Effect of exposure to *Neospora caninum*, *Salmonella*, and *Leptospira interrogans* serovar Hardjo on the economic performance of Irish dairy herds

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ABSTRACT

The objective of the current study was to quantify the effects of exposure to *Salmonella*, *Neospora caninum*, and *Leptospira interrogans* serovar Hardjo (*L. hardjo*) on dairy farm profitability and to simulate the effect of vaccination for *Salmonella* and *L. hardjo* on dairy farm profitability. The production effects associated with exposure to each of these pathogens in study herds were defined under 3 categories: (1) milk production effects, (2) reproduction effects (including culling), and (3) mortality effects. The production effects associated with exposure to *Salmonella*, *N. caninum*, and *L. hardjo* were incorporated into the Moorepark Dairy Systems Model. In the analysis, herds negative for exposure to *Salmonella*, *N. caninum*, and *L. hardjo* were assumed baseline herds, with all results presented relative to this base. In simulations examining the effect of vaccination for *Salmonella* and *L. hardjo* on farm profitability, vaccinated herds (vaccination costs included) were considered as baseline herds and results were presented relative to this base. Total annual profits in unvaccinated herds were reduced by €77.31, €94.71, and €112.11 per cow at milk prices of €0.24, €0.29, and €0.34/L, respectively, as a result of exposure to *Salmonella*. In the current study, herds positive for exposure to *Salmonella* recorded a 316-kg reduction in milk yield, whereas no association was detected between exposure to *N. caninum* or *L. hardjo* and milk production. Exposure to both *N. caninum* and *L. hardjo* was associated with compromised reproductive performance. Herds positive for exposure to *N. caninum* and *Salmonella* had greater rates of adult cow mortality and calf mortality, respectively. Vaccination for both *Salmonella* and *L. hardjo* was associated with improved performance in study herds. Exposure to *N. caninum* resulted in a reduction in annual farm profits of €11.55, €12, and €12.44 per cow at each milk price, whereas exposure to *L. hardjo* resulted in a reduction in annual farm profits of €13.83,

€13.78, and €13.72 per cow at each milk price. Herds that tested positive for exposure to *Salmonella* and *L. hardjo* were compared with herds vaccinated for the respective pathogens. Herds vaccinated for *Salmonella* generated €67.09, €84.48, and €101.89 per cow more profit at each milk price compared with herds positive for exposure. Similarly, herds vaccinated for *L. hardjo* generated €9.74, €9.69, and €9.63 per cow more profit compared with unvaccinated exposed herds. However, herds that tested negative for exposure to *Salmonella* and *L. hardjo* generated additional profits of €10.22 and €4.09 per cow, respectively, compared with vaccinated baseline herds.

Key words: *Salmonella*, *Neospora caninum*, *Leptospira interrogans* serovar Hardjo (*L. hardjo*), dairy farm profitability

INTRODUCTION

Salmonella enterica ssp. *enterica* serovar Dublin and *Salmonella enterica* ssp. *enterica* serovar Typhimurium are the 2 most frequently isolated serovars of *Salmonella* in cattle (Wray and Sojka, 1977). *Salmonella* Dublin is host adapted to cattle (Wray and Sojka, 1977). Fecal-oral spread is the most common method of *Salmonella* transmission (Poppe, 2011; Nielsen, 2013). Abortion in the absence of any other clinical signs is associated with infection with *Salmonella* Dublin (Wray and Sojka, 1977; Poppe, 2011). Previous studies have identified a seasonal pattern in the rate of *Salmonella*-induced abortions with the incidence of abortions peaking in autumn (Wray and Sojka, 1977). Infection with *Salmonella* has also been associated a reduction in milk yield in dairy cows (Bazeley, 2006; Nielsen et al., 2012). An increased rate of calf mortality has also been associated with the presence of *Salmonella* on farms (Taylor et al., 2001; Nielsen et al., 2007).

Neospora caninum is a cyst-forming protozoan parasite, first described in 1988 (Dubey et al., 1988). Dogs and related canids are definitive hosts of *N. caninum* (McAllister et al., 1998; Lindsay et al., 1999), and cattle have been confirmed as intermediate hosts of *N. caninum*. Vertical transmission is the most efficient

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route of *N. caninum* transmission (Dubey et al., 2007). *Neospora caninum* has a worldwide distribution and numerous studies have identified the pathogen as a major cause of bovine abortion (Anderson et al., 2000). Abortion is the primary clinical sign of *N. caninum* in cattle (Goodswen et al., 2013); abortions induced by *N. caninum* can occur at any time of year but are most common in mo 5 to 8 of pregnancy (Anderson et al., 2000). Clinical manifestations in calves including stillbirth, perinatal mortality, the birth of weak calves, and the birth of calves with neurological disorders have also associated with *N. caninum* infection (McAllister 2007; Brickell et al., 2010). A study by Bartels et al. (2006) identified decreases in milk production and an increased culling risk associated with infection with *N. caninum*. A Canadian study documented an increased rate of services per conception in animals that were seropositive to *N. caninum* (Muñoz-Zanzi et al., 2004).

