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

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Interpretative Summary

In this study a simulation model was used to estimate the economic losses associated with *Salmonella*, *N. caninum*, and *L. hardjo* in Irish dairy herds. Exposure to each of these pathogens resulted in reduced farm profits. Herds vaccinated for *Salmonella* and *L. hardjo* generated greater profits compared to unvaccinated herds that tested positive for exposure to these pathogens. However, profits in vaccinated herds were lower compared to herds that were negative for exposure to *Salmonella* and *L. hardjo*. The results of this study highlight that optimum economic performance was achieved in herds where there was no exposure to the pathogens under investigation compared to both exposed and vaccinated herds.

OUR INDUSTRY TODAY

Impact 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 impact of exposure to *Salmonella*, *N. caninum*, and *L. hardjo* on dairy farm profitability; in addition to simulating the impact 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 three 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 as baseline herds with results presented relative to this base. In the 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 a milk price of €0.24, €0.29, and €0.34 per litre 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* were 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 while 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 to herds vaccinated for each respective pathogen. Herds vaccinated for *Salmonella* generated €67.09, €84.48, and €101.89 per cow more profit at each milk price compared to herds positive for exposure. Similarly, herds vaccinated for *L. hardjo* generated €9.74, €9.69, and €9.63 per cow more profit compared to 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 to vaccinated baseline herds.

Keywords: *Salmonella*; *N. caninum*; *L. hardjo*; dairy farm profitability

INTRODUCTION

Salmonella enterica subspecies *enterica* serovar Dublin and *Salmonella enterica* subspecies *enterica* serovar Typhimurium are the two most frequently isolated serovars of *Salmonella* in cattle (Wray and Sojka 1977). *Salmonella* Dublin is host adapted to cattle (Wray and Sojka 1977). Faecal-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 *S*. Dublin (Wray and Sojka 1977; Poppe, 2011). Previous studies have identified a seasonal pattern in the rate of *Salmonella* induced abortions with 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 (Nielsen et al., 2012; Bazeley, 2006). 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).

*N*eospora *caninum* (*N. 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). Cattle have been confirmed as intermediate hosts of *N. caninum*. Vertical transmission is the most efficient route of *N. caninum* transmission (Dubey et al., 2007). *N. 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 (Goodswin et al., 2013). *N. caninum* induced abortions can occur at any time of year, but are most common in months five to eight 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 infection with *N. caninum* (McAllister 2007; Brickell et al., 2010). A study by Bartels et al. (2006) identified reductions 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* (Munoz-Zani et al., 2000).

Cattle are maintenance hosts for leptospires associated belonging to serovar *hardjo* (Leonard et al., 2004; Grooms et al., 2006). Two types of serovar *hardjo* have been identified: *Leptospira interrogans* serovar *hardjo* (type Hardjoprajitno) and *L*. borgetersenii serovar hardjo (type hardjo-bovis) (Leonard et al., 2004; Grooms et al., 2006). Urinary shedding is the most efficient method of transmission *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 thus leading to reproductive failure (Grooms et al., 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 a sudden decrease or cessation in milk production known as “milk drop syndrome” and abortion. “Milk drop syndrome” is characterised by a sudden drop or cessation in milk production, with the milk appearing thick, blood tinged, yellow in colour, 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 et al., 2000). Abortions associated with *L. hardjo* can occur at any time of the year bur are most common in the third trimester of pregnancy (Radostits et al., 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 (Guitian et al., 1999; Dhaliwal *et al*., 1996 a; Dhaliwal et al., 1996 b).

