, e.g., quarantine. Similarly, some biocontainment measures are mandated, e.g., testing for BVD, but others are not, e.g., vaccination.

Given this existing diversity in approach to both pathogen-specific and nonpathogen-specific diseases, the Irish Department of Agriculture, Food and the Marine (DAFM)

launched a National Farmed Animal Biosecurity Strategy (2021–2024) with a vision that Irish farms achieve high biosecurity status through strategic initiatives that, for example, envisages each farmer having a risk-assessed biosecurity plan (DAFM, 2020). (For more information, please see (gov.ie - Animal Health & Welfare Biosecurity (www.gov.ie)).) Additionally, there is a national biosecurity Technical Working Group convened by Animal Health Ireland (AHI) (see Biosecurity Technical Working Group - Animal Health Ireland for more information on the Technical Working Group) which provides the knowledge, education, and coordination required to support effective control programmes for non-regulated diseases of livestock such as BVD, IBR (Infectious Bovine Rhinotracheitis), calf diseases, Johne's disease, mastitis, and the parasitoses. Both DAFM and AHI, along with other agri-industry partners, collaborate to deliver biosecurity recommendations for Irish dairy, and other enterprise farmers.

While adoption of biosecurity practices varies in Ireland, this appears to be the same in other countries. For example, between 19% (Bishop et al., 2010) and 73% (Mil-Homes, 2020) of dairy farms internationally are reported as having a closed dairy herd, while a recent Irish survey found that 28% of dairy farms were closed (McCarthy et al., 2021a). In the Irish dairy sector, a closed herd means no inward movement of cattle to the herd (Sayers et al., 2013). The low percentage of closed herds in Ireland can be explained by ongoing dairy herd expansion. A wide variation exists also in the proportion of dairy farmers internationally who test purchased cattle which is between 25% (Denis-Robichaud et al., 2019) and 88% (Sarrazina et al., 2014). Ireland is on the lower end with 25% of dairy farmers testing purchased cattle (McCarthy et al., 2021a). Similarly, between 3% (Villaamil et al., 2020) and 45% (Aleri et al., 2020) of dairy farmers reported quarantining their cattle in different countries; in Ireland, 79% of dairy farmers reported using quarantine (McCarthy et al., 2021a). The high Irish figure likely reflects postquota abolition risk aversion.

Given the importance of biosecurity measures to prevent the spread of infectious diseases, the objective of this study was to estimate the economic implications of selected biosecurity measures. Specifically, we tested whether 1) vaccinating cattle against several diseases, 2) testing bulk tank milk for diseases, and 3) not pooling colostrum, are positively associated with economic outcomes, measured as gross margins (GMs) per cow. We restricted our empirical analyses to three of the most commonly adopted practices because of the low adoption rate of other practices among dairy farmers. However, an overview of the uptake of the commonly implemented biosecurity practices on Irish dairy farms is provided as [Supplementary Appendix](#).

Materials and Methods

Methodology

In general, farmers adopt new technologies based on the perceived benefits of the new technology (Chavas and Nauges, 2020). Based on this assumption, farmers will adopt a biosecurity practice if the expected potential net (economic) benefits from adoption are greater compared to not adopting the practice. At the same time, farmers know that healthier animals are more productive, and they will aim to improve animal health and welfare if this is likely to increase profit,

i.e., the expected benefits outweigh the costs. However, biosecurity is about managing risk as the probability of a disease outbreak and the potential impacts are not known with certainty. Therefore, if a farmer perceives the likelihood of a disease outbreak to be low, perceived benefits will likely be lower than the costs of implementation. In contrast, a farmer who is risk averse and is afraid of a disease outbreak on the own farm, will have very different perceived benefits of adopting biosecurity measures. This partly explains why the adoption of biosecurity measures is heterogeneous across farms. Therefore, the decision to adopt biosecurity practices depends on factors such as the farmer's own motivation, attitude to risk, the actions of other farmers, government policy (Ceddia et al., 2008; Heikkila, 2011).