Cattle are maintenance hosts for leptospires belonging to serovar Hardjo (Leonard et al., 2004; Grooms, 2006). Two types of serovar Hardjo have been identified: *Leptospira interrogans* serovar Hardjo (type Hardjoprajitno; *L. hardjo*) and *L. borgpetersenii* serovar Hardjo (type Hardjo-bovis; Leonard et al., 2004; Grooms, 2006). Urinary shedding is the most efficient method of transmission of *L. hardjo* between cattle (Bearden, 2011), with susceptible cattle becoming infected through ingestion or inhalation of leptospires from the contaminated environment. Leptospires may also persist in the genital tract of cattle, leading to reproductive failure (Grooms, 2006). *Leptospira* organisms have been found in the semen of bulls and can be transferred to cows during natural service (Bearden, 2011). The clinical manifestations of infections due to leptospirosis in cattle include "milk drop syndrome" and abortion. Milk drop syndrome is characterized by a sudden decrease (drop) or cessation in milk production, with the milk appearing thick, blood tinged, yellow in color, and almost colostrum-like (Ellis et al., 1976; Higgins et al., 1980). Abortion due to *L. hardjo* can occur several weeks after the initial infection and abortion is often the only clinical manifestation of infection with *L. hardjo* (Radostits, 2000). Abortions associated with *L. hardjo* can occur at any time of the year but are most common in the third trimester of pregnancy (Radostits, 2000). Infection due to leptospirosis can also result in stillbirths and the birth of weak calves (Bearden, 2011). Previous international studies have identified compromised reproductive performance associated with *L. hardjo* infections on farms (Dhaliwal et al., 1996a,b; Guitian et al., 1999).

Numerous studies worldwide have investigated the economic effects at the farm level of *Salmonella*, *N. caninum*, and *L. hardjo*. An investigation of the direct losses

associated with infection in *N. caninum* in Canadian dairy herds documented an annual loss of Can\$2,305 (€1,566) per farm for a 50-cow dairy herd (Chi et al., 2002), which equates to a loss of €31 per cow. Similarly, Pfeiffer et al. (1997) estimated that the annual loss in a 200-cow New Zealand dairy herd due to infection with *N. caninum* was NZ\$3,900 (€2,385) per herd or €12 per cow. In a simulation study, the economic loss associated with *N. caninum* in Dutch dairy herds was quantified as €2,053 per herd (€32/cow) in the first year following an abortion epidemic (Bartels et al., 2006).

With regard to *Salmonella*, an outbreak in a 100-cow dairy herd in the United Kingdom was associated with a 19,430-L reduction in total herd milk output, resulting in a financial loss of £3,600 or €36 per cow (Bazeley, 2006). A Danish study examining infection with *Salmonella* Dublin estimated gross margin losses of €49 per cow in the year following infection and an average gross margin loss of €8 per cow in the 10 yr following infection in herds with very good management (Nielsen et al., 2013). However, in herds with very poor management, gross margin losses due to infection with *Salmonella* Dublin were estimated at €326 per cow in the year following infection and were on average €188 per cow in the 10 yr following infection (Nielsen et al., 2013). In another Dutch study, Visser et al. (1997) documented an average of Dfl. (Dutch florins) 55 (€23) per cow due to infection with *Salmonella* Dublin in 40 Dutch dairy herds. Although fewer studies are available on *L. hardjo*, one study by Bennett (1993) estimated an annual loss of £6,000 (€7,000) due to leptospirosis infection in a 100-cow dairy herd in the United Kingdom, which equates to a loss of €70 per cow.

It is evident from the studies presented here that infection with *Salmonella*, *N. caninum*, and *L. hardjo* can cause significant economic losses on dairy farms. However, limited information is available on the economic effect of these pathogens in Irish dairy herds. Irish dairying is based on an extensive, pasture-based system of livestock production, operating at a stocking rate of, on average, 1.9 livestock units (LU) per hectare (Dillon, 2011). Such systems involve calving cows to coincide with the period of maximum grass growth; that is, spring (Dillon et al., 1995), with cows being fed grazed grass outdoors for up to 235 d of lactation (Drennan et al., 2005). However, limited information exists on the economic effect of these pathogens in such pasture-based dairy production systems Irish dairy herds. The results of this study can therefore be compared with studies in countries where confinement systems of dairy production predominate.

The abolition of the European Union milk production quotas in 2015 presents an opportunity for Irish dairy farmers to increase milk production for the first time in

a generation (Shalloo et al., 2012; Quinlan, 2013). This potential can only be realized if the losses associated with infectious diseases, including but not exclusively those caused by *Salmonella*, *N. caninum*, and *L. hardjo*, are minimized, ensuring the productivity and sustainability of the Irish dairy industry. Heretofore, the costs associated with exposure to *Salmonella*, *N. caninum*, and *L. hardjo* in Irish dairy herds and the effect of exposure to these pathogens on the profitability of Irish dairy herds have not been quantified. The objective of this study was to quantify the costs associated with exposure to *Salmonella*, *N. caninum*, and *L. hardjo* in unvaccinated Irish dairy herds. In addition, we quantified the effect of vaccination for *Salmonella* and *L. hardjo* on farm profitability compared with herds that tested positive and negative for exposure to *Salmonella*, *N. caninum*, and *L. hardjo*.