There have been numerous studies on the economic effects at farm-level of *Salmonella*, *N. caninum*, and *L. hardjo* in the international literature. An investigation of the direct losses associated with infection in *N. caninum* in Canadian dairy herds documented an annual loss of CDN$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 losses associated with *N. caninum* in Dutch dairy herds was quantified as €2,053 per herd (€32/cow) in the first year following the 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 years following infection in herds with very good management (Nielsen et al., 2013). However, in herds with very poor management gross margins 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 years following infection (Nielsen et al., 2013). In another Dutch study Visser et al. (1997) documented an average loss of Dfl. 55 (€23) per cow due to infection with *Salmonella* Dublin in 40 Dutch dairy herds. While there are fewer studies 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 there is limited information available on the economic impact 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 per hectare (LU/Ha) (Dillon, 2011). Such systems involve calving cows to coincide with the period of maximum grass growth i.e. springtime (Dillon *et al*., 1995), with cows being fed grazed grass outdoors for up to 235 days of lactation (Drennan *et al*., 2005). However there is limited information available on the economic impact of these pathogens in such pasture-based dairy production systems Irish dairy herds. The results of this study can therefore be compared to studies in countries where confinement systems of dairy production predominate.

The abolition of the European Union (EU) milk production quotas in 2015 will present an opportunity for Irish dairy farmers to increase milk production for the first time in a generation (Quinlan 2013; Shalloo et al., 2012). This potential can only be realised if the losses associated with infectious diseases including but not exclusively *Salmonella*, *N. caninum*, and *L. hardjo* are minimised thus 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 impact of exposure to these pathogens on the profitability of Irish dairy herds has not being 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 the impact of vaccination for *Salmonella* and *L. hardjo* on farm profitability was quantified when compared to 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 a study by O'Doherty et al., (2013) which investigated the temporal trends in bulk milk antibody levels of these pathogens in Irish dairy herds. Briefly, bulk milk samples were collected from 312 study herd at four time points in 2009 (March, June, August, and November) and were tested for antibodies against *Salmonella*, *N. caninum*, and *L. hardjo* using commercially available Enzyme Linked Immunosorbant Assay (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. There is no vaccine for *N. caninum* licenced for use in the Republic of 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 four sampling time points in 2009 (O' Doherty et al., 2013) i.e. if a herd recorded at least one positive bulk milk reading in 2009 the herd 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* has previously been documented by O'Doherty (2014). These production losses were defined under three 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 (SAS Version 9.1, USA) were used to quantify the association between both *Salmonella*, *N. caninum*, and *L. hardjo* bulk milk antibody status 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 EBI value, and median calving date in 2009. Unvaccinated herds positive for exposure to *Salmonella* produced 316 kg les milk compared to 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 a $20*10^3$ and a $28*10^3$ lower SCC, respectively compared to unvaccinated herds.

Reproductive performance losses

Similarly, 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-day calving rate (i.e. the number of primiparous and multiparous cows that calved in the first six week 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 days that were born to cows in the herd on the 30th of June), 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 the 30th of June), 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 EBI value, 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 day longer calving interval, in primiparous cows a 10 day increase in calving spread and produced 4% less calves per cow per year compared to negative herds. Unvaccinated herds positive for exposure to *Salmonella* produced 3% less calves per cow per year compared to unvaccinated negative herds. Unvaccinated herds positive for exposure to *L. hardjo* had a 12% lower 42-day calving rate and a 9% higher rate of carryover cows and produced 8% less calves per cow per year compared to unvaccinated negative herds. Herds vaccinated for *L. hardjo* had a 5% higher 42-day calving rate and a 3% lower rate of empty cows and produced 3% more calves per cow per year compared to unvaccinated herds.

Mortality rates

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

Economic analysis

Production data (Tables 1, 2, and 3) were incorporated into the Moorepark Dairy Systems Model (**MDSM**; Shalloo et al., 2004 a) to simulate the effect of exposure to a 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 labour utilisation, 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 reseeding), 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 390kg DM/cow. Full labour costs were included in the model with one labour 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 the feed requirement for milk production, maintenance, pregnancy and BW change. The profitability effects associated with exposure to the three pathogens were calculated across three base milk prices of €0.24, €0.29, and €0.34 per litre , 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 month 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. Vaccines were assumed to be 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 the 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, labour, and livestock movement components within the model for both vaccinated and unvaccinated herds.

