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Diagnostic properties of milk diversion and farmer-reported mastitis to indicate clinical mastitis status in dairy cows using Bayesian latent class analysis

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HIGHLIGHTS

- Milk diversion can be useful for indicating clinical mastitis in dairy cows.
- Reporting quality affects diagnostic value of milk diversion and reported mastitis.
- Milk diversion episodes of 4–7 days gave optimal diagnostic properties.

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ABSTRACT

The development of digital farming gives bovine mastitis research and management tools access to large datasets. However, the quality of registered data on clinical mastitis cases or treatments may be inadequate (e.g. due to missing records). In automatic milking systems, the decision to divert milk from the bulk milk tank during milking is registered (i.e. milk diversion indicator) for every milking and could potentially indicate a clinical mastitis case. This study accordingly estimated the diagnostic performance of a milk diversion indicator in relation to farmer-recorded clinical mastitis cases in the absence of a "gold standard". Data on milk diversion and farmer-reported clinical mastitis from 3,443 lactations in 13 herds were analyzed. Each cow lactation was split into 30-DIM periods in which it was registered whether milk was diverted and whether clinical mastitis was reported. One 30-DIM period was randomly sampled for each lactation and this was the unit of analysis, this procedure was repeated 300 times, resulting in 300 datasets to create autocorrelation-robust results during analysis. We used Bayesian latent class analysis to assess the diagnostic properties of milk diversion and farmer-reported clinical status. We analyzed different episode lengths of milk diversion of 1 or more milk diversion days until 10 or more milk diversion days for two scenarios: farmers with poor-quality (51% sensitivity, 99% specificity) and high-quality (90% sensitivity, 99% specificity) mastitis registrations. The analysis was done for all 300 datasets. The results showed that for the scenario where the quality of clinical mastitis reporting was high, the sensitivity was similar for milk-diversion threshold durations of 1–4 days (0.843 to 0.793 versus 0.893). Specificity increased when the number of days of milk diversion increased and was ≥98% at a milk-diversion threshold durations of 8 or more consecutive milk diversion days. In the scenario where the quality of clinical mastitis reporting was low, the sensitivity of milk diversion and reported clinical mastitis cases was similar at milk-diversion threshold durations of 1–7 days (0.687 to 0.448 versus 0.503 to 0.504) while specificity exceeded the 98% at milk-diversion threshold durations of 7 or more consecutive milk diversion days. In both scenarios, a milk diversion threshold duration of 4–7 days achieved the most desirable combined sensitivity and specificity. This study concluded that milk diversion can be a valid alternative to farmer-reported clinical mastitis as it performs similarly in indicating actual clinical mastitis.

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1. Introduction

Differences in the reported incidence of clinical mastitis in dairy herds could be due to actual differences in mastitis incidence, differences in farmers' skill at observing clinical mastitis, their consistency in recording clinical signs, individual perceptions of the definition of clinical mastitis, and different thresholds for initiating treatment (Espetvedt et al., 2013; Vaarst et al., 2002). The underreporting of clinical mastitis cases has been reported by other authors (Bartlett et al., 2001; Wolff et al., 2012) and it may bias the results of analyses that use clinical mastitis case data if the rate of underreporting differs between farmers. Currently, the main methods for assessing the number of clinical cases on a farm is to ask the farmer to record the number of clinical cases (e.g. van den Borne et al., 2010) or to use treatment records of farms (Wolff et al., 2012). Both methods are time consuming and can result in imperfect data, as they depend on the farmer's willingness to report (Wolff et al., 2012).

A possible alternative indicator is whether the farmer changes the milk-diversion setting for specific cows in the automatic milking system (AMS) management software, to ensure that the milk from cows with mastitis is not transferred to the bulk tank for human consumption, but is discarded. If a farmer chooses to divert milk for several consecutive days, there is a high probability that the milk is being discarded either due to antibiotic treatment or other treatments requiring milk withdrawal, or due to unfavorable milk quality. In the case of antibiotic treatment, farmers have a high incentive to divert the milk to avoid antibiotic residues and associated penalties. While treatment records may be incomplete or unavailable, milk diversions are consistently and automatically recorded by the AMS.

Milk diversion records have been recently evaluated in combination with reported clinical mastitis (RCM) and AMS mastitis alerts using RCM as the reference standard (Bonestroo et al., 2020). To truly evaluate the performance of milk diversion alone as an indicator of clinical mastitis, we must account for the fact that farmer-RCM cases are imperfect as not all cases are detected and not all detected cases are reported and refrain from using AMS mastitis alerts in combination with milk diversion. As AMS mastitis alerts are highly correlated with milk diversion and farmer-RCM, they influence the diagnostic properties of both indicators. Bayesian latent class analysis has been used to evaluate diagnostic test properties in the absence of a "gold standard"; it allows the superiority of a novel test over an old test to be tested, even when the old test is the "gold standard" in a field (Johnson et al., 2019). Examples of its use in mastitis related research are comparison of the diagnostic properties of polymerase chain reaction testing and bacteriological culturing in diagnosing *Streptococcus agalactiae* intramammary infection in cows (Holmøy et al., 2018; Mahmmod et al., 2013a) and of polymerase chain reaction testing and bacteriological culturing in diagnosing *Staphylococcus aureus* intramammary infection in cows (Mahmmod et al., 2013b; Toft et al., 2019). Bayesian latent class analysis could be used to estimate the sensitivity and specificity of both milk diversion and farmer-recorded clinical mastitis for the detection of clinical mastitis in AMS-managed herds.