MATERIALS AND METHODS

Herd-Level Antibody Status Classification

Classification of herd-level exposure status to *Salmonella*, *N. caninum*, and *L. hardjo* has been described in detail in O' Doherty et al. (2013), which investigated temporal trends in bulk milk antibody levels of these pathogens in Irish dairy herds. Briefly, bulk milk samples were collected from 312 study herds at 4 time points in 2009 (March, June, August, and November) and were tested for antibodies against *Salmonella*, *N. caninum*, and *L. hardjo* using commercially available ELISA kits. Information on the vaccination protocols for *Salmonella* and *L. hardjo* were collected using farmer-declared survey data. The ELISA test results and vaccination status of each herd were combined to determine the antibody status (test negative vs. test positive) of study herds. Herds were classified as vaccinated or unvaccinated for *Salmonella* and *L. hardjo* based on the survey information. No vaccine for *N. caninum* is licensed for use in Ireland. Unvaccinated herds were classified as negative for exposure to each respective pathogen if the herd recorded a negative bulk milk antibody reading at all of the 4 sampling time points in 2009 (O' Doherty et al., 2013); that is, if a herd recorded at least one positive bulk milk reading in 2009, it was classified as positive for exposure to the respective pathogen.

Production Effects

The production losses associated with exposure to *Salmonella*, *N. caninum*, and *L. hardjo* have been documented by O' Doherty (2014). These production losses were defined under 3 categories: (1) milk production

losses, (2) reproductive performance (including culling) losses, and (3) mortality losses.

Milk Production Losses

Linear fixed-effect models in PROC GLM of SAS (version 9.1, SAS Institute Inc., Cary, NC) were used to quantify the associations between both bulk milk antibody status of *Salmonella*, *N. caninum*, and *L. hardjo* and vaccination status for *Salmonella* and *L. hardjo* with herd level milk yield, fat yield, protein yield, and SCS (geometric mean SCC). Production parameters were included in the model as dependent variables and disease or vaccination status as independent variables. Fixed effects included herd size, average parity, proportion of Holstein-Friesian animals, average economic breeding index value, and median calving date in 2009. Unvaccinated herds positive for exposure to *Salmonella* produced 316 kg less milk compared with unvaccinated negative herds. No association was detected between exposure to *N. caninum* or *L. hardjo* and milk production. Herds vaccinated for *Salmonella* and *L. hardjo* had SCC that were 20×10^3 and 28×10^3 cells/mL lower, respectively, compared with SCC in unvaccinated herds.

Reproductive Performance Losses

Linear fixed-effect models were used to determine the association between disease and vaccination status for *Salmonella*, *N. caninum*, and *L. hardjo* with reproductive performance variables, including herd-level 42-d calving rate (i.e., the number of primiparous and multiparous cows that calved in the first 6 wk of the calving season as a proportion of the total number of primiparous and multiparous cows that calved throughout the entire calving season), calving spread, calving interval (i.e., the average number of days between successive calvings for cows that calved in both 2009 and 2010), percentage of calves per cow per year (i.e., the number of calves that were alive at 28 d that were born to cows in the herd on June 30), replacement rate (i.e., the number of first-calving cows in the herd as a proportion of all cows in the herd), culling rate (i.e., the number of cows sold, sent to abattoir or died as a proportion of all cows in the herd on June 30), percentage of cows not in calf (i.e., the number of cows in the herd that did not have a calf in 2009 or 2010 as a proportion of all cows in the herd), and the percentage of carryover cows in study herds (i.e., the number of cows that calved during the previous calving season but did not calve during the subsequent calving season and were not culled, as a proportion of all cows in the herd). Fixed effects in the models included average economic breeding index val-

ue, proportion of Holstein-Friesian animals, herd size, and average parity. Models that included the variable calves per cows per year as a dependent variable were also controlled for the variable herd-level replacement rate. Herds positive for exposure to *N. caninum* had a 6-d-longer calving interval, a 10-d increase in calving spread in primiparous cows, and produced 4% fewer calves per cow per year compared with negative herds. Unvaccinated herds positive for exposure to *Salmonella* produced 3% fewer calves per cow per year compared with unvaccinated negative herds. Unvaccinated herds positive for exposure to *L. hardjo* had a 12% lower 42-d calving rate and a 8% higher rate of carryover cows and produced 9% fewer calves per cow per year compared with unvaccinated negative herds. Herds vaccinated for *L. hardjo* had a 5% higher 42-d calving rate and a 3% lower rate of empty cows, and produced 3% more calves per cow per year compared with unvaccinated herds.

Mortality Rates

Linear fixed-effect models were also used to quantify the association between antibody and vaccination status (as independent variables) for *Salmonella*, *N. caninum*, and *L. hardjo* with neonatal mortality, young-calf mortality, and adult cow mortality (dependent variables). Models were adjusted for herd size in 2009, and models with adult cow mortality as dependent variables were adjusted for parity in 2009. Herds positive for exposure to *N. caninum* had an 8% greater rate of adult cow mortality compared with negative herds. Unvaccinated herds positive for exposure to *Salmonella* had a 1.5% greater rate of calf mortality compared with unvaccinated negative herds, whereas herds vaccinated for *Salmonella* had a 1.14% greater rate of calf mortality compared with unvaccinated herds.

