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Dairy farmer income, working time, and antimicrobial use under different dry cow therapy protocols

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ABSTRACT

Mastitis is one of the most common diseases of dairy cattle. It has a high impact on-farm economy, farmers' working time, and antimicrobial usage (AMU). Selective dry cow therapy (SDCT) is an effective means of reducing AMU without negatively affecting udder health. The objective of our study was to evaluate the impact of SDCT implementation on farmer income, working time, and AMU, using a bioeconomic model. A stochastic dairy simulation model (DairyHealthSim) based on a weekly model was used to simulate herd dynamics, reproduction, milk production, culling decisions, health outcomes, and the management of health events. A specific module was developed for the simulation of quarter-level IMI acquisition and elimination during the lactation and dry-off periods, and 25 different farm settings were defined to represent herds with various udder health situations. We then defined 20 scenarios of SDCT by combining both the use of different thresholds of SCC and milk bacteriology for treatment allocation and the use of internal teat sealant (ITS). All SDCT protocols had little effect on farmer income, and we identified some protocols with a positive farm gross margin (up to Can$15.83/dried cow; at time of writing, Can$1 = US$0.72). We also found that adding an ITS to all cows led to greater economic gain. The application of SDCT had little effect on farmers' working time, except when milk bacteriology was used for decision making. Antimicrobial treatment to all cows above 200,000 cells/mL at last control, with the use of ITS on all cows, seems a good choice in most dairy farms. These findings could be used to convince farmers to adopt this strategy at dry-off.

Key words: dairy cow, mastitis, udder health, bioeconomic model, selective dry cow therapy

INTRODUCTION

Dry cow therapy (**DCT**) is the administration of intramammary antimicrobials to some or all mammary quarters or cows at the end of a lactation (dry-off). Dry cow therapy has 2 objectives: (1) curing infections present at dry-off and (2) preventing new infections during the dry period (Bradley and Green, 2004). Historically, antimicrobial therapy has been promoted and implemented for all quarters of all animals (i.e., blanket dry cow therapy [**BDCT**]), whether infected or not (Ruegg, 2017). The World Health Organization raised concerns about the excessive use of antimicrobials and the impact on antimicrobial resistance, which affects both human and animal health (World Health Organization, 2014). As a consequence, the nonjudicious use (such as for prophylaxis) of antimicrobials should generally be avoided. Selective DCT (**SDCT**) is a method that can be used to reduce the prophylactic usage of antimicrobials at dry-off. With SDCT, only infected animals (detected via a diagnostic test) are treated with an antimicrobial, hence, treatment is limited to its curative role and is not a preventive treatment anymore (Kabera et al., 2021a).

Although it is widely used in some countries, SDCT is still uncommon on most dairy farms worldwide as BDCT remains highly popular (McCubbin et al., 2022). The application of BDCT is responsible for a large proportion of the total use of antimicrobials on dairy farms, as was recently demonstrated for Canada (Lardé et al., 2020). Conversely, a change from BDCT to SDCT can lead to substantial reduction in the use of antimicrobials, as was shown in the Netherlands where the country-level use of antimicrobials was reduced by 36% after implementation of mandatory SDCT (Santman-Berends et al., 2021). A meta-analysis also reported a mean herd-level potential

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The list of standard abbreviations for JDS is available at adsa.org/jds-abbreviations-24. Nonstandard abbreviations are available in the Notes.

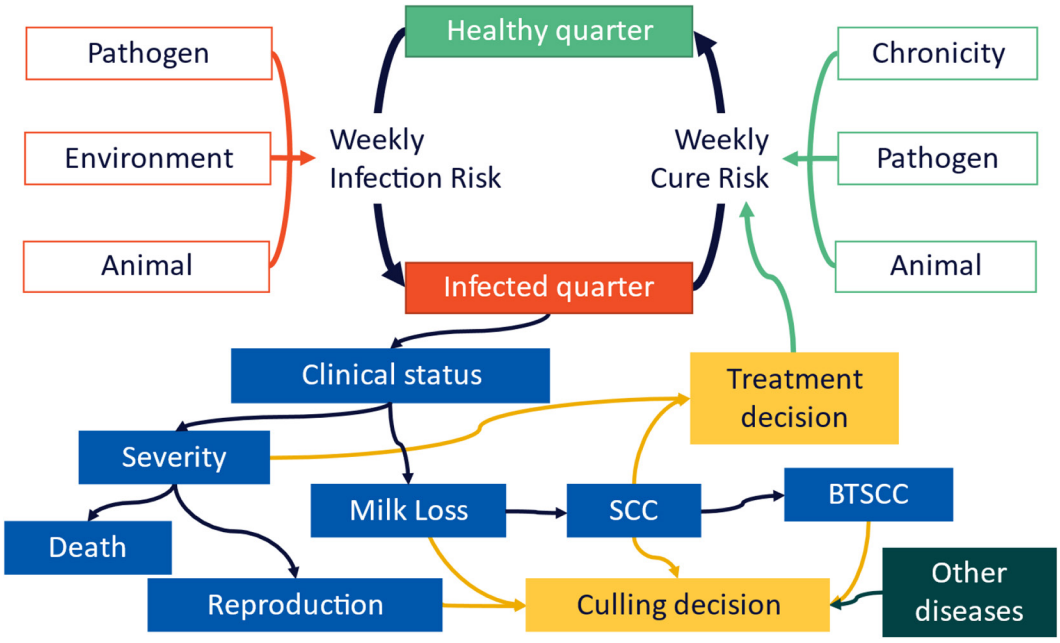

Figure 1. Epidemiologic model framework used to simulate IMI of dairy cattle in a bioeconomic model (BTSCC = bulk tank somatic cell count). Other diseases include lameness, for example. Light green represents the healthy status and cure probability, orange represents the infected status and the infection risk, blue represents the consequences of an IMI, yellow represents a decision, and dark green represents the other parts of the model.

reduction of antimicrobial usage (**AMU**) of up to 66% after SDCT implementation in a herd (Kabera et al., 2021a).

For the prevention of new IMI during the dry period, the use of internal teat sealants (**ITS**) is an interesting and efficient alternative to antimicrobials (Dufour et al., 2019). These products form a plug in the teat cistern, offering a physical barrier to new IMI during dry-off, hence reducing new IMI rates during dry-off and IMI prevalence at calving (Rabiee and Lean, 2013; Kabera et al., 2021a). Some authors consider that ITS are necessary for a safe implementation of SDCT in all situations (Bradley et al., 2018), whereas others consider that in herds with a low IMI incidence during dry-off, ITS are not economically relevant for SDCT implementation (Rajala-Schultz et al., 2019).

Different methods are available at dry-off to discriminate cows or quarters having an IMI from healthy ones (McCubbin et al., 2022), namely SCC, clinical mastitis (**CM**) history of animals, sensor systems, and on-farm culture systems.