This also illustrates why adopters and nonadopters of biosecurity practices may be quite different from each other (see Rubin, 1973, 1974; Imbens and Wooldridge, 2009; Wooldridge, 2010). Thus, it is difficult to simply attribute the differences in farm economic performance to the adoption decision. For example, dairy farmers more likely to implement biosecurity practices may also be those who have better managerial ability. But, better managerial ability, which is unobserved, is likely correlated with higher farm economic outcomes. This represents a classic self-selection problem. Thus, estimating the impact of biosecurity practices based on observational data is difficult since there is no information on the counterfactual outcome. In other words, we do not observe the same farm without biosecurity measures. Given that the decision to adopt biosecurity practices is likely correlated with managerial ability, the issue of self-selection is crucial, and an appropriate econometric technique is required to address the problem.

In this study, we employed an inverse-probability-weighted regression adjustment (IPWRA) technique (Wooldridge, 2010)—the so-called “doubly robust” method since it combines both a regression adjustment and an inverse-probability weighting approach—to estimate the average treatment effect on the treated (ATT) of adopting biosecurity measures on farm economic performance. To control for selection bias, previous studies using nonexperimental data have employed either an instrumental variable (IV), a Propensity Score Matching (PSM), or a Difference-in-Difference (DiD) technique. However, the challenge of finding a suitable instrument in the adoption equation makes it quite an onerous task to employ an IV approach. PSM, on the other hand, has the disadvantage that it cannot eliminate the bias due to variables that cannot be observed despite being able to eliminate bias due to observable characteristics. In addition, the DiD approach requires the presence of a panel data—data that include observations over time.

To estimate the ATT, the IPWRA treatment effect (TE) estimator for observational data can provide an unbiased estimate by allowing exogenous covariates to be related to the farm economic performance (potential outcome) and the biosecurity adoption decision (treatment). The estimate from this technique is consistent if unobservable factors that affect treatment assignment are not correlated with the potential outcome (Angrist and Pischke, 2009; Wooldridge, 2010). Thus, before implementing our main IPWRA model, we first conducted sensitivity analyses where we implemented endogenous TE models and then tested for the presence of endogeneity following Wooldridge (2010). In our models, we failed to reject the hypothesis that the treatment and potential

outcome models are uncorrelated (Supplementary Table A5). Thus, we implemented the IPWRA and presented this as our main result.

In the doubly robust estimation method, inverse-probability weights are computed from logit or multinomial logit (MNL) regression models of farmers' adoption decisions (Equation 1). By correctly specifying any one of the models (potential outcome or treatment model), the resulting estimate is both consistent and efficient, since the double-robust property of the estimator only requires that one of the two models is correctly specified (Bang and Robins, 2005; Wooldridge, 2010). Using the estimated probability weights of the treatment model, a weighted ordinary least square (OLS) estimator is fitted on the outcome model to obtain the expected outcome of the probabilities of adoption and nonadoption of the specific biosecurity practice. The difference in mean outcomes between adopters and nonadopters of the specific biosecurity practice provides estimates of the average productivity effect of the adoption decision (Tambo and Matimelo, 2021). According to Wooldridge (2010), the doubly robust method relaxes the no correlation assumption between the error terms of both models and thus uses a control-function (CF) approach by including the residuals from the biosecurity adoption model as a regressor in the economic performance model. The notations for the model used are given below:

$$Y_{i0} = E(Y_{i0} | X_i) + \varepsilon_{i0} \quad (1)$$

$$Y_{i1} = E(Y_{i1} | X_i) + \varepsilon_{i1} \quad (2)$$

$$L_i = E(L_i | Z_i) + \mu_i \quad (3)$$

$$E(\varepsilon_{ij} | X_i, Z_i) = E(\varepsilon_{ij} | Z_i) = E(\varepsilon_{ij} | X_i) = 0 \text{ for } j \in \{0, 1\} \quad (4)$$

where the subscript i denotes individual-level observations, Y_{i0} is the potential outcome for the nonadopters, and Y_{i1} is the potential outcome for the adopters; and each one of these potential outcomes is determined by its expected value conditional on a set of regressors X_i and an unobserved random component, ε_{ij} . In the same way, the treatment, L_i is given by its expected value conditional on a set of regressors, Z_i which can be similar to X_i . Thus, equations (1–3) describe the parametric TE models while equation (4) includes endogeneity into the TE framework relaxing the condition of no correlation between unobservable in the farm economic performance model and the biosecurity adoption decision model. For this estimation, we implement diagnostics (overidentification) and a test for balance of the covariates following Rosenbaum and Rubin (1983) and Imai and Ratkovic (2014).