Economic Analysis

Production data (Tables 1, 2, and 3) were incorporated into the Moorepark Dairy Systems Model (MDSM; Shalloo et al., 2004) to simulate the effect of exposure to each pathogen on farm net profitability. In addition, the economic impact of vaccination for *Salmonella* and *L. hardjo* was simulated using the MDSM. The MDSM is a stochastic budgetary simulation model of a dairy farm. The MDSM integrates animal inventory and valuation, milk production, feed requirement, land and labor utilization, and economic analysis. The MDSM allows investigation of the effects of varying biological, technical, and physical processes on farm profitability. Variable costs (fertilizer, contractor charges, medical and veterinarian, AI, silage, and reseedling), fixed costs (machinery maintenance and running costs, farm

maintenance, car, telephone, electricity, and insurance) and all farm receipts (milk, cull cow, and calf) were based on current costs and prices (Table 4; Teagasc, 2013). Land area assumed in the model was 40 ha, with cow numbers fixed at 100 cows. Concentrate usage was fixed at 390 kg of DM/cow. Full labor costs were included in the model, with 1 labor unit costing €22,855. The MDSM assumed that all male calves were sold and replacements were reared off-farm from birth. The model uses the net energy system (Jarrige, 1989) to calculate feed requirements for milk production, maintenance, pregnancy, and BW change. The profitability effects associated with exposure to the 3 pathogens were calculated across 3 base milk prices of €0.24, €0.29, and €0.34/L, assuming a reference milk content of 36.0 g of fat/kg and 33.0 g of protein/kg (i.e., the reference used by the majority of Irish dairy manufacturers; Geary et al., 2012). Calf and cull cow values were based on average prices, with cull cows valued at €400 and male calves valued at €100 at 1 mo of age. Vaccination costs were included for *Salmonella* and *L. hardjo* in the model at €7.25 and €3.50 per dose, respectively, for the herds that stated that they used vaccines. We assumed that vaccines were administered in accordance with manufacturer guidelines in the model. Annual tuberculosis and brucellosis costs and routine animal treatment costs were included in the model. Artificial insemination costs were estimated using 1.7 inseminations per conception, costing €25.40 and a service charge of €11.43. The key default parameters included in the model are shown in Table 4. Outputs from the MDSM include physical outputs such as feed budget, nutrient balance sheet, and financial indicators (e.g., operating cash flow, profit and loss account, and balance sheet). Incorporating the biological data associated with exposure to *Salmonella*, *N. caninum*, and *L. hardjo* had an effect on milk receipts, feed demand, labor, and livestock movement components within the model for both vaccinated and unvaccinated herds.

Scenarios

Two scenarios were investigated to allow examination of the effect of exposure to *Salmonella*, *N. caninum*, and *L. hardjo* in unvaccinated herds and to allow examination of the effect of vaccination for *Salmonella* and *L. hardjo* compared with herds that tested both positive and negative for exposure to these pathogens.

- Scenario 1 included unvaccinated herds only. Herds negative for exposure to each pathogen (*Salmonella*, *N. caninum*, and *L. hardjo*) were assumed as baseline herds, and the results generated

Table 1. Milk production losses associated with exposure to *Neospora caninum*, *Salmonella*, and *Leptospira interrogans* serovar Hardjo (*L. hardjo*) in study herds

Pathogen	Difference in LSM	P-value	Source
<i>N. caninum</i> (negative vs. positive herds)			O' Doherty (2014)
No associations identified	—	—	
<i>Salmonella</i>			O' Doherty (2014)
Negative vs. positive herds (unvaccinated herds only)			
Milk yield, kg	316	0.006	
Fat yield, kg	14	0.003	
Protein yield, kg	12	0.003	
Unvaccinated vs. vaccinated herds			
SCC, $\times 10^3$ cells/mL	20	0.04	
<i>L. hardjo</i>			O' Doherty (2014)
Negative vs. positive herds (unvaccinated herds only)			
No associations identified	—	—	
Unvaccinated vs. vaccinated herds			
SCC, $\times 10^3$ cells/mL	28	0.01	

Table 2. Reproductive performance losses associated with exposure to *Neospora caninum*, *Salmonella*, and *Leptospira interrogans* serovar Hardjo (*L. hardjo*) in study herds

Pathogen	Difference in LSM	P-value	Source
<i>N. caninum</i> (negative vs. positive herds)			O' Doherty (2014)
Primiparous calving spread, d	−10	0.04	
Calving interval in 2010, d	−6	0.004	
Calves/cow in 2010	0.04	0.03	
<i>Salmonella</i>			O' Doherty (2014)
Negative vs. positive herds (unvaccinated herds only)			
Calves/cow in 2009	0.03	0.04	
Unvaccinated vs. vaccinated herds			
No associations identified	—	—	
<i>L. hardjo</i>			O' Doherty (2014)
Negative vs. positive herds (unvaccinated herds only)			
Multiparous 42-d calving rate in 2009, %	14	0.02	
Rate of carryover cows in 2009, %	−9	0.03	
Calves/cow in 2009	0.08	0.03	
Multiparous 42-d calving rate in 2010, %	10	0.02	
Multiparous calving spread, d	10	0.02	
Unvaccinated vs. vaccinated herds			
Primiparous 42-d calving rate in 2009, %	−6	0.04	
Calves/cow in 2010	−0.03	0.05	
Multiparous 42-d calving rate in 2010, %	−4	0.05	
Rate of cows not calved in 2010, %	3	0.005	

Table 3. Mortality losses associated with exposure to *Neospora caninum*, *Salmonella*, and *Leptospira interrogans* serovar Hardjo (*L. hardjo*) in study herds

Pathogen	Difference in LSM	P-value	Source
<i>N. caninum</i> (negative vs. positive herds)			O' Doherty (2014)
Adult cow mortality in 2009, %	−8	0.05	
<i>Salmonella</i>			O' Doherty (2014)
Negative vs. positive herds (unvaccinated herds only)			
Young-calf mortality in 2009, % of calves born	−1.5	0.01	
Unvaccinated vs. vaccinated herds			
Neonatal mortality in 2009, % calves born	−1.14	0.007	
<i>L. hardjo</i>			O' Doherty (2014)
Negative vs. positive herds (unvaccinated herds only)			
No associations identified	—	—	
Unvaccinated vs. vaccinated herds			
No associations identified	—	—	

Table 4. Default herd parameters in the Moorepark Dairy Systems Model

Parameter	Value
Farm size, ha	40
Concentrate cost, €/t	270
Fertilizer cost, €/t	
Calcium ammonium nitrate	300
Urea	380
Replacement rate, %	19
Replacement heifer cost, €	1,540
Cull cow value, €/head	400
Male calf value €/head	100

by unvaccinated test-positive herds were presented relative to this base.