Additional labor and increased expenditures, due to both the technique and detrimental effects on udder health, are the main concerns of farmers and veterinarians regarding the implementation of SDCT (Scherpenzeel et al., 2016b; Higgins et al., 2017). The limited negative impacts when implementing SDCT on subsequent udder health is well documented (von Konigslow et al., 2020; Kabera et al., 2021a). However, few studies have specifically studied the economics of SDCT implementation. Although most reported a cost reduction for farmers when using SDCT compared with BDCT (Scherpenzeel et al., 2018; Hommels et al., 2021; Rowe et al., 2021), some limitations of these studies have been identified (Ferchiou et al., 2021; McCubbin et al., 2022): (1) Old data were used for the parametrization of models. For example, in parametrization of IMI rates during the dry period, although older studies found a higher risk of CM and higher SCC in early lactation for untreated cows (Østerås and Sandvik, 1996; Scherpenzeel et al., 2014), newer ones did not find any significant difference between treated and untreated animals (McParland et al., 2019; Rowe et al., 2020; Kabera et al., 2021a; Rowe et al., 2023). This could also be explained by the absence of ITS treatment in the older studies, while the newer one used it. These small differences could still have a significant effect on long-term simulations and on the economic calculations of the models. Another example is that calculations of milk losses due to subclinical mastitis (**SCM**) are calculated by formulas that seem to exaggerate its extent compared with newer formulas (Seegers et al., 2003; Halasa et al., 2009a). (2) Most studies do not mention ITS usage or comparison of its usage versus its nonusage (Huijps and Hogeveen, 2007; Scherpenzeel et al., 2018; Rowe et al., 2021). This would be helpful to know the economical usefulness of ITS. (3) Some studies did not consider some important economic consequences of SDCT (e.g., farmers' workload, cost of DHI analyses; Hommels et al., 2021; Rowe et al., 2021). (4) Most models have few

Table 1. Objectives of output indicators after parametrization of the IMI model[1]

Output indicator	Clinical mastitis incidence (Cases/cow-year)	Bulk tank SCC (cells/mL)	Proportion of cows with SCC ≥200,000 cells/mL (%)	Pathogen-specific clinical mastitis incidence (Cases/cow-year)					
				Escherichia coli	*Klebsiella* spp.	*Staphylococcus aureus*	*Streptococcus uberis*	NAS	SLO[2]
Objective after parametrization	0.31	180,000	18	0.1	0.01	0.05	0.04	0.06	0.04

[1]Based on Olde Riekerink et al. (2008), Reyher et al. (2011), and Fauteux et al. (2014).
[2]SLO = *Streptococcus*-like organisms.

available scenarios of SDCT implementation used. They do not compare a lot of techniques of treatment selection, which makes the economic comparison of the different techniques difficult. Also, only one study compares the same technique in herds with different udder health profiles (Scherpenzeel et al., 2018). Evaluating the economic impact in different herds is an important information to generalize this technique to most herds. (5) Most studies evaluating economic impact of a decision use partial and closed bioeconomic modeling approaches. A partial or closed bioeconomic model means that the models do not interact with the different subsystems of a dairy farm (e.g., effect of a loss of production on food consumption), and these are often too deterministic in their approach (e.g., a predetermined incidence of CM in a simulated herd; Ferchiou et al., 2021). A new study addressing these issues would help veterinarians in assisting farmers to implement SDCT more willingly.

The main objective of our study was to compare different BDCT and SDCT protocols by assessing multiple indicators: farmer's income, workload, and AMU on farms with different udder health profiles. A second objective was to compare, via the same approach, the usage of ITS in different SDCT and BDCT scenarios.

MATERIALS AND METHODS

To achieve our different objectives, we developed a new module of IMI (described in the following sections) inserted in a bioeconomic model of dairy herd described in detail elsewhere (Ferchiou et al., 2021) and adapted for Québec, Canada, dairy farms. This bioeconomic model simulates individual cows in a dairy farm on a weekly basis in an agent-based Markov-chain framework. Each cow has an individual status including reproduction management, diseases, animal growth, milk production, culling, and feeding management. This status is calculated every week and may change in function of the algorithms. General data concerning the herd is derived from these individual statuses. In this context, the new module interacts with all the relevant modules simulating the cows within the farm. For the simulations of IMI, we added a mathematical simulation of quarter-based pathogen-specific IMI via a sensible-infected-sensible (**SIS**) approach, as proposed and experimented by others (Zadoks et al., 2002; Halasa et al., 2009b; Gussmann et al., 2018; Figure 1). The entire model, including this new module, was coded in Python (version 5.4; Python Software Foundation, Wilmington, DE; Van Rossum and Fred, 2009), and is described in length in Supplemental Figure S1 (see Notes).

We mimicked an eastern Canadian dairy farm in our modeling. Because most of the herds in this region are tiestall herds, this was the housing type selected for this

Table 2. Pathogen-specific input parameters used in a bioeconomic model

Pathogen	Additional risk of infection for heifers in their first week of lactation (%)	Probability of having a clinical mastitis at first week of infection[1]	Weekly relapse risk[2]	Distribution of severity score of clinical mastitis[1]			Healthy quarter dry period new infection risks[3]
				Mild	Moderate	Severe	
Staphylococcus aureus	3	0.2	0.03	0.62	0.33	0.05	0.0563
Escherichia coli	0	0.75	0	0.3	0.45	0.25	0.0563
Klebsiella spp.	0	0.9	0	0.35	0.48	0.17	0.0104
NAS	0	0.03	0.005	0.6	0.35	0.05	0.1583
SLO[4]	0	0.15	0.01	0.46	0.47	0.07	0.0271
Streptococcus uberis	0	0.6	0.02	0.45	0.45	0.1	0.0271

[1]Based on Reyher et al. (2011).

[2]Based on Gussmann et al. (2018).

[3]Adapted from Kabera et al. (2020).

[4]*Streptococcus*-like organisms: gram-positive, catalase-negative cocci.

study. This decision affected the maximum density of animals in the herd (i.e., no possibility of overcrowding; note that this parameter could be modified for future analyses using the same bioeconomic model), and cows would be dried off or culled to respect that rule. It also affected the incidence of IMI as it was calibrated with data originating from that type of farm, as described thereafter. The herd was composed of a maximum of 100 lactating cow, and mature cows (third lactation or greater) produced an average of 11,100 kg during a 305-d production. The herd bulk milk SCC was defined as function of the modeled IMI, and, as such, was rather an output of the model described thereafter. A herd milk production restriction was included to represent the quota system in Canada, which forces herds to produce a specific quantity of milk fat with a restricted allowance to under- or overproduce around this quantity. Different data sources representing dairy farms in eastern Canada were used to obtain the most representative model possible (Olde Riekerink et al., 2008; Reyher et al., 2011; Fauteux et al., 2014).