Data

The data used in this study are from the Irish National Farm Survey (NFS). The NFS, established in 1972 by Teagasc, collects data on an annual basis from a statistically representative sample of approximately 900 farms representing a population of about 80,000 farms in the Republic of Ireland. Teagasc is the Irish Agriculture and Food Development Authority that provides agricultural extension, education, and research. The data are collected as part of the fulfillment

Table 1. Descriptive statistics and definition of variables of farm and farmers' characteristics

Variable	Definition	Mean	SD
Herd size	Number of dairy cows(milking and dry)	90.53	54.92
Dairy forage area	Size of foragearea used for dairy production(ha)	42.93	23.54
Farm size	utilizable agricultural area(ha)	68.10	36.72
Stocking rate	Dairy cows per dairy forage area	2.10	0.50
Specialization	Dairy cows as a proportion of all livestock	0.67	0.13
Low specialization	= 1 if specialization <66%	0.42	
Medium specialization	= 1 if specialization = 66 – 75%	0.31	
High specialization	= 1 if specialization >75%	0.27	
Debt to asset ratio	Debt to equity ratio (%)	6.23	9.3
Feed use	Liters of milk produced per kg of purchased feed	5.80	2.66
SCC	Somatic cell count (bulk tank) (in 1,000)	164.49	65.23
Age	Age of farm holder (years)	54.39	10.64
Household	Number of household members	3.44	1.53
South	= 1 if the farm is located in the south	0.66	
East and midlands	= 1 if the farm is located in the east and midlands	0.17	
Northwest	= 1 if the farm is located in the northwest	0.17	
Economic indicator			
Dairy GM/ cow (€/cow)	Dairy gross margin per dairy cow	1,187.19	314.04
Number of observations		267	

Source: Authors' calculations from NFS data. SD, standard deviation.

of Ireland to provide data to the EU Farm Accountancy Data Network (FADN). The FADN monitors farms' incomes and business activities and is based on a harmonized bookkeeping system. Detailed data on key financial and physical indicators at the farm level (i.e., sales, purchases, costs, subsidies, liabilities, assets), as well as farm (e.g., size, animal numbers, etc.) and farmer characteristics (e.g., off-farm employment and income, farm inheritance, household composition, age structure), are collected from farms each year. Additional data are also being collected in relation to environmental issues.

Farms in the NFS are categorized into six farming systems based on the proportion of the total standard output that comes from each farm enterprise (Dillon et al., 2019); specialized dairying, dairying other, cattle rearing, cattle other, mainly sheep, and tillage. For this study, we restricted our data to dairy farms, and a sample of 267 dairy farms was used. In addition to standard farm accountancy data, Teagasc also administers a supplementary survey each year. The focus of this supplementary survey changes depending on the current situation; therefore, supplementary data are generally available for individual years only.

In this study, we utilized data from a supplementary survey on biosecurity practices that was added to the 2019 NFS survey. As mentioned, these data are not routinely collected in the NFS and are, thus, only available for 2019. Hence, our dataset is cross-sectional data for the year 2019. In this supplementary survey, among other topics, dairy farmers were asked questions in relation to animal health and biosecurity, as well as antibiotic use. More specifically, in order to prevent diseases coming on to farm, farmers were asked to indicate whether they test bought-in cattle for diseases (including the different types of diseases tested against if yes); vaccinate cattle (including indicating the different types of diseases vaccinated against if yes); get bulk tank milk tested for diseases

(other than somatic cell count (SCC)); pool colostrum from more than one animal; maintain a closed herd; and quarantine bought-in stock. Using farmers' unique identifier within the NFS, we matched dairy farmers' answers to these questions and their farm economic performance variables that we used for our analyses.