- Scenario 2. *Salmonella* and *L. hardjo* vaccinated herds were compared with unvaccinated positive herds and negative herds. Vaccinated herds were assumed as baseline herds, and the results generated by both unvaccinated test-positive herds and unvaccinated test-negative herds were presented relative to this base. This scenario aimed to assess whether vaccinated herds delivered a greater economic performance compared with an unvaccinated herd that was either positive or negative.

Profitability was estimated for the farm as a whole, on a per cow basis, and per kilogram of milk produced.

RESULTS

N. caninum

Herds positive for exposure to *N. caninum* produced 27 kg (0.5%) less milk per cow per year compared with the (negative-herd) baseline (Table 5). The volume

of milk sold was 2,474 kg (0.5%) lower in *N. caninum* test-positive herds compared with the baseline herd. Replacement costs were €558 greater in *N. caninum* test-positive herds compared with the baseline. Herds positive for exposure to *N. caninum* generated total costs that were €932 greater compared with the baseline (Table 6). Herds positive for exposure to *N. caninum* generated milk receipts that were equal in value to the negative baseline (Table 6). Total profits per farm were €1,155, €1,200, and €1,244 lower compared with the baseline in herds positive for exposure to *N. caninum* based on milk prices of €0.24, €0.29, and €0.34/L, respectively (Table 6). At a milk price of €0.29/L, farm profits in herds positive for exposure to *N. caninum* were reduced by €12 per cow and €0.002 per kg compared with the negative baseline.

Salmonella

Scenario 1. Unvaccinated *Salmonella* positive herds had a 316 kg (6%) lower 305-d milk yield per cow compared with the baseline (unvaccinated negative herds; Table 5). Consequently, these positive herds generated a 31,411 kg (6%) lower volume of milk sales and 2,369 kg (6%) less milk solid sales. Total costs generated by unvaccinated herds that tested positive for exposure to *Salmonella* were €633 lower compared with the negative baseline (Table 7). Unvaccinated herds that tested positive for exposure to *Salmonella* generated milk receipts that were €8,423, €10,152, and €11,800 lower at milk prices of €0.24, €0.29, and €0.34/L compared with the negative baseline (Table 7). In unvaccinated herds positive for exposure to *Salmonella*, total profits per farm were reduced by €7,731, €9,471, and €11,211 compared with the negative baseline based on milk

Table 5. Effect of exposure to *Neospora caninum*, *Salmonella*, and *Leptospira interrogans* serovar Hardjo (*L. hardjo*) and vaccination status for *Salmonella* and *L. hardjo* on the physical outputs of a simulated 100-cow dairy herd

Physical output	Exposure and vaccination status					
	Negative and vaccinated (baseline)	<i>N. caninum</i> positive ¹	Unvaccinated <i>Salmonella</i> positive	Unvaccinated <i>L. hardjo</i> positive	<i>Salmonella</i> unvaccinated ²	<i>L. hardjo</i> unvaccinated ²
Land area, ha	40.5	40.6	39.22	40.8	40.5	40.7
Cows calving, no	100	100	100	100	100	100
Stocking rate, LU ³ /ha	2.37	2.36	2.45	2.35	2.37	2.36
Milk yield, kg/cow	5,108	5,081	4,792	5,077	5,108	5,091
Milk delivered, kg	499,358	496,884	467,947	496,815	499,430	497,926
Milk solids, kg	37,646	37,632	35,277	37,742	37,652	37,712
Grass, kg of DM/cow	3,661	3,627	3,517	3,595	3,661	3,626
Grass silage, kg of DM/cow	1,131	1,181	1,123	1,223	1,131	1,181
Concentrate, kg of DM/cow	398	398	398	398	398	398

¹Bulk milk antibody positive.

²Comprises both negative and positive herds.

³Livestock units.

Table 6. Economic effect of exposure to *Neospora caninum* in a simulated 100-cow dairy herd at 3 potential milk prices (€0.24, €0.29, and €0.34 per liter)

Financial output	Exposure status to <i>N. caninum</i>	
	Negative (baseline)	Positive ¹
Costs, €		
Labor	29,193	29,102
Replacements	29,245	29,803
Total	155,425	156,357
Milk receipts, €		
at €0.24/L	133,941	133,872
at €0.29/L	161,425	161,317
at €0.34/L	188,908	188,762
Profit		
Profit/cow, €		
at €0.24/L	58	46
at €0.29/L	334	322
at €0.34/L	611	599
Profit/kg of milk, €c		
at €0.24/L	1.13	0.91
at €0.29/L	6.55	6.35
at €0.34/L	11.96	11.78
Total profit/farm, €		
at €0.24/L	5,784	4,629
at €0.29/L	33,445	32,245
at €0.34/L	61,105	59,861

¹Bulk milk antibody positive.

prices of €0.24, €0.29, and €0.34/L, respectively (Table 7). At a milk price of €0.29/L, farm profits per cow and per kilogram of milk were reduced by €94.71 and €0.016, respectively, in herds positive for exposure to *Salmonella* compared with the negative baseline.