Scenarios

Two scenarios were investigated to allow examination of the impact of exposure to *Salmonella*, *N. caninum* and *L. hardjo* in unvaccinated herds and to allow examination of the impact of vaccination in the case of *Salmonella* and *L. hardjo* when compared to 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 by unvaccinated test-positive herds were presented relative to this base.
- Scenario 2. *Salmonella* and *L. hardjo* vaccinated herds were compared to both 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 if vaccinated herds deliver a greater economic performance compared to an unvaccinated herd which are either positive or negative.

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

RESULTS

N. caninum

Scenario one

Herds positive for exposure to *N. caninum* produced 27 kg (0.5%) less milk per cow per year compared to the negative baseline (Table 5). The volume of milk sold therefore was 2,474 kg (0.5%) lower in *N. caninum* test-positive herds compared to the baseline (negative herds). Replacement costs were €558 greater in *N. caninum* test-positive herds compared to the baseline. Herds positive for exposure to *N. caninum* generated total costs that were €932 greater compared to the baseline (Table 6). Herds positive for exposure to *N. caninum* generated milk receipts that were equal in value compared to the negative baseline (Table 6). Total profits per farm were €1,155, €1,200, and €1,244 lower compared to the baseline in herds positive for exposure to *N. caninum* based on a milk price of €0.24, €0.29 and €0.34 per litre, respectively (Table 6). At a milk price of €0.29 per litre farm profits in herds positive for exposure to *N. caninum* were reduced by €12 per cow and €0.002 per kg compared to the negative baseline.

Salmonella

Scenario one

Unvaccinated *Salmonella* positive herds produced a 316 kg (6%) lower 305 day milk yield per cow when compared to the baseline (unvaccinated negative herds) (Table 5). Consequently, these positive herds generated 31,411 kg (6%) lower volume of milk sales and a 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 to the negative baseline (Table 7). Unvaccinated herds that tested positive for exposure to *Salmonella* generated milk receipts which were €8,423, €10,152, and €11,800 lower at a milk price of €0.24, €0.29, and €0.34 per litre compared to 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 to the negative baseline based on a milk price of €0.24, €0.29 and €0.34 per litre, respectively (Table 7). At a milk price of €0.29 per litre farm profits per cow and per kg milk were reduced by €94.71 and €0.016, respectively in herds positive for exposure to *Salmonella* compared to the negative baseline.

Scenario two.

Relative to vaccinated herds, unvaccinated herds that tested positive for exposure to *Salmonella* had a 316 kg (6%) lower 305 day milk yield per cow (Table 5). Consequently, unvaccinated *Salmonella* test positive herds generated 31,411 kg lower milk sales and a 2,369 kg lower milk solids compared to the vaccinated baseline. There was 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 compared to the vaccinated baseline (Table 7). Unvaccinated herds negative for exposure to *Salmonella* generated total costs which were €1,376 lower compared to the vaccinated baseline (Table 7). Milk receipts in unvaccinated *Salmonella* positive herds were €8,423, €10,152, and €11,800 lower when compared to the vaccinated baseline based on milk prices of €0.24, €0.29 and €0.34 per litre (Table 7). Herds negative for exposure to *Salmonella* generated milk receipts that were equal in value compared to the vaccinated baseline (Table 7). Unvaccinated herds that tested positive for exposure to *Salmonella* generated total profits per farm that were €6,709, €8,488, and €10,189 lower compared to the vaccinated baseline based on a milk price of €0.24, €0.29 and €0.34 per litre, respectively (Table 7). Compared to vaccinated herds, unvaccinated herds positive for exposure to *Salmonella* generated a €84.48 per cow and a €0.014 per kg milk lower profit (Table 7) at a milk price of €0.29 per litre. Herds negative for exposure to *Salmonella* generated a total profit per farm that was €1,022 greater based on a milk price of 24.5, 29.5 and 34.5 cents per litre (€c/l) compared to the vaccinated baseline (Table 7). Profits per cow were €10.22 greater and profits per kg milk were €0.002 higher in herds negative for exposure to *Salmonella* relative to the vaccinated baseline (Table 7).