Infection Dynamics

Six different pathogens or categories of pathogens were included in the model, including *Escherichia coli*, *Staphylococcus aureus*, *Streptococcus uberis*, *Klebsiella* spp., NAS, and *Streptococcus*-like organisms (**SLO**). They aim to represent most of the pathogens identified on Canadian farms (Cameron et al., 2013; Kabera et al., 2020).

For each uninfected quarter, a weekly risk of acquiring an IMI was calculated for each pathogen. The calculation of that risk was performed using the equation proposed by Gussmann et al. (2018). All pathogens, except *Staph. aureus,* were considered environmental pathogens, and thus, Equation 1 was used to calculate the weekly risk:

$$p_{pathogen} = 1 - e^{-\beta_{pathogen} \times Susc_{quarter}}. \quad [1]$$

For *Staph. aureus*, Equation 2 for contagious pathogens was used:

$$p_{pathogen} = 1 - e^{-\beta_{pathogen} \times Prevalence_{pathogen} \times Susc_{quarter} \times RF_{aureus}}. \quad [2]$$

In this equation, $p_{pathogen}$ is the weekly risk of acquiring a new IMI by a specific pathogen on a given quarter. $\beta_{pathogen}$ is the transmission rate for that specific pathogen. This factor was obtained via a trial-and-error approach until the output indicators obtained from the simulation (CM incidence for each pathogen, bulk tank SCC, and proportion of cows with SCC ≥200,000 cells/mL) were in line with those found in our data sources from Canada (Olde Riekerink et al., 2008; Reyher et al., 2011; Fauteux et al., 2014). These objectives for output indicators are provided in Table 1. Susceptibility of a quarter ($Susc_{quarter}$) was based on the number of lactations of the animal and on the number of days in milk in a given week (Supplemental Table S1, see Notes; adapted from Olde Riekerink et al., 2007). An additional risk factor considering quarter interdependence for *Staph. aureus* infections (risk of a new *Staph. aureus* IMI if another quarter of the same cow is already infected) was also added (RF_{aureus}; Supplemental Table S2, see Notes), based on data obtained from the Canadian National Cohort of Dairy Farms (Reyher et al., 2011, 2013). The prevalence of *Staph. aureus* (proportion of quarters in the farm already infected by *Staph. aureus* at a given time) was added ($Prevalence_{pathogen}$) to the equation used to compute *Staph. aureus* IMI weekly risk. Finally, a risk of infection was added at the first week of the first lactation to simulate the IMI of heifers at first calving (Table 2).

Each IMI during lactation could lead to either CM or SCM. The probability of being a CM was defined for each new IMI occurring during the lactation period

Table 3. Infected quarter dry period cure probabilities (%) used in a bioeconomic model simulating eastern Canadian dairy farms

Infectious agent	Treated	Reference	Untreated	Reference
Staphylococcus aureus				
Nonchronic infection	77.0	Halasa et al. (2009c, 2010)	29.5	Halasa et al. (2009c, 2010)
Chronic infection	55.0	Halasa et al. (2009c, 2010); we used the same ratio chronic:nonchronic as in van den Borne et al. (2010)	23.1	Halasa et al. (2009c, 2010); we used the same ratio chronic: nonchronic as in van den Borne et al. (2010)
Streptococcus uberis	89.0	Halasa et al. (2009c, 2010)	31.9	Halasa et al. (2009c, 2010)
NAS	82.9	Arruda et al. (2013)	44.0	Kabera et al. (2020)
Streptococcus-like organisms	88.0	Arruda et al. (2013)	47.0	Kabera et al. (2020)
Klebsiella spp.	100	Arruda et al. (2013); Kabera et al. (2020)	70.0	Kabera et al. (2020)
Escherichia coli	90.0	Halasa et al. (2009c, 2010)	44.9	Halasa et al. (2009c, 2010)

(Table 2). A level of severity was assigned to each CM (mild, moderate, or severe; Wenz et al., 2001). The distribution of these severity scores was based on data from the Canadian National Cohort of Dairy Farms (Table 2; Reyher et al., 2011). The duration of a CM was defined as 1 wk. In case of an absence of cure, the infection transited to a SCM (i.e., an IMI without clinical signs). Each week, a SCM had a risk of flaring up to a CM (Table 2). The probability of death (27%; Le Page et al., 2023) and the effect on reproductive performances were computed for cows affected by severe CM (Supplemental Table S3, see Notes; adapted from Fuenzalida et al., 2015).

For CM and SCM, a weekly probability of detection of the infection by the farmer was defined (Supplemental Table S3). If detected, the IMI was computed as treated. Treatments and withdrawal time were computed as per the label of the medication. Each week, the risk of cure was defined as a function of whether the IMI was detected or not. This intended to emulate a lack of detection by the farmer. Once cured, the quarter would be considered healthy at the beginning of the next week, and thus susceptible again to infections. Furthermore, for *Staph. aureus*, infections were considered chronic if they lasted for more than 6 wk. In that case, specific lower cure probabilities for chronic IMI were applied (Supplemental Table S4, see Notes). A 45-min veterinary visit cost was computed for 50% of severe CM cases.

The dry cow period was considered a single unit in the SIS model (i.e., all risks of infection or cure were only calculated once) during the first week of dry-off; hence, there was no transition of infectious state during this period. In the first week of the dry-off period, infected quarters had a probability of cure, and every healthy quarter (including recently cured quarters) was assigned a probability of new infection. The new infection and cure probabilities were based on the randomized control trial by Kabera et al. (2020; Tables 2 and 3). An algorithm for the treatment decision was defined for the DCT.

The model simulated individual SCC tests every 4 wk, comparable to a herd on regular testing scheme, and the SCC values were used for simulating the farmer's decision making for each cow. Individual SCC calculations are described thereafter. Last SCC before dry-off, quarter-based milk bacteriology at dry-off, and a combination of those 2 tests were the methods used for the detection of IMI at dry-off for SDCT implementation by the farmer (Figure 2). The quarter-based milk bacteriology sensitivity (probability of detecting an infection) was set at 82.2% and its specificity at 62.0% (probability of detecting a noninfection), based on Kabera et al. (2021b). Four thresholds were defined for the SCC-based treatment decision (50,000, 100,000, 150,000, and 200,000