Table 1 outlines the mean values of the variables used in this analysis and their description. Dairy GM per dairy cow (reported at the bottom of Table 1) is the dependent variable for the outcome equations to measure economic returns of biosecurity practices. The average GM per cow in the sample is €1,187.

The explanatory variables consisted of farm and farmer characteristics to account for the heterogeneity in biosecurity adoption outlined above, as well as regional variables to account for differences in production based on location. In general, the north-west region is characterized by higher rainfall and less suitable soils for grass growth, the south region is seen as a traditional dairy region where the majority of dairy farms are located, while the east and midland's region has seen a recent increase in dairy cow numbers and milk yields. In line with these regional differences, performance of dairy farms differs across regions.

Farm characteristics included measures of farm size, stocking rate, farm specialization, and variables to account for farmer management ability. The average herd size in the sample was just over 90 cows. This includes all dairy cows and dry cows. Due to the seasonal production in Ireland, it is standard practice to dry off all dairy cows at the end of the year. Our sample farms have a stocking rate of 2.1 dairy cows per hectare forage area. Cows are generally grazed outside from early spring to late autumn, but due to paddock systems and separate fields, herds from different farms do not come in contact. In relation to farm management ability, we

Table 2. Distribution of farmers in the data who adopted different biosecurity practices

Biosecurity practices	<i>n</i>	%
% of farmers who		
Vaccinate cattle (at least against 1 disease)	229	86.09
Vaccinate against 0 or 1 disease	75	28.09
Vaccinate against 2 or 3 diseases	87	32.58
Vaccinate against more than 3 diseases	105	39.33
Farmers who test bulk tank milk for diseases (other than SCC)	170	64.64
Farmers who do not pool colostrum (from more than one animal)	116	44.96
Number of observations	267	

Source: Authors' calculations from the NFS data.

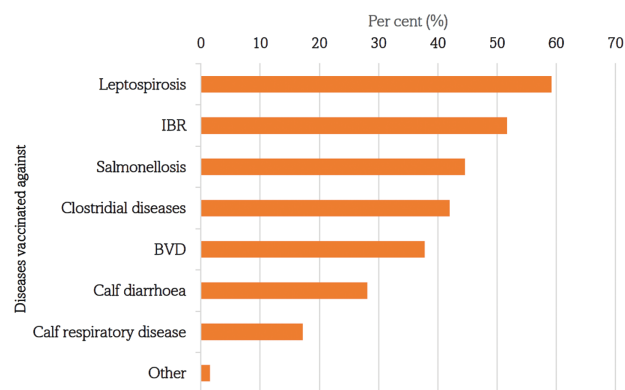
used milk SCC, a measure of the cellular immune response to bacterial pathogens in the udder, as a proxy for managerial ability. Lower values represent better microbial milk quality and indicate better managerial ability. SCC values are available on a monthly basis; and the presented value is the mean over all months. Feed use measures the efficient use of inputs where a higher number implies that more milk is produced per kg of concentrates fed. Again, this is used as a proxy for managerial ability. We used the degree of dairy specialization (categorized as low, medium, and high specialization following Kelly et al., 2013) to control for how specialized the farm is in dairy production. Over time, dairy farms in Ireland have become more specialized, but most farms still have some beef output on the farm. For example, in 2019 about three quarters of gross output of dairy farms came from the dairy enterprise. This is in contrast to many other developed countries where farms often tend to be more specialized in one production method. In addition, we used the debt-to-asset ratio, a general measure of risk attitude to control for farmers' risk aversion. Debt-to-asset ratio has previously been used in the literature to control for farmers' attitude to risk (see Diederer et al., 2003; Keelan et al., 2009; Laple et al., 2015). Debt-to-asset ratio measures farmers' liability in relation to the farm equity. In relation to biosecurity adoption, this is related to the fear of diseases entering the farm. That is, farmers who are more risk averse (i.e., have lower debt-to-asset ratio) will be more likely to adopt biosecurity measures. In relation to farmer characteristics, we included age and number of household members as proxies of available family labor. The average age of the farmers in the sample is 54 yr.