Scenario 2. Relative to vaccinated herds, unvaccinated herds that tested positive for exposure to *Salmonella* had a 316-kg (6%) lower 305-d milk yield per cow (Table 5). Consequently, unvaccinated *Salmonella* test-positive herds generated milk sales that were 31,411 kg lower and milk solids that were 2,369 kg lower compared with the vaccinated baseline. We detected no difference in physical outputs between unvaccinated herds negative for exposure to *Salmonella* and vaccinated herds (Table 5). Total costs generated by unvaccinated herds that tested positive for exposure to *Salmonella* were €2,099 lower than that of the vaccinated baseline (Table 7). Unvaccinated herds negative for exposure to *Salmonella* generated total costs that were €1,376 lower compared with the vaccinated baseline (Table 7). Milk receipts in unvaccinated *Salmonella* positive herds were €8,423, €10,152, and €11,800 lower compared with the vaccinated baseline based on milk prices of €0.24, €0.29, and €0.34/L (Table 7). Herds negative for exposure to *Salmonella* generated milk receipts that were equal in value to those of vaccinated baseline herds (Table 7). Unvaccinated herds that tested positive for exposure to *Salmonella* generated total

Table 7. Economic effect of exposure to and vaccination for *Salmonella* in a simulated 100-cow dairy herd at 3 potential milk prices (€0.24, €0.29, and €0.34 per liter)

Financial output	Exposure status to <i>Salmonella</i>			
	Negative (baseline)	Unvaccinated positive ¹	Vaccinated (baseline)	Unvaccinated ²
Costs, €				
Labor	29,193	29,193	29,193	29,193
Replacements	29,245	29,244	29,244	29,244
Total	155,425	154,792	156,801	155,425
Milk receipts, €				
at €0.24/L	133,941	125,518	133,941	133,960
at €0.29/L	161,425	151,273	161,425	161,447
at €0.34/L	188,908	177,028	188,908	188,935
Profit				
Profit/cow, €				
at €0.24/L	58	-19	48	47
at €0.29/L	334	240	324	323
at €0.34/L	611	499	601	600
Profit/kg of milk, €c				
at €0.24/L	1.13	-0.41	0.93	0.91
at €0.29/L	6.55	5.00	6.35	6.33
at €0.34/L	11.96	10.41	11.76	11.75
Total profit/farm, €				
at €0.24/L	5,784	-1,947	4,762	4,663
at €0.29/L	33,445	23,974	32,422	32,328
at €0.34/L	61,105	49,894	60,083	59,992

¹Bulk milk antibody positive.²Comprises both negative and positive herds.

Table 8. Economic effect of exposure to and vaccination for *Leptospira interrogans* serovar Hardjo (*L. hardjo*) in a simulated 100-cow dairy herd at 3 potential milk prices (€0.24, €0.29, and €0.34 per liter)

Financial output	Exposure status to <i>L. hardjo</i>			
	Negative (baseline)	Unvaccinated positive ¹	Vaccinated (baseline)	Unvaccinated ²
Costs, €				
Labor	29,193	29,193	29,193	29,193
Replacements	29,245	29,244	29,244	29,244
Total	155,425	156,209	156,188	156,278
Milk receipts, €				
at €0.24/L	133,941	134,206	133,941	134,160
at €0.29/L	161,425	161,705	161,425	161,664
at €0.34/L	188,908	189,205	188,908	189,168
Profit				
Profit/cow, €				
at €0.24/L	58	44	54	49
at €0.29/L	334	321	330	325
at €0.34/L	611	597	607	602
Profit/kg of milk, €c				
at €0.24/L	1.13	0.87	1.05	0.87
at €0.29/L	6.55	6.32	6.47	6.32
at €0.34/L	11.96	11.77	11.88	11.77
Total profit/farm, €				
at €0.24/L	5,784	4,401	5,375	4,867
at €0.29/L	33,445	32,067	33,036	32,542
at €0.34/L	61,105	59,733	60,696	60,217

¹Bulk milk antibody positive.²Comprises both negative and positive herds.

profits per farm that were €6,709, €8,488, and €10,189 lower than the vaccinated baseline based on milk prices of €0.24, €0.29, and €0.34/L, respectively (Table 7). Compared with vaccinated herds, unvaccinated herds positive for exposure to *Salmonella* generated €84.48 per cow and a €0.014/kg of milk lower profit (Table 7) at a milk price of €0.29/L. Herds negative for exposure to *Salmonella* generated a total profit per farm that was €1,022 greater based on milk prices of €0.24, €0.29, and €0.34/L compared with the vaccinated baseline (Table 7). Profits per cow were €10.22 greater and profits per kilogram of milk were €0.002 higher in herds negative for exposure to *Salmonella* relative to the vaccinated baseline (Table 7).