L. Hardjo

Scenario one

Unvaccinated herds that tested positive for exposure to *L. hardjo* recorded a 31 kg (0.6%) lower 305 day milk yield per cow compared to the baseline (Table 5). Consequently the total quantity of milk sold across the herd was 2,543 kg lower (0.5%). However, unvaccinated herds that tested positive for exposure to *L. hardjo* generated a 96 kg (0.3%) higher volume of milk solids compared to the negative baseline due to an increase in milk solids concentrations (Table 5). Unvaccinated herds that tested positive for exposure to *L. hardjo* generated total costs which were €784 greater compared to the negative baseline (Table 8). Unvaccinated herds that tested positive for exposure to *L. hardjo* generated milk receipts that were equal in value compared to 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 to the negative baseline based on a milk price of €0.24, €0.29 and €0.34 per litre, respectively (Table 8). At a milk price of €0.29 per litre farm profits in herds positive for exposure to *L. hardjo* were reduced €13.78 per cow compared to the negative baseline. On a profit per kg milk basis profits in herds positive for exposure to *L. hardjo* were reduced €0.023 per kg relative to negative herds a milk price of €0.29 per litre.

***Scenario two*.**

Unvaccinated herds positive for exposure to *L. hardjo* had a 31 kg lower 305 day milk yield compared to the vaccinated baseline (Table 5). There was no difference in the physical performance of unvaccinated herds that were negative for exposure to *L. hardjo* compared to the vaccinated baseline (Table 5). Total costs in unvaccinated herds that tested positive for exposure to *L*. hardjo were equal to the vaccinated herds (Table 8). Unvaccinated herds negative for exposure to *L. hardjo* generated total costs which were €763 lower compared to the vaccinated baseline (Table 8). Unvaccinated *L. hardjo* positive herds generated milk receipts that were equal in value relative to the vaccinated baseline (Table 8). Herds negative for exposure to *L. hardjo* generated milk receipts that were equal in value compared to 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 per litre compared to the vaccinated baseline (Table 8). Relative to vaccinated herds, unvaccinated herds positive for exposure to *L. hardjo* generated a €9.69 lower profit per cow and a €0.002 per kg lower profit per kg milk at a milk price of €0.29 per litre (Table 8). Herds negative for exposure to *L. hardjo* generated total profits per farm that were €409 greater at each milk price compared to the vaccinated baseline (Table 8). Profits were €4.09 per cow and €0.002 cents per kg greater in herds negative for exposure to *L. hardjo* compared to the vaccinated baseline at a milk price of €0.29 per litre (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 to subsequently simulate the association between exposure to these pathogens and farm profitability. In addition, the impact of vaccination against *Salmonella* and *L. hardjo* on farm profitability was also quantified when compared to both unvaccinated test positive and test negative herds. The current study highlighted that farm profitability is reduced in unvaccinated herds having evidence of exposure to *Salmonella*, *N. Caninum*, and *L. hardjo*. The analysis also suggests that vaccination had a positive influence on farm profitability when compared to unvaccinated herds that tested positive for exposure to *Salmonella* and *L. hardjo*. However herds vaccinated for *Salmonella* and *L. hardjo* had lower profits compared to 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 the pathogens under investigation on the performance in dairy herds. The implementation of suitable control programmes 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 compared to herds that tested positive for exposure. A cost benefit analysis is therefore necessary to determine which control measures when implemented in positive herds deliver the optimum economic benefit.

N. caninum

N. caninum can result in a longer calving interval (Macaldowie et al., 2004; Williams et al., 2000; O'Doherty, 2014. Evans et al. (2006), Shalloo et al. (2014), and Geary et al. (2012) have shown that longer calving intervals have been associated with lower 305–day 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 27 kg lower milk yield. Additionally, a later mean calving date as a consequence of the longer calving interval will result in a reduction in 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 total costs associated with exposure to *N. caninum* highlighted in the current study is contributed to by the increased use of grass silage. The higher total costs in exposed herds was also contributed to by increased replacement costs due to the 8% increase in adult cow mortality (O' Doherty, 2014).