An overview of adopted biosecurity practices is presented in Table 2. The complete list of biosecurity practices included in the survey and the adoption rate of these practices is presented as Supplementary Figure A1. In addition, the socio-economic and farm characteristics of adopters and nonadopters of the biosecurity practices analyzed in this study are provided in Supplementary Tables A1–A3). As a general observation, farmers in our sample were more likely to adopt biocontainment practices than bioexclusion practices. As indicated earlier, the survey collected data on other biosecurity and bio-exclusion practices, but these are not analyzed in this present study. This is because the number

of farmers adopting these practices was low, thus making it difficult to conduct an econometric analysis with a small number of farmer using the practices. In addition, while the questions were presented to all farmers in the NFS, we only analyzed data for dairy farmers in this current study. Moreover, not all questions were applicable to every farmer. For instance, the question relating to testing bought-in cattle would not be applicable to farmers who maintained a closed herd.

The most frequently adopted bioexclusion practices were maintaining a closed herd (36%), quarantining purchased cattle (30%), and testing purchased cattle for diseases (13%), while only 4.4% of farmers sent their heifers to be contract-reared. It should be noted that neither “closed herd” nor “quarantine” was defined in the questionnaire, but the former is understood to mean no inward movement of cattle (Sayers et al., 2013) and the latter isolation of brought in cattle for at least 4 wk (McCarthy et al., 2021a) in Ireland. Important biocontainment measures include vaccination, herd screening, and using individual cow, (not pooled) colostrum. That is, a practice of not pooling colostrum from more than one animal. Pooling colostrum from more than one animal can increase the risk of pathogen transmission (e.g., *Mycobacterium avium* subspecies *paratuberculosis* (MAP) or *Mycoplasma* spp.) from infected dams to their own and other dams' offspring. Given that in most dairy herds individual dam disease status is unknown, colostrum pooling is always a risk for disease transmission.

The most frequently adopted biocontainment practices from our sample were vaccination (86%), bulk tank milk testing for diseases (65%), and not pooling colostrum (45%). While 86% of farmers vaccinated against at least one disease, for the purposes of determining the economic effect of vaccination, we distinguished the economic effect of vaccination by the number of different diseases vaccinations against. For example, 28% of farmers either did not vaccinate at all or vaccinated against one disease only, one-third of farmers vaccinated against two or three diseases, while the remainder (39%) vaccinate against more than three diseases. Furthermore, with respect to vaccination, dairy farmers were more likely to vaccinate against cow than calf diseases (Figure 1). The high vaccination rates against leptospirosis and IBR reflect legacy practice and the development of a (mandatory) national program of IBR control, respectively. In the year when the data were collected (2019), mandatory national disease control programs were

**Figure 1.** Diseases vaccinated against by dairy farmers (*n* = 229).

in place for bovine viral diarrhoea (BVD), and bovine tuberculosis (BTB) and voluntary disease control programs were in place for MAP and IBR in Ireland. There were no national control programs for leptospirosis, salmonellosis, clostridial, or calf diseases at the time of data collection. While the use of vaccines to control infectious diseases is relatively common on dairy farms internationally, this can vary widely between diseases. For example, 5% of dairy farmers vaccinated against salmonellosis in Great Britain (Velasova et al., 2017) and 46% vaccinated against bovine viral diarrhoea in Northern Ireland (Cowley et al., 2014). Herd screening for antibodies to infectious diseases can be achieved by test-

ing bulk tank milk samples (e.g., Collins et al., 2017). This practice is becoming more common on larger, more intensive dairy farms internationally. At the same time, feeding pooled colostrum to dairy calves (although counterproductive to effective biosecurity practice) is also common, with internationally between 20% and 82% of farmers doing this (Mee, 2020).