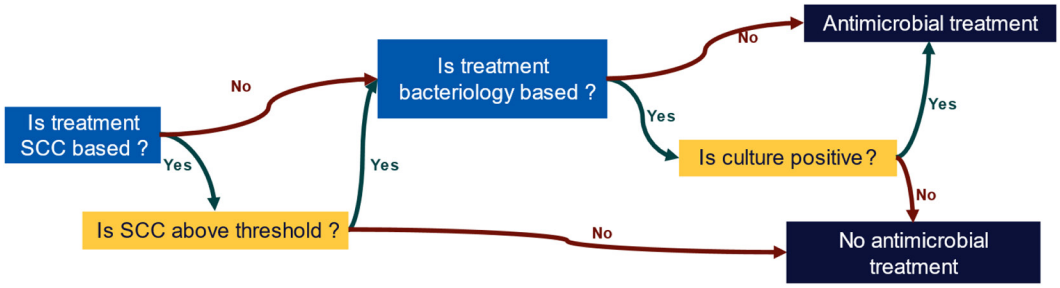

Figure 2. Algorithm for dry cow therapy selection in a bioeconomic model. Light blue represents a question linked with the dry cow therapy scenario, yellow represents a question regarding the indicators of the mode, and dark blue represents the final treatment decision.

cells/mL). The use of an ITS alone or in combination with an antibiotic was computed to provide a multiplicative preventive factor for the risk of new infections of 0.48 compared with the application of antibiotics alone, which provided a factor of 0.62 (Dufour et al., 2019). In total, 20 scenarios of DCT protocols were defined based on practical combinations of SCC, milk bacteriology, and ITS (Table 4). Briefly, scenario 1 represented a BDCT without teat sealant, scenario 5 represented an SDCT approach where an SCC threshold of 200,000 cells/mL was used without quarter-milk bacteriology and without the use of ITS, scenario 6 represented an SDCT based on quarter-based bacteriology, scenario 15 represented an SDCT approach where an SCC threshold of 200,000 cells/mL was used with ITS, and scenario 20 represented an SDCT approach where an SCC threshold of 200,000 cells/mL was used with quarter-milk bacteriology and with the use of ITS.

Consequences of an IMI During Lactation

Each pathogen was computed to induce a specific milk loss at quarter level. We distinguished milk losses for either SCM or CM. Due to the absence of available parametrization data, milk loss was not set to be different between the different grades of CM. Milk losses were represented as a triangular distribution and were thus stochastic (Supplemental Table S5, see Notes; adapted from Gröhn et al., 2004; Gonçalves et al., 2018). After a CM, the milk production returned to normal, following a geometric progression calibrated using the data used for milk loss parametrization (Gröhn et al., 2004).

Somatic cell count was calculated at cow level by using the sum of the 4 quarters' milk loss. We inverted the causal relationship (inflammation causing a loss of milk) but kept the correlation between cells and milk loss mainly because interdependence of quarter's SCC prevented a SCC calculation quarter by quarter (Barkema et al., 1997). The cow's SCC was, therefore, indirectly modelized as a function of these latter parameters. For cows with CM, the SCC was calculated by fitting an exponential equation to Equation 3, provided by Seegers et al. (2003):

$$Cells = 50{,}000 \times e^{1.3863 \times Milk\ loss}, \quad [3]$$

where *Cells* is the SCC in the milk (in cells/mL), and *Milk loss* is the 4 quarters' milk loss sum. For the other cows (SCM and healthy ones), the SCC was calculated by fitting the exponential Equations 4 and 5 to the data provided by Halasa et al. (2009a):

$$Cells_{L1} = 49{,}585 \times e^{4.9945 \times Milk\ loss}, \quad [4]$$

$$Cells_{L2} = 57{,}904 \times e^{2.483 \times Milk\ loss}, \quad [5]$$

where $Cells_{L1}$ is the SCC of primiparous cows, and $Cells_{L2}$ is the SCC of multiparous cows. During the transition from an CM to a subclinical or healthy state, the highest value of SCC was used as the cow's SCC. Furthermore, for healthy cows without any milk loss, a dilution effect of SCC was calculated using Equation 6, provided by Green et al. (2006):

$$Corrected\ SCC = Original\ SCC - 0.485 \times Milk\ production, \quad [6]$$

where *Milk production* is the daily milk production (in kg/d). Milk from cows with an SCC above 7,000,000 cells/mL was deemed to be kept out of the bulk tank until improvement.

Culling Decisions

An algorithm was defined for culling decisions. Two possibilities were defined: do not breed (**DNB**) status (cessation of breeding attempts, and thus, future culling after completion of lactation) and removal from the herd (immediate culling of the animal).

Table 4. List of all dry cow therapy scenarios used in the study simulating eastern Canadian dairy farms with the difference of mean between reference scenario and the other scenario for gross margin, annual labor time, and antimicrobial usage[1]

	Selection method for antimicrobial treatment			Difference of mean compared with scenario 1 (±95% CI)		
Scenario number	SCC threshold	Quarter-based bacteriology	Internal teat sealant	Gross margin (Can$)	Annual labor time (h/yr)	Antimicrobial usage (DCD/cow/yr)
1	BDCT	No	None	Referent	Referent	Referent
2	50,000			812 ± 1,471	−0.78 ± 0.04	−0.8 ± 0.01
3	100,000			1,189 ± 1,471	−1.97 ± 0.04	−2.08 ± 0.01
4	150,000			−55 ± 1,491	−2.24 ± 0.04	−2.44 ± 0.01
5	200,000			−770 ± 1,453	−2.38 ± 0.04	−2.59 ± 0.01
6	BDCT	Yes		−105 ± 1,441	13.98 ± 0.06	−2.45 ± 0.01
7	50,000			−289 ± 1,489	9.39 ± 0.06	−2.54 ± 0.01
8	100,000			72 ± 1,468	2.1 ± 0.06	−2.66 ± 0.01
9	150,000			−712 ± 1,471	−0.09 ± 0.05	−2.72 ± 0.01
10	200,000			−1,289 ± 1,469	−1.05 ± 0.05	−2.76 ± 0.01
11	BDCT	No	On all cows	−1,227 ± 1,472	2.68 ± 0.04	0 ± 0.01
12	50,000			−576 ± 1,473	1.96 ± 0.04	−0.8 ± 0.01
13	100,000			285 ± 1,476	0.77 ± 0.04	−2.07 ± 0.01
14	150,000			565 ± 1,467	0.35 ± 0.04	−2.48 ± 0.01
15	200,000			977 ± 1,483	0.21 ± 0.04	−2.64 ± 0.01
16	BDCT	Yes		−685 ± 1,448	16.63 ± 0.07	−2.47 ± 0.01
17	50,000			−567 ± 1,472	12.06 ± 0.07	−2.56 ± 0.01
18	100,000			127 ± 1,461	4.67 ± 0.06	−2.68 ± 0.01
19	150,000			1,269 ± 1,473	2.43 ± 0.05	−2.77 ± 0.01
20	200,000			438 ± 1,479	1.41 ± 0.05	−2.82 ± 0.01

[1]BDCT = blanket dry cow therapy; DCD = defined course dose, represents one antimicrobial treatment of an animal given at its labeled dose and duration (Lardé et al., 2021). At time of writing, Can$1 = US$0.72.