L. Hardjo

Scenario 1. Unvaccinated herds that tested positive for exposure to *L. hardjo* recorded a 31 kg (0.6%) lower 305-d milk yield per cow compared with the baseline (Table 5). Consequently, the total quantity of milk sold across the herd was 2,543 kg less (0.5%). However, unvaccinated herds that tested positive for exposure to *L. hardjo* generated 96 kg (0.3%) greater volume of milk solids compared with the baseline due to an increase in milk solids concentrations (Table 5). Unvaccinated herds that tested positive for exposure to *L. hardjo* generated total costs that were €784 greater

compared with the negative baseline (Table 8). Unvaccinated herds that tested positive for exposure to *L. hardjo* generated milk receipts that were equal in value to that of the negative baseline (Table 8). Unvaccinated herds positive for exposure to *L. hardjo* generated total profits per farm that were €1,383, €1,378, and €1,372 lower compared with the negative baseline, based on milk prices of €0.24, €0.29, and €0.34/L, respectively (Table 8). At a milk price of €0.29/L, farm profits in herds positive for exposure to *L. hardjo* were reduced by €13.78 per cow compared with the negative baseline. On a profit per kilogram of milk basis, profits in herds positive for exposure to *L. hardjo* were reduced by €0.023/kg relative to negative herds at a milk price of €0.29/L.

Scenario 2. Unvaccinated herds positive for exposure to *L. hardjo* had a 305-d milk yield 31 kg lower than that of the vaccinated baseline (Table 5). We detected no difference in the physical performance of unvaccinated herds that were negative for exposure to *L. hardjo* compared with that of the vaccinated baseline (Table 5). Total costs in unvaccinated herds that tested positive for exposure to *L. hardjo* were equal to those of the vaccinated herds (Table 8). Unvaccinated herds negative for exposure to *L. hardjo* generated total costs that were €763 lower compared with that of the vaccinated baseline (Table 8). Unvaccinated *L. hardjo*-positive herds generated milk receipts that were equal

in value to that of the vaccinated baseline (Table 8). Herds negative for exposure to *L. hardjo* generated milk receipts that were equal to that of the vaccinated baseline (Table 8). Unvaccinated herds that tested positive for exposure to *L. hardjo* generated total profits per farm that were €969 lower at a milk price of €0.29/L compared with the vaccinated baseline (Table 8). Relative to vaccinated herds, unvaccinated herds positive for exposure to *L. hardjo* generated €9.69 less profit per cow and €0.002/kg of milk lower profit at a milk price of €0.29/L (Table 8). Herds negative for exposure to *L. hardjo* generated total profits per farm that were €409 greater at each milk price compared with the vaccinated baseline (Table 8). Profits were €4.09/cow and €0.002/kg greater in herds negative for exposure to *L. hardjo* compared with the vaccinated baseline at a milk price of €0.29/L (Table 8).

DISCUSSION

The objectives of the present study were to simulate the economic implications associated with exposure to *N. caninum*, *Salmonella*, and *L. hardjo* in Irish dairy herds and then to simulate the association between exposure to these pathogens and farm profitability. In addition, the effect of vaccination against *Salmonella* and *L. hardjo* on farm profitability was quantified when compared with both unvaccinated test-positive and test-negative herds. Farm profitability was reduced in unvaccinated herds having evidence of exposure to *Salmonella*, *N. caninum*, and *L. hardjo*. The analysis suggested that vaccination had a positive influence on farm profitability compared with unvaccinated herds that tested positive for exposure to *Salmonella* and *L. hardjo*. However, herds vaccinated for *Salmonella* and *L. hardjo* had lower profits compared with negative herds. The losses reported in the present study most likely reflect the losses associated with endemic infection (i.e., a low incidence over lactation and persistently elevated bulk milk antibody readings over the entire lactation; O' Doherty et al., 2013) and thus provide important information on the long-term adverse effects of exposure to these pathogens on performance in dairy herds. The implementation of suitable control programs is therefore necessary to prevent economic losses from occurring. Herds negative for exposure to *Salmonella*, *N. caninum*, and *L. hardjo* may have implemented biosecurity measures to maintain a negative disease status, which may have incurred a financial cost. However, herds negative for exposure to these pathogens generated greater profits than herds that tested positive for exposure. A cost-benefit analysis is therefore necessary to determine those control measures that deliver the

optimum economic benefit when implemented in positive herds.

N. caninum

Neospora caninum can result in a longer calving interval (Williams et al., 2000; Macaldowie et al., 2004; O' Doherty, 2014). Evans et al. (2006), Shalloo et al. (2014), and Geary et al. (2012) have shown that longer calving intervals are associated with lower 305-d milk yields. Increased calving intervals will result in cows spending more days in late lactation and more days dry, with a subsequent reduction in milk yield (Patton, 2012). The results of the present study support these findings, with *N. caninum*-positive herds recording a milk yield that was 27 kg lower. Additionally, the later mean calving date (because of the longer calving interval) will reduce the amount of grazed grass in the diet (Shalloo et al., 2014). As grass silage is 2.8 times more expensive than grazed grass (Finneran et al., 2010), the increased use of grass silage contributed to the increased total costs associated with exposure to *N. caninum* in the current study. Increased replacement costs due to the 8% increase in adult cow mortality (O' Doherty, 2014) also contributed to higher total costs in exposed herds.

Previous studies have documented annual losses of between €31 and €50 associated with infection with *N. caninum* in Canadian and Dutch dairy herds, respectively (Chi et al., 2002; Bartels et al., 2006). In the present study, total farm profits in herds that tested positive for exposure to *N. caninum* were reduced by €12 per cow. The difference in losses between studies may be, in part, because the costs associated with *N. caninum*-induced abortions were included in the Canadian and Dutch dairy studies, whereas no information was available on the number of abortions in herds in the current study (O' Doherty, 2014). The greater losses reported in the Dutch study may have resulted from the inclusion of herds with a history of abortion due to *N. caninum*, whereas the present study examined losses associated with exposure to *N. caninum*. In addition, the associations documented in the current study are based on actual study herd data (O' Doherty, 2014), whereas some values used by Chi et al. (2002) were based on estimated values. Finally, the Irish system of dairy farming is predominantly pasture-based with spring calving, which is different from the confinement systems in other countries, this also may have resulted in the differences in the figures among international studies. Regardless of study differences, exposure to *N. caninum* has been shown to result in reduced farm profitability, losses that may persist in a herd over

many years due to efficient vertical transmission of the parasite from infected dam to fetus. Herd diagnosis and subsequent control of *N. caninum* is necessary, therefore, and it is important to highlight the potential economic effect of this pathogen at the farm level to achieve effective control.