Table 3 presents GM/cow by selected biosecurity practices. With an increasing number of vaccinations, GM/cow increases. Similarly, farmers who test bulk tank milk for diseases also have higher GM/cow than farmers who do not. In contrast, farmers that do not pool colostrum from more than one animal have lower GM/cow than farmers that mix colostrum. This can be explained by the fact that farmers who pool colostrum from more than one animal generally have larger herds and more intensive farms. Our econometric analysis in the following will reveal whether any economic effects can be attributed to the biosecurity practices.

Table 3. Gross margin per cow (GM/cow) of the economic analysis of adoption of biosecurity practices

	GM/cow		
	1 or 0	2 or 3	3 or more
Vaccination	1,080.28 (379.89)	1,180.52 (306.33)	1,269.09 (238.54)
Testing milk	1,142.64 (273.69)	1,230.71 (271.22)	
Not pool colostrum	1,234.91 (258.23)	1,133.47 (370.00)	

Source: Authors' calculations from the NFS data.

Results and Discussion

Biosecurity adoption decision

The full (outcome and treatment models) estimation results of vaccination adoption are presented in Table 4, while Table 5 presents the full estimation results of the remaining two biosecurity practices. In terms of the vaccination

Table 4. Outcome and treatment effect results of IPWRA models for vaccination adoption

	Outcome (GM/cow) model		
	(0 or 1)	(2 or 3)	(> 3)
Herd size	0.59 (0.59)	1.91*** (0.60)	0.92** (0.46)
DSR	169.79*** (53.74)	58.45 (67.73)	60.63 (50.45)
Specialization (base: Low)			
Medium	-53.82 (66.19)	108.39 (71.33)	57.83 (66.29)
High	-168.16** (73.83)	62.06 (64.07)	59.84 (50.55)
Feed use	29.31** (11.67)	72.62*** (18.01)	-1.23 (13.43)
SCC	-1.22*** (0.38)	-0.38 (0.32)	-0.84* (0.47)
Region (base: Northwest)			
East midlands	-81.38 (113.50)	-21.85 (97.89)	182.71** (89.44)
South	-34.23 (66.42)	-1.58 (63.68)	182.60** (72.96)
	Treatment (vaccination adoption) model ^a		
Herd size		0.02*** (0.01)	0.03*** (0.01)
DSR		-0.70* (0.40)	-0.23 (0.45)
Feed use		-0.19*** (0.06)	-0.16** (0.07)
SCC		-0.003 (0.00)	-0.01*** (0.00)
Debt to asset ratio		-0.07** (0.03)	-0.04* (0.02)
Specialization (base: Low)			
Medium		1.03** (0.44)	0.83* (0.46)
High		0.56 (0.41)	0.34 (0.44)
Age		0.02 (0.02)	0.01 (0.02)
Household		-0.02 (0.13)	-0.06 (0.13)
Region (base: Northwest)			
East midlands		-0.53 (0.58)	0.42 (0.71)
South		0.24 (0.47)	1.61*** (0.54)
Observations (n=263)			

Notes: Estimates based on a doubly robust treatment effect using IPWRA estimator.

^aBase category is model 1 (0 or 1).

Robust standard error in parenthesis; Significance level: *** $P < 0.01$, ** $P < 0.05$, * $P < 0.10$

adoption decision (treatment model), the results from the first-stage multinomial logit (MNL) regression analysis given in Table 4 showed that larger herd sizes, better management ability, extent of dairy specialization and debt to equity ratio are related to the use of vaccination as a biosecurity measure (and more so, vaccination against more diseases). Our results indicate that risk attitude is related to vaccination, in the sense that more risk-prone farmers are less likely to adopt this biosecurity measure. The results of the outcome model indicate that higher stocking density (0 or 1 vaccination) or larger herd size (2+ vaccinations) are significantly associated with GM/cow. In addition, better managerial ability, either represented by SCC or feed efficiency, is significantly related to higher GM/cow.