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 in part be due to the fact that 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 farmer is predominantly pasture-based and spring calving which will introduce discrepancies between 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 foetus. Herd diagnosis and subsequent control of *N. caninum* is necessary, therefore, and it is important to highlight the potential economic impact of this pathogen at farm level to achieve effective control.

Salmonella

Exposure to *Salmonella* in unvaccinated herds in the present study was associated with substantial financial losses. The reduction in profits per cow in the present study as a result of exposure to *Salmonella* are in agreement with a study by Nielsen et al. (2013), who documented an average gross margin loss of €8, €84, €163 and €188 per cow across four management types; very good management, good management, poor management, and very poor management over a 10 year 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), are similar to those recorded by 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/litre, 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 carry-over cows would also result in a reduction in milk yield as such animals spend more days in late lactation or dry thereby contributing to the lower milk yield evident amongst *L. hardjo* test-positive herds. The reduction in the 42-day calving rate associated with exposure to *L. hardjo* also leads to an increased calving spread and related reductions in milk yield similar to 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 €0.29r/litre, 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. There are a number of factors which may have contributed to the apparent discrepancy in losses between both studies. Firstly, 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 a 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 in comparison to 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 the value of €8,448 (€84.48/cow). Similar to vaccination for *Salmonella*, unvaccinated herds that tested positive for exposure *L. hardjo* generated €970 (i.e. €9.70/cow) lower total farm profits compared to 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 to vaccinated herds, suggesting that avoiding exposure to these pathogens offers the most 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 is required.

CONCLUSIONS

The present study highlighted that exposure to *Salmonella*, *N. caninum*, and *L. hardjo* resulted in significant financial losses. The reduction in total farm profits as a result of exposure to *Salmonella* in unvaccinated herds were between three and four times greater than the combined reduction in farm profits associated with exposure to *N. caninum* and *L. hardjo*. The calculation of farm profitability as a profit per cow and as a profit per kg milk in the present study will aid individual dairy producers to estimate the economic impact of exposure to the pathogens under investigation on their own herds not only in Ireland but also in regions with a similar system of dairy production internationally. The greater profitability among vaccinated *Salmonella* and *L. hardjo* herds compared to unvaccinated test-positive herds highlights the potential role of vaccination in future control programmes, while the greater profits in the test negative herds suggests that the optimum solution is to avoid disease exposure.

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Table 1: Milk production losses associated with exposure to *N. caninum*, *Salmonella*, and *L. hardjo* in study herds.

Pathogen	Difference in LSM	P-value	Source
N. caninum (negative vs. positive herds)			
No associations identified	n/a	n/a	
Salmonella			
[negative vs. positive herds (unvaccinated herds only)]			
milk yield, kg	316	0.006	
milk fat yield, kg	14	0.003	
PP milk protein yield, kg	12	0.003	O' Doherty 2014
Unvaccinated vs. vaccinated herds			
SCC, cells/ml $*10^3$	20	0.04	
L. hardjo			
[negative vs. positive herds (unvaccinated herds only)]			
No associations identified	n/a	n/a	
Unvaccinated vs. vaccinated herds			
SCC, cells/ml $*10^3$	28	0.01	

Table 2: Reproductive performance losses associated with exposure to *N. caninum*, *Salmonella*, and *L. hardjo* in study herds.

Pathogen	Difference in LSM	P-value	Source
N. caninum (negative vs. positive herds)			
Primiparous calving spread, d	-10	0.04	
Calving interval in 2010, d	-6	0,004	
Calves/cow in 2010	0.04	0.03	
Salmonella			
[negative vs. positive herds (unvaccinated herds only)]			
Calves/cow in 2009	0.03	0.04	
Unvaccinated vs. vaccinated herds			
No associations identified	n/a	n/a	
L. hardjo			
[negative vs. positive herds (unvaccinated herds only)]			O' Doherty 2014
Multiparous 42-d calving rate in 2009, %	14	0.02	
Rate of carryover cows 2009, %	-9	0.03	
Calves/cow in 2010	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	4 (-3)	

Table 3: Mortality losses associated with exposure to *N. caninum*, *Salmonella*, and *L. hardjo* in study herds.