Salmonella

Exposure to *Salmonella* in unvaccinated herds in the present study was associated with substantial financial losses. The reductions in profits per cow in the present study as a result of exposure to *Salmonella* are in agreement with those in the study by Nielsen et al. (2013), who documented average gross margin losses of €8, €84, €163, and €188 per cow across 4 management types; very good management, good management, poor management, and very poor management over a 10-yr period in Danish dairy herds. Even though the management level of herds in the present study was not included in the model, the annual losses reported in this study (i.e., €94/cow) were similar to those recorded in herds with a good level of management in the Danish study, even though no fixed costs were included in that study. The simulation outputs of the present study suggest that, at a milk price of €0.24/L, the reduction in farm profits in test-positive herds would result in dairy farmers operating at a loss under Irish conditions. Prolonged periods of low milk price could therefore lead to unsustainable losses on farms without suitable contingencies in place. An investigation by O' Doherty et al. (2013) documented a prevalence of bulk milk antibodies to *Salmonella* of 49% in Irish dairy herds. As those herds were geographically representative of the national population of dairy farmers (O' Doherty et al., 2013), exposure to *Salmonella* is common in Ireland. Since the removal of European market supports in 2005, Irish dairy producers have been exposed to fluctuating milk prices. The importance of implementing suitable control measures for *Salmonella* species, therefore, should not be underestimated, and focused research on *Salmonella* prevention and control in Irish dairy herds is urgently required.

L. hardjo

Exposure to *L. hardjo* was associated with an increase in total costs in the current study. Exposure to *L. hardjo* was associated with compromised reproductive performance and an increased rate of carryover cows (O' Doherty, 2014). Carryover cows require additional feed resources, leading to increased costs (Butler et al., 2010). A higher rate of carryover cows would also result

in a reduction in milk yield because such animals spend more days in late lactation or dry, thereby contributing to the lower milk yield evident among *L. hardjo*-positive herds. The reduction in the 42-d calving rate associated with exposure to *L. hardjo* also leads to increased calving spread and related reductions in milk yield similar to the situation outlined for *N. caninum*.

Exposure to *L. hardjo* resulted in a reduction of total farm profits of €1,378 at a milk price of €0.29/L, equating to €14 per cow. A study by Bennett (1993) documented a loss of €70 per cow in the first year following introduction of *L. hardjo* in a UK dairy herd, which is higher than the loss reported in the present study. Several factors might have contributed to the apparent discrepancy in losses between these studies. First, the losses reported by Bennett (1993) relate to introduction of *L. hardjo*, whereas the current study did not record infection dates, with data more probably reflecting endemic infection, as described previously. Infection with *L. hardjo* has been associated with the reduction in milk yield known as milk drop syndrome (Ellis et al., 1976; Higgins et al., 1980) and, as such, Bennett (1993) included losses due to reduced milk production when estimating the cost of the leptospirosis outbreak. In the current study, however, no such association was detected between milk production and exposure to *L. hardjo* (O' Doherty, 2014), which may account for the lower losses in the present study compared with the UK study. Nonetheless, herds exposed to *L. hardjo* will incur a reduction in farm profitability, and mechanisms of control will be of benefit to infected herds.

Vaccination

In the present study, herds vaccinated for *Salmonella* recorded superior profits to unvaccinated positive herds to a value of €8,448 (€84.48/cow). Similar to vaccination for *Salmonella*, unvaccinated herds that tested positive for exposure to *L. hardjo* generated €970 (i.e., €9.70/cow) lower total farm profits compared with vaccinated herds. This finding is of considerable importance in promoting the control of *Salmonella* and *L. hardjo* in Ireland and highlights the benefits to be gained from vaccination in positive herds. In addition, herds negative for exposure to both *Salmonella* and *L. hardjo* generated greater profits compared with vaccinated herds, suggesting that avoiding exposure to these pathogens offers the greatest economic benefit to dairy farmers. However, no information is available on the costs associated with maintaining a disease-free status in herds that tested negative for exposure, and follow-up studies examining the cost benefit of controlling these pathogens are required.

CONCLUSIONS

Exposure to *Salmonella*, *N. caninum*, and *L. hardjo* resulted in significant financial losses for Irish dairy farmers. The reduction in total farm profits because of exposure to *Salmonella* in unvaccinated herds was between 3 and 4 times greater than the combined reduction in farm profits associated with exposure to *N. caninum* and *L. hardjo*. The calculation of farm profitability as profit per cow and as profit per kilogram of milk in the present study will aid individual dairy producers in estimating the economic effect of exposure to the pathogens under investigation in their own herds, not only in Ireland but also in other regions with similar systems of dairy production. The greater profitability among vaccinated *Salmonella* and *L. hardjo* herds compared with unvaccinated test-positive herds highlights the potential role of vaccination in future control programs, whereas the greater profit in the test-negative herds suggests that the optimal solution is to avoid disease exposure.

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