Table 5 presents the full (outcome and treatment models) estimation results of adoption of bulk tank milk testing and not pooling colostrum. In relation to the adoption decisions, results from the first-stage logit model show that farmers with larger herd sizes are more likely to test bulk tank milk for diseases, while the opposite is true for not pooling colostrum. Probably not surprisingly, increasing SCC is positively associated with the probability to test bulk tank milk for diseases. The results of the outcome models show that herd size and

managerial ability (represented by feed-use and SCC) are significantly associated with GM/cow.

Treatment effect estimation of biosecurity measures

As mentioned, the presented empirical results are estimates from a “doubly-robust” method estimated via an IPWRA estimator of the association between adoption of biosecurity practice and farm economic performance. As our data are cross-sectional, it is worth noting that our results indicate an association between biosecurity practices and farm economic performance rather than a causal inference. Table 6 reports the results from the “vaccination” model. In this model, we estimated the economic association of vaccinating against one disease or not at all, using two or three vaccinations, and vaccinating against more than three diseases after controlling for regional characteristics, farm management ability, farmer’s attitude to risk, and farmer characteristics. Our empirical findings indicate that using two or more vaccinations is associated with economic gain in dairy farming with higher gains associated with the number of vaccinations. Specifically, using two or three vaccinations is associated with an economic gain of €67 GM/cow while using more than three vaccinations

Table 5. Outcome and treatment effect results of IPWRA models for adoption of bulk tank milk testing and not pooling colostrum

	Test bulk tank milk		Not pooling colostrum	
	Outcome (GM/cow) model		Outcome (GM/cow) model	
	Nonadopters	Adopters	Nonadopters	Adopters
Herd size	-0.76(0.89)	1.10*** (0.32)	1.54*** (0.56)	1.91*** (0.67)
DSR	78.49(102.76)	45.03(39.99)	56.36(51.76)	53.61(45.74)
Specialization (base: Low)				
Medium	-86.17(101.03)	46.29(41.78)	99.59(69.01)	77.42(57.47)
High	-15.34(79.78)	41.41(47.61)	11.55 (50.82)	1.77(62.05)
Feed use	6.29(8.14)	31.05*** (11.12)	22.43* (11.93)	16.96(11.68)
SCC	-1.62*** (0.47)	-1.31*** (0.27)	-0.51(0.38)	-1.42*** (0.36)
Region (base: Northwest)				
East midlands	37.65(122.17)	111.72(72.66)	181.09** (91.39)	-13.81(94.31)
South	9.03(105.62)	113.00** (58.56)	170.84*** (64.28)	-4.37(66.74)
		Treatment model ^a		Treatment model ^a
Herd size		0.02*** (0.00)		-0.01*** (0.00)
DSR		-0.21 (0.31)		-0.15(0.30)
Feed use		0.01(0.06)		-0.04(0.06)
SCC		0.004*(0.00)		-0.001(0.002)
Debt to asset ratio		0.01(0.02)		0.02(0.02)
Specialization (base: Low)				
Medium		0.11(0.37)		-0.24(0.34)
High		-0.01(0.36)		-0.14(0.33)
Age		0.03*(0.02)		-0.05*** (0.01)
Household		-0.14(0.10)		-0.05(0.10)
Region (base: Northwest)				
East midlands		1.68*** (0.61)		0.57(0.51)
South		1.52*** (0.44)		0.63(0.41)
Observations		260		254

Notes: Estimates based on a doubly robust treatment effect using IPWRA estimator. Robust standard error in parenthesis; Significance level: *** $P < 0.01$, ** $P < 0.05$, * $P < 0.10$.
^aBase category is model 1 (nonadopters).

Table 6. Economic association (doubly robust estimates) of vaccination, testing milk and not pooling colostrum and farm economic performance (GM/cow)

	POM (0 or 1)	ATT 2 or 3	ATT More than 3
Vaccination (€/cow)	1,113.29*** (30.85)	67.23*(40.03)	78.11**(40.21)
Testing bulk tank milk (€/cow)	POM 1,128.23*** (45.62)	ATT 102.56** (50.25)	
No pooling colostrum (€/cow)	1,197.88*** (28.99)	-44.88(35.77)	

Notes: Estimates based on a doubly robust treatment effect using IPWRA estimator.