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

Table 4: Herd default parameters in the Moorepark dairy systems model

Parameter	Amount
Farm size (ha)	40
Concentrate cost, €/t	270
Fertilizer cost, €/t	
CAN	300
Urea	380
Replacement rate, %	19
Replacement heifer cost, €	1,540
Cull cow value, €/head	400
Male calf value €/head	100

Table 5: Effect of exposure to *N. caninum*, *Salmonella*, and *L. hardjo* on the physical outputs of a simulated 100 cow dairy herd.

Physical output	Exposure and vaccination status to *N. caninum*, *Salmonella*, and *L. hardjo*					
	Negative and vaccinated (Baseline)	*N. caninum* positive[1]	Unvaccinated *Salmonella* positive	Unvaccinated *L. hardjo* positive	*Salmonella* Unvaccinated[2]	*L. hardjo* 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
Socking rate, LU/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 DM/cow	3,661	3,627	3,517	3,595	3,661	3,626
Grass silage, kg DM/cow	1,131	1,181	1,123	1,223	1,131	1,181
Concentrate, kg DM/cow	398	398	398	398	398	398

[1] Bulk milk antibody positive

[2] Comprises of both negative and positive herds

Table 6: Economic impact of exposure to *N. caninum* in a simulated 100 cow dairy herd.

	Exposure status to *N. caninum*,	
Financial output	Negative (Baseline)	Positive[1]
Costs		
Labour costs, €	29,193	29,102
Replacement costs, €	29,245	29,803
Total costs, €	155,425	156,357
Milk Receipts, €		
@ €0.24/L	133,941	133,872
@ €0.29/L	161,425	161,317
@ €0.34/L	188,908	188,762
Profit		
Profit/cow, €		
@ €0.24/L	58	46
@ €0.29/L	334	322
@ €0.34/L	611	599
Profit/kg milk, €c		
@ €0.24/L	1.13	0.91
@ €0.29/L	6.55	6.35
@ €0.34/L	11.96	11.78
Total profit/farm, €		
@ €0.24/L	5,784	4,629
@ €0.29/L	33,445	32,245
@ €0.34/L	61,105	59,861

[1]Bulk milk antibody positive

Table 7: Economic impact of exposure to and vaccination for *Salmonella* in a simulated 100 cow dairy herd.

	Exposure status to *Salmonella*			
Financial output	Negative (Baseline)	Unvaccinated positive[1]	Vaccinated (Baseline)	Unvaccinated[2]
Costs				
Labour costs, €	29,193	29,193	29,193	29,193
Replacement costs, €	29,245	29,244	29,244	29,244
Total costs, €	155,425	154,792	156,801	155,425
Milk Receipts, €				
@ €0.24/L	133,941	125,518	133,941	133,960
@ €0.29/L	161,425	151,273	161,425	161,447
@ €0.34/L	188,908	177,028	188,908	188,935
Profit				
Profit/cow, €				
@ €0.24/L	58	-19	48	47
@ €0.29/L	334	240	324	323
@ €0.34/L	611	499	601	600
Profit/kg milk, €c				
@ €0.24/L	1.13	-0.41	0.93	0.91
@ €0.29/L	6.55	5.00	6.35	6.33
@ €0.34/L	11.96	10.41	11.76	11.75
Total profit/farm, €				
@ €0.24/L	5,784	-1947	4,762	4,663
@ €0.29/L	33,445	23,974	32,422	32,328
@ €0.34/L	61,105	49,894	60,083	59,992

[1] Bulk milk antibody positive

[2] Comprises of both negative and positive herds

Table 8: Economic impact of exposure to and vaccination for *L. hardjo* in a simulated 100 cow dairy herd.

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

[1] Bulk milk antibody positive

[2] Comprises of both negative and positive herds