Causes for the DNB status were fertility issues (≥7 AI or ≥300 DIM), low milk production (Supplemental Table S6, see Notes), ≥6 lactations, and udder health issues (more than 3 CM cases in the current lactation or more than 3 tests above 1,000,000 cells/mL).

Triggering removal of cows from the herd occurred in 3 situations: excessive bulk tank SCC, excessive density of animals in the farm, and herd-level overproduction compared with the quota allowance. Excessive bulk tank SCC was defined as 4 wk ≥400,000 cells/mL. Each time such an event occurred, the cow with the highest DIM within the DNB cow list was immediately culled. This procedure was repeated each week until the bulk tank SCC decreased to <400,000 cells/mL. Each week, the herd had an excessive density of animal (>1 cow/stall) or an overproduction compared with the quota allowance; cows on the DNB list having the highest number of DIM were culled at the beginning of the week. Cows with a DNB status were removed from the herd mainly for that reason. Another reason for removing a cow from the herd was lameness. An algorithm was created to simulate the occurrence and consequences of lameness in the herd, as described by Robcis et al. (2023). Lame cows having a score of 4 out of 5 (Sprecher et al., 1997) for more than 4 wk, or a score of 5 for more than 3 wk, were immediately removed from the herd.

Economic Model

The gross margin (**GM**) is the amount of money a farm keeps after subtracting all operational costs (feed [comprising fertilizer, seed, and chemicals costs], work, medication, reproduction, and veterinary costs) from the gross revenue (income from selling milk, cows, and calves). We calculated the GM for each year of the simulation of each repetition. Fixed costs were considered unchanged among scenarios (mechanization, utilities, housing costs, milking costs) and were thus not considered in our calculations. All prices used for GM calculation are presented in Table 5.

Due to large variations across herds and difficulties in the parametrization, Dairy Health Sim did not simulate the complete daily work flow of the farmer. Alternatively, the difference in working time was considered for interventions regarding mammary health (milk bacteriology, intramammary treatments, and systemic treatments). The estimated amounts of time spent for a given intervention are also presented in Table 5. They were estimated by an analysis of previously published data (Aghamohammadi et al., 2018) and expert-based opinion from the authors experience in farms from our practice (Centre hospitalier universitaire vétérinaire, Saint-Hyacinthe, Québec). A sensitivity analysis (analysis under different parameters) was computed for feed costs and time spent by the farmer.

Table 5. List of prices (Can$; at time of writing, Can$1 = US$0.72) used for the calculation of the gross margin and time used for the calculation of farmer's time expenditure in simulated herds

Item	Price (Can$)	Time of intervention[1] (min)	Source
Bacteriology culture (per quarter)	2.76	3	Largest distributor of veterinary drugs in eastern Canada
Dry-off antimicrobial (per quarter)	6.12	0.5	
Internal teat sealant (per quarter)	2.90	0.5	
Nonsteroidal anti-inflammatory drug (one dose)	43.55	1	
Hypertonic infusion (one dose)	5.00	10	
Intramammary ceftiofur infusion (one complete course)	13.22	2	
Intramammary cephapirin infusion (one complete course)	16.16	2	
Parenteral antimicrobials (one complete course)	38.35	6	
Farmer hourly rate	22.00		Statistiques Canada (2023)
Selling price of pregnant heifers (per animal)	2,548.00		
Veterinarian hourly rate	168.03		Ministry of Agriculture, Fishing and Food of Québec
Selling price of one liter of milk	0.936		Les Producteurs de lait du Québec (2023)
Selling price of culled cow (per kg)	2.18		Les Producteurs de bovins du Québec (2023)
Selling price of calves (per kg)	5.90		
Cost of one megacalorie of total mixed ration	0.47		Based on the average of farms in our practice[2]
Price of one insemination	42.00		

[1]Based on Aghamohammadi et al. (2018) and the authors' experience for the farms in our practice.
[2]Centre hospitalier universitaire vétérinaire, Saint-Hyacinthe, Québec.

The difference of means of each indicator (GM, farmer's working time, and AMU) was calculated for each scenario compared with the reference scenario (scenario 1). Results are expressed as values of the scenario minus those of the reference scenario.

For each scenario, we started with a steady simulation obtained from the baseline hygiene and milking farm's setting with BDCT and ITS on all cows as this combination of practices is often observed in eastern Canadian herds (scenario 11; Table 4). Temporal stability (i.e., absence of abnormal variations of parameters from week to week) of our model demographics (number of milking cows, number of dry cows) and IMI incidence within the herd were assessed. The realism (i.e., data obtained from the model were similar to what was observed for eastern Canadian herds) of our simulation was evaluated by comparing the model with data from Canadian cohort studies (Olde Riekerink et al., 2008; Reyher et al., 2011; Fauteux et al., 2014). The 20 scenarios of DCT were then applied separately and ran for 20 yr, starting on the steady herd simulated thanks to scenario 11. The first 5 yr were excluded from the analysis as a stabilization period (transition time). Analyses were thus based on the 15 remaining years of simulation for each scenario. Each scenario was repeated 100 times, for a total of 1,500 yr of simulation available for the analysis of each scenario.

Finally, a total of 25 farm settings, affecting the baseline risk of IMI and reflecting different farm situations, were defined. The goal was to reflect the diversity of IMI rates in eastern Canadian farms. We proposed to use 2 variables, housing and milking, to simulate the 2 main areas of control of IMI on a dairy farm and to provide a broad possibility of IMI rates for each pathogen link either with an improved or deteriorated hygiene of the farm's environment or of its milking practices. The incidence of infections in these different farm settings was parametrizated by adding a multiplying factor to the β factor (Supplemental Table S7, see Notes). A sensitivity analysis was conducted through the application of the 25 farm settings (i.e., by varying the farm's hygiene and milking parameters) for scenarios 1, 5, 6, 15, and 20 (Table 4). These scenarios represented a good sample of all the available DCT techniques.

RESULTS

Udder Health Indicators

The results for the medium, lowest, and highest IMI farm settings (Table 6) show a good temporal stability (demographics and IMI incidences and prevalences) and match the objectives set for calibration (Table 1). For the baseline IMI farm setting, by etiology, the annual CM incidence was 0.043 cases per cow for *Staph. aureus* (SD: 0.023), 0.099 for *E. coli* (SD: 0.030), 0.017 for *Klebsiella* spp. (SD: 0.016), 0.072 for NAS (SD: 0.26), 0.034 for SLO (SD: 0.018), and 0.046 for *Strep. uberis* (SD: 0.22). On average, 80 cows were dried off each year, and 98 cows were milked per week.