Robust standard error in parenthesis; Significance level: *** $P < 0.01$, ** $P < 0.05$, * $P < 0.10$.

Average treatment effect on the treated is reported; POM = potential outcome mean.

is associated with an economic gain of €78 GM/cow when compared to using one or not vaccinating at all. Note that we grouped vaccinating against one or not vaccinating at all in a group. Treating no vaccinations as a separate group did not provide a sufficient sample size to conduct an empirical analysis. Thus, the higher the number of diseases farmers vaccinated against, the higher the economic gains associated with such vaccination measure.

Table 6 also reports the results from testing milk against diseases and not pooling colostrum. The findings indicate that testing milk against diseases is associated with an economic gain of €103 GM/cow, which is significant at the 5% level. The importance of bulk tank milk screening has been documented in past studies (see Jayaro et al., 2003; Kelly et al., 2009; McCarthy et al., 2021b). This provides further empirical evidence of the likely economic importance of adopting on-farm disease prevention measures.

Our empirical findings in Table 6 also showed that not pooling colostrum from more than one animal is not significantly associated with GM per cow, when we control for farm and farmer characteristics as well as unobserved characteristics. In addition, the potential outcome means (POM) is positive and significant suggesting that farmers who do not pool colostrum may not be necessarily worse off economically (i.e., in terms of GM per cow) relative to farmers who pool colostrum from more than one animal. This finding is important for policy, as farmers often believe that not pooling colostrum leads to reduced profit.

Robustness checks

We conducted further analyses to check the robustness of our results. Considering that the results from the IPWRA method may be sensitive to the distributional assumptions imposed on the model, we use TEs propensity score matching (PSM) and the generalized propensity score (GPS) technique—a continuous treatment matching method (Hirano and Imbens, 2004). These methods do not impose any distributional assumptions to ascertain the robustness of our findings. We apply PSM to the binary treatment variables (i.e., farmers who test bulk tank milk for disease and farmers who do not pool colostrum) and the GPS to the variable with more than two levels (i.e., vaccination). The PSM (or the generalized form) involves matching adopters and nonadopters of biosecurity practices that are similar in terms of observable variables. The matching

variables used are the same as the explanatory/control variables used in the IPWRA method. Supplementary Figure A2 shows the dose–response function (DRF) of the GPS showing increasing expected potential outcomes as the number of diseases vaccinated against increases which confirms the positive and significant effect of the ATT in our main results. A test of the balancing property of the covariates showed that the balancing property is satisfied at level 0.05. Supplementary Figure A3 shows that there is substantial overlap in the distribution of the propensity scores of biosecurity adopters and nonadopters, suggesting a satisfaction of the common support condition necessary to validate the model. Comparing the variance ratio between the raw data and matched data showed that the two groups are effectively matched based on the variables used. After confirming that our matching methods passed the matching quality, we then estimate the ATTs and results are presented in Supplementary Table A4.

The results revealed higher ATTs (€128 GM per cow) for farmers who test bulk tank milk for diseases, and this is statistically significant at the 1% level. The slightly higher estimates from the PSM relative to the IPWRA may be due to the assumptions defining the structural model when using the PSM technique which may have introduced bias when using the technique. Results also show that not pooling colostrum from more than one animal has a negative sign but this is not statistically significant. This is similar to the estimates from the IPWRA.

Conclusion

Our study revealed that vaccination and testing bulk tank milk for diseases is associated with economic benefits resulting in higher GMs per cow, while our findings do not provide evidence of any economic benefits associated with not pooling colostrum. But, importantly, not pooling colostrum from more than one animal as a biosecurity practice is not negatively associated with economic outcomes of farms. These findings are important from a policy perspective to support increased adoption of biosecurity practices among dairy farmers globally.

Supplementary Data

Supplementary data are available at *Journal of Animal Science* online.

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Conflict of Interest Statement

The authors declare no real or perceived conflicts of interest.

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