Table 7 shows the udder health indices obtained for different dry cow protocols when using the baseline farm's hygiene and milking setting (farm setting [**FS**] 13, as the reference of FS in our model parametrization; see Supplemental Table S7). In general, the choice of a given DCT approach had a small effect on the main udder health indices. For instance, compared with BDCT, in the SDCT

Table 6. Various udder health indicators as a function of 3 IMI incidence scenarios in a bioeconomic model simulating eastern Canadian dairy farms (mean ± SD)

IMI incidence farm setting[1]	Lowest	Medium	Highest
Clinical mastitis incidence (case/cow-year)	0.14 ± 0.04	0.32 ± 0.05	0.73 ± 0.08
IMI incidence (case/cow-year)	0.74 ± 0.08	1.3 ± 0.10	2.31 ± 0.12
Bulk tank SCC (cells/mL)	111,702 ± 9,163	159,899 ± 15,116	295,232 ± 27,767
Proportion of cows above 200,000 cells/mL (%)	7.5 ± 1.6	17 ± 2.0	36 ± 3.0
Voluntary culling rate (%)	18.4 ± 3.6	20.1 ± 3.8	25.5 ± 4.4
Antimicrobial usage (defined course dose/cow per year)	3.7 ± 0.19	4.0 ± 0.19	4.6 ± 0.22

[1]These farm settings represent different farm with specific risks of IMI, with 24 scenarios. Here we represented those with the overall lowest, medium, and highest risks, respectively.

scenario based on an SCC threshold of 200,000 cells/mL at last test (**SCC200**) combined with quarter-milk bacteriology, the incidence of IMI was proportionally 2.3% higher, IMI had a longer duration by 7.9%, the bulk tank somatic cell count (**BTSCC**) was 4.7% higher, and the CM incidence was 2.0% higher. In all other scenarios, these changes were smaller. These differences between BDCT and the described SDCT approach were more pronounced in the farm setting with an improved hygiene and milking situation; the incidence of IMI was 0.5% lower, IMI had a longer duration by 7.8%, bulk tank SCC was 4.2% higher, and CM incidence was 5.2% higher. Compared with the BDCT scenario in the BDCT with the ITS scenario, the incidence of IMI was proportionally 0.09% lower, the BTSCC was 0.01% lower, and the CM incidence was proportionally 1.0% lower. Compared with the SCC200 scenario, in the SCC200 with the ITS scenario, the incidence of IMI was 1.5% higher, the IMI duration was 6.0% shorter, the BTSCC was 3.9% lower, and the CM incidence was 2.1% lower.

Economic Results

Table 4 shows the results for the annual GM as a mean difference of GM between the reference scenario (BDCT without ITS) and the other SDCT scenarios. The average standard deviation of the scenarios' GM in the base farm setting (FS13) was Can$24,498/yr (minimum: 23,542; maximum: 25,209; at time of writing, Can$1 = US$0.72). The most profitable scenarios were as follows: (1) SDCT decision based on SCC alone, using a 100,000 cells/mL threshold, (2) SDCT with ITS based on SCC, using a 150,000 cells/mL threshold combined with bacteriology, and (3) SDCT with ITS based on SCC alone at a 200,000 cells/mL threshold (Can$1,189/yr, Can$1,268/yr, and Can$972/yr of GM gain compared with BDCT, respectively). The less profitable were the following ones: (1) SDCT with ITS and (2) SCC alone, using a 100,000 cells/mL threshold (Can$−1,227/yr and Can$−1,289/yr, respectively). Selective dry cow therapy with quarter-milk bacteriology alone (i.e., SCC = 0) was slightly less profitable than BDCT (Can$−105 of GM per year compared with the BDCT). The addition of ITS to any SDCT protocol was not profitable unless an SCC threshold above 100,000 cells/mL was used (e.g., a gain of Can$1,747 of GM was estimated when adding ITS to an SCC protocol using a threshold of 200,000 cells/mL). Supplemental Table S8 (see Notes) shows the variations in the various financial items underlying changes in GM.

The results regarding the farmer's working time needed for achieving udder health tasks are presented in Table 4 as a mean difference between the reference scenario (BDCT) and the other SDCT scenarios. The SD was, on average, 0.9 h/yr for each scenario in the base farm setting (FS13; minimum: 0.5; maximum: 1.3). Working time was reduced as the SCC threshold increased (resulting in a lower number of cows to treat at dry-off). The addition of ITS increased the annual time

Table 7. Udder health indicators (mean ± SD) for different dry cow therapy protocols estimated using a bioeconomic model of eastern Canadian dairy farms

Scenario of dry cow therapy[1]	Clinical mastitis incidence (cases/cow-year)	Medium bulk tank SCC (cells/mL)	IMI incidence (Cases/cow-year)
BDCT [1]	0.305 ± 0.123	159,900 ± 17,963	1.244 ± 0.063
BDCT and ITS [11]	0.305 ± 0.118	159,900 ± 17,690	1.244 ± 0.064
SCC200 [5]	0.31 ± 0.117	166,358 ± 18,272	1.225 ± 0.064
SCC200 and ITS [15]	0.302 ± 0.116	159,021 ± 17,212	1.236 ± 0.062
Bacteriology [6]	0.306 ± 0.116	162,184 ± 18,103	1.23 ± 0.061
SCC, ITS, and bacteriology [20]	0.302 ± 0.117	158,868 ± 17,852	1.238 ± 0.061

[1]BDCT = blanket dry cow therapy; ITS = internal teat sealant; SCC200 = selective dry cow therapy using a threshold of 200,000 cells/mL at last control; bacteriology = selective dry cow therapy using a quarter-based bacteriology. Numbers in brackets represent identification number of each scenario.

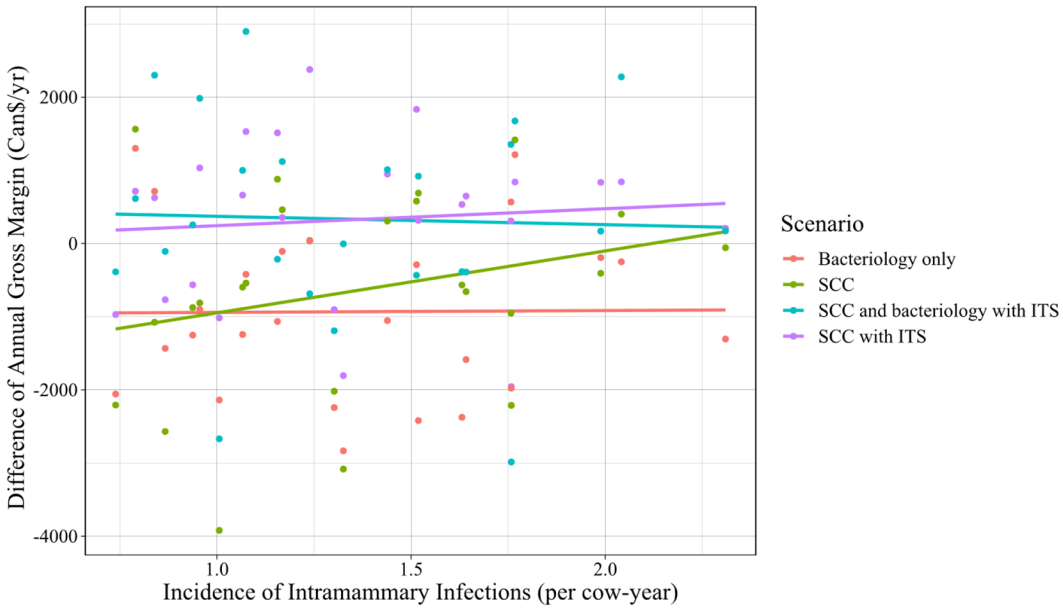

Figure 3. Differences in annual GM (Can$/yr; at time of writing, Can$1 = US$0.72) between the reference (blanket dry cow therapy without internal teat sealant [ITS]) and different scenarios of selective dry cow therapy using different SCC thresholds for treatment decision and as a function of the simulated IMI incidence on simulated eastern Canadian dairy farms. Linear trends for a few selective dry cow therapy scenarios not using the SCC or using an SCC threshold of 200,000 cells/mL and using or not an ITS are illustrated. Negative values indicate superiority of the alternative scenario compared with blanket dry cow therapy.

spent on average by 2.7 h/yr (minimum: 2.5; maximum: 2.7). Using bacteriology testing at dry-off increased the annual time spent by 14.0 h/yr; this increase was inversely correlated with the SCC threshold. A combined SCC (threshold of 200,000 cells/mL) and bacteriology DCT protocol resulted in a 1.1 h/yr reduction of the farmer's workload as compared with BDCT.

The results for AMU are presented in Table 4 as the mean difference of AMU (in defined course dose [**DCD**]/cow-year) between the reference scenario (BDCT) and the other SDCT scenarios. Defined course dose represents one treatment of antimicrobial given for it specified regimen on it label (Lardé et al., 2021). The SD was, on average, 0.15 DCD per cow-year for each scenario in the base farm setting (FS13; minimum: 0.12; maximum: 0.22). The AMU was inversely correlated with the SCC threshold (up to −2.59 DCD/cow-year). The use of bacteriology at dry-off was associated with the lowest AMU (up to −2.76 DCD/cow-year). The use of ITS had little effect on AMU and had the biggest effect at higher SCC thresholds (up to a reduction of 0.06 DCD/cow-year).

Figure 3 shows the difference in GM between the reference scenario and the different SDCT scenarios for the different farm hygiene and milking settings and as a function of the simulated IMI prevalence. The differences in GM between the BDCT scenario and the bacteriology scenarios were slightly affected by the IMI incidence in our scenarios. The difference in GM between the BDCT scenario and the SDCT with SCC at a threshold of 200,000 cells/mL scenario was mildly affected by IMI incidence (Can$846/yr for one IMI/cow-year); this effect was reduced when adding the use of ITS to the scenario (Can$231/yr for one IMI/cow-year).

Sensitivity analysis of the working time spent for mastitis and the cost of feed showed only a small effect of these variables on the difference in GM among scenarios (up to Can$489/yr), with no significant change in the ranking among scenarios.

DISCUSSION

Udder Health Indicators

The model parameters were calibrated with the different output indicators in mind (IMI incidence, CM incidence, BTSCC, proportion of cows with an SCC above 200,000 cells/mL, and CM incidence for each pathogen). We obtained a realistic simulation when comparing the output indicators obtained from our model to those found in the literature (Olde Riekerink et al., 2007, 2008; Reyher et al., 2011; Fauteux et al., 2014) and to those we encountered in our daily practice at the Bovine Ambulatory Clinic of the Veterinary Medicine Faculty of the Université de Montréal. We observed differences of udder health indicators between SDCT protocols as expected (Table 7); they are very small and comparable to those

observed in recent studies. We observed a small effect of the ITS on various parameters, which can explain the variations of GM. The farm housing and milking settings achieved their goal of providing farms with different but realistic IMI incidence and CM incidence values.

Although the simulation of IMI via an SIS approach has already been achieved by some authors (Allore and Erb, 1999; Zadoks et al., 2002; Halasa et al., 2009b; Gussmann et al., 2018), the model we developed has some new and interesting features. First, this model is integrated in a larger model representing a whole dairy farm. This results in a more realistic model, as udder health is not an isolated issue, but one of the many issues faced by a farmer. It is especially important in our culling module, where all usual decision factors for removing cows are considered, including udder health criteria (Haine et al., 2017). This holistic approach of a farm addresses one of the limitations observed in many bioeconomic models of dairy farms (Ferchiou et al., 2021). Second, our model has some interesting features for *Staph. aureus* infections (i.e., chronicity of infection and interquarter infection risk). This allows a more realistic model for *Staph. aureus* infections, which are frequent in Canadian farms, as mentioned by most Canadian literature (Olde Riekerink et al., 2008). This latter feature could possibly be used for other contagious pathogens commonly found in other parts of the world. Finally, we accounted for different SCC calculations for CM and SCM (Seegers et al., 2003; Halasa et al., 2009a) as well as the dilution effect of SCC due to milk production (Green et al., 2006). We believe this resulted in a more realistic production loss and SCC estimation in our model compared with previously published models of IMI.

As in any simulation model, care must be taken when interpreting the data, as it is a simplification of complex biological and human processes. We considered only a few pathogens, those with the highest impacts on Canadian dairy farms. We also simplified the SCC calculation process to a cow-based calculation and not a quarter-based calculation. However, in a real-life situation, each quarter has its own SCC, which can be very different from one another, and each quarter's IMI status may affect the other quarters' SCC (Barkema et al., 1997; Djabri et al., 2002). This complex interaction was simplified to a cow-level calculation, because the data points were not sufficient to model this complex biological process, this simplification could influence the economic results of our model. Also, we considered that a quarter could only be infected by one pathogen at a time. This simplification had 2 objectives: an easier calculation of an infection's impact, as few data are available on mixed infections, and the simulation of a protection factor for a higher SCC (Suriyasathaporn et al., 2000), as this effect could not be computed for individual quarters. This simplification was deemed not completely unrealistic as few cases of mixed infections with the pathogens included in our model were observed in the studies we used as references (Reyher et al., 2011; Kabera et al., 2020). Finally, some parts of the model (e.g., reproduction, lameness) were not fully parametrized as an eastern Canadian farm, this could also affect our results.

Economic Results

Different scenarios of DCT were evaluated in the current study. Their GM varied between a gain of Can$1,300/yr and a loss of Can$1,300/yr. These variations are well below the SD of the GM in our different scenarios (mean: Can$23,542/yr), indicating that a change of the DCT protocol would probably be economically unnoticeable in real farm settings. Nonetheless, we found some interesting trends. The use of SCC without ITS was profitable up to a threshold of 100,000 cells/mL. Above this, the protocols were less profitable than a standard BDCT protocol. This phenomenon could be explained by the higher number of quarters left untreated and, thus, more susceptible to a new infection, or possibly already infected but not detected and left untreated with antimicrobials, using the higher SCC thresholds and leaving them unprotected by an ITS. This could also explain the positive effect of ITS on all cows at higher SCC thresholds. Some SDCT studies included ITS in their protocols (Halasa et al., 2009b; Patel et al., 2017; Hommels et al., 2021), whereas others did not (Huijps and Hogeveen, 2007; Scherpenzeel et al., 2016a, 2018), but no economic study compared different groups with or without ITS. Our findings suggest that an ITS is useful in SDCT protocols based on an SCC threshold above 100,000 cells/mL. The economic impact of the SDCT protocols based on an SCC threshold of 200,000 cells/mL with an ITS on all cows was Can$12.13 more per dried cow compared with BDCT. This was in the upper range of most recent findings in the literature (e.g., increases of US$7.85/dried cow [Rowe et al., 2021], US$0.70/cow-dried [Hommels et al., 2021], or €2.45/dried cow [Scherpenzeel et al., 2018]). Although the methods, economic index evaluated, and economic realities reported in the literature differ, they tend to show a slight benefit of using an SCC-based SDCT compared with a BDCT (Halasa et al., 2009b; Hommels et al., 2021; Rowe et al., 2021). The only bioeconomic model that investigated the costs of different DCT protocols found a deficit of −6.98€/dried cow on average without taking into account the SCC analysis costs (Halasa et al., 2010). The difference between the latter model and ours may be explained by the different economic parametrizations (Europe vs. Canada) and by the more recent data

used for the parametrization of our model (Calculation of SCC and milk losses and the effects of SDCT on the mammary gland health). Moreover, we did not include the cost of SCC analysis directly in our calculation as we expected that all farms, applying an SDCT or not, were already on such a program. The cost of regular testing for an equivalent farm would be roughly Can$10,000/yr in Québec (personal communication). In that context, adhesion to a SCC testing program for the sole purpose of implementing an SDCT is not profitable, and bacteriology-based SDCT would be a good alternative.

Selective DCT based on quarter-milk bacteriology alone had a very low impact on the GM (Can$−1.32/dried cow). Only one study evaluated the economic impact of a bacteriology-based SDCT protocol (Rowe et al., 2021); the authors found a benefit of US$2.14/dried cow compared with BDCT. Although we found a slight loss, these findings suggest that the use of a quarter-based bacteriology protocol is economically close to that of BDCT. Our most profitable scenario was a combination of SCC at a 150,000 cells/mL threshold and quarter-milk bacteriology with the use of ITS. So far, no other study has investigated a combined SCC/bacteriology protocol.

The evaluation of SDCT at different farm hygiene and milking settings, which aimed to represent different farm's IMI incidence situations (linked with the technical abilities of the farmers, the prevention of mastitis, and so on), showed that overall, the IMI incidence had a low effect on the economic impact of DCT strategies. The results were consistent in the 4 investigated protocols. However, SCC-based protocols were slightly more profitable in a higher IMI incidence context. The addition of ITS to a SCC protocol resulted in a lower effect of the IMI incidence on the GM difference. The higher number of quarters left without any treatment in the lower IMI incidence context, and thus the larger number of quarters susceptible to a new IMI if no ITS is used, could explain this effect. This result is different from some results found in the literature, where SDCT led to a higher gain in a low IMI incidence context (Scherpenzeel et al., 2018) or to a similar gain (Hommels et al., 2021). Bacteriology-based protocols were not affected by the IMI incidence context. These results suggest that these specific SDCT strategies could be implemented with similar economic consequences on farms with different udder health contexts, even on farms with higher IMI incidences.

Farmer's Working Time and AMU

Working time is one of the main concerns of farmers when implementing an SDCT protocol (McCubbin et al., 2022). Here, we found that SCC-based protocols were mostly time-savers, whereas bacteriology increased the working time of the farmer. Overall, these effects are moderate. Selective DCT strategies making use of combined methods offered an intermediate and tended to have a similar impact at a higher SCC threshold (which leads to a lower number of bacteriological tests being conducted). The addition of ITS had a similar impact in all our scenarios. These findings show that the SDCT impact on the farmer's working time is limited for most of the investigated protocols when compared with the SD in our scenarios. Only bacteriology-based protocols with a low SCC threshold had an important effect (because, in that case, most quarters will be tested). This difference of time might be valued differently if it is planned time (dry-off treatment) or unplanned time (mastitis treatment), the latter being considered costlier by most farmers. As such, time to implement ITS might be a good investment for the farmer. So far, no other studied reported such information.

As expected, AMU was always lower in SDCT scenarios and negatively correlated with the SCC threshold. Quarter-milk bacteriology had a high impact on AMU (up to −2.45 DCD/cow per year), and the combined method had an even higher impact (up to −2.68 DCD/cow per year). The use of an ITS had a low impact, and this impact was more visible at higher SCC thresholds and when using bacteriology as it reduced the number of new IMI during dry-off and, thus, led to a reduction of subsequent treatments during lactation (up to −0.06 DCD/cow per year).

Considering these results, the scenario with a combination of SCC at a 200,000 cells/mL threshold and ITS could be considered a good choice for most farms. Compared with BDCT, it resulted in a slight gain of GM, a high reduction of AMU, and a similar workload while staying a simple and practical protocol, resulting in an easier acceptance by farmers. These results were consistent for all farm settings investigated.

CONCLUSIONS

We developed a module for quarter-level IMI transmission in a larger bioeconomic dairy herd health management simulation model. It produces a realistic simulation of IMI on a farm. It shows that SDCT has little effect on the GM and that it can save labor, while greatly reducing AMU. It also shows that ITS usually has a positive effect on the GM when used in SDCT protocols. These findings may be used to address the fears of farmers regarding implementation of SDCT, while encouraging the reduction of AMU on dairy farms. Regarding our evaluation criteria, antimicrobial treatment to all cows above 200,000 cells/mL at last control, with the usage of ITS on all cows, seemed a good choice for most dairy farms.

NOTES

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Nonstandard abbreviations use: AMU = antimicrobial usage; BDCT = blanket dry cow therapy; BTSCC = bulk tank SCC; CM = clinical mastitis; DCD = defined course dose; DCT = dry cow therapy; DNB = do not breed; FS = farm setting; GM = gross margin; ITS = internal teat sealant; SCC200 = selective dry cow therapy using a threshold of 200,000 cells/mL at last control; SCM = subclinical mastitis; SDCT = selective dry cow therapy; SIS = sensible-infected-sensible; SLO = *Streptococcus*-like organisms.

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