The aim of this study was to estimate the performance of a milk diversion indicator relative to farmer-recorded clinical mastitis as an indicator of clinical mastitis cases in AMS-managed herds, accounting for varying degrees of missed cases in farmer reporting. In addition, we wanted to investigate different thresholds in terms of consecutive milk diversion days to determine the milk diversion episode duration having the best diagnostic properties as an indicator of observed clinical mastitis.

2. Materials and methods

2.1. Data retrieval

Table 1 gives the general description of the herds used in this study. The mean daily milk yield was 34.18 kg, the mean milk diversion was 0.03 times per recorded day, and the mean farmer-RCM incidence was 37.91 cases per 100 cow years.

Fig. 1 gives an overview of the eligibility criteria and their effects on the number of observations and the steps of analysis. A retrospective study was conducted using data from DelPro management systems (DeLaval International AB, Tumba, Sweden), stored in a central DeLaval database. The data was retrieved from 5 Canadian, 3 American, 1 Argentinian, 1 Italian, and 3 Dutch herds. The dataset contained AMS data, information on whether milk was diverted from the bulk tank, and farmer-detected and -registered clinical mastitis. The herds were managed using a VMS series AMS (DeLaval International AB, Tumba, Sweden). Cows were eligible to be included when at least 20 days of milk production observations were available from 21–50 DIM (reducing the dataset from 7,669 cow lactations to 4,624 cow lactations). The time period of the selected data was herd specific and was chosen to range from 15 days before the first RCM case until 15 days after the last RCM case, as farms in the dataset started to report clinical mastitis at different points in time (starting from 10 July 2018 to 28 August 2018, reducing the dataset from 4,624 cow lactations to 3,451 cow lactations). When a

Table 1
The number of milking days, number of lactations, mean diversion-day share, number of diversion days, incidence of reported clinical mastitis, number of clinical mastitis cases reported, mean daily milk yield, and average lactation number in each herd.

Herd number	Number of observations (milking days)	Number of lactations	Mean diversion days per day	Number of diversion days	Incidence CM [a] (cases/100 cow years)	Number of CM cases	Mean daily milk yield	Average lactation number
1	117,442	877	0.02	2,125	13.99	45	31.12	2.39
2	28,478	186	0.06	1,597	60.24	47	25.57	2.32
3	44,875	330	0.03	1,242	23.59	29	40.16	2.07
4	20,286	109	0.03	618	55.78	31	33.62	2.26
5	26,514	179	0.07	1,836	81.22	59	35.68	2.74
6	88,040	573	0.06	5,139	12.02	29	35.81	2.36
7	53,403	331	0.01	586	25.29	37	42.01	2.50
8	36,281	208	0.03	1,011	53.32	53	34.78	2.30
9	25,011	187	0.03	746	32.11	22	39.67	2.17
10	9,690	73	0.03	281	37.67	10	31.50	2.30
11	21,238	146	0.02	476	20.62	12	30.29	3.39
12	20,798	146	0.01	287	33.34	19	29.65	2.68
13	15,887	98	0.02	309	43.65	19	34.52	2.55
Mean	39,072.54	264.85	0.03	1,250.23	37.91	31.69	34.18	2.46
Std.dev.	31,171.52	227.00	0.02	1,318.34	20.26	15.62	4.65	0.34
Min.	9,690	73	0.01	281	12.02	10	25.57	2.07
Max.	117,442	877	0.07	5,139	81.22	59	42.01	3.39

[a] CM = farmer-reported clinical mastitis.

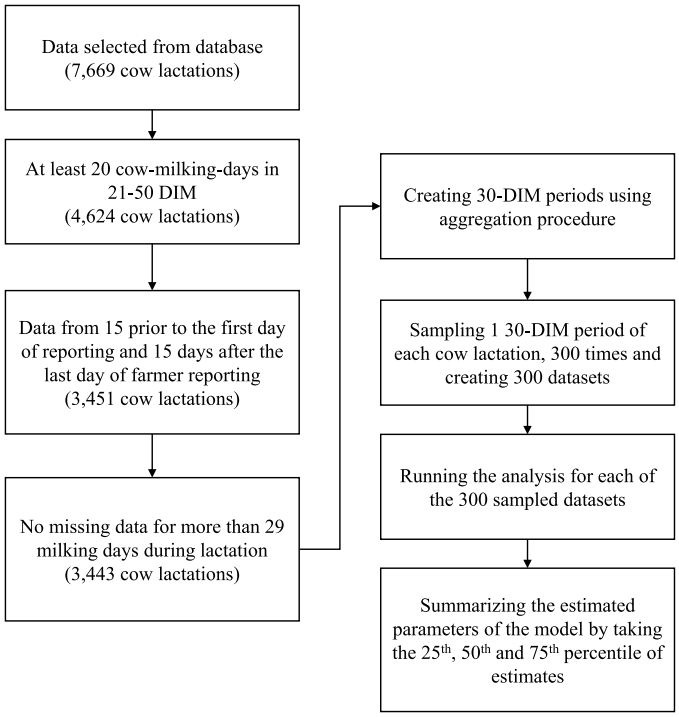

Fig. 1. A flow diagram displaying the number of cow lactations resulting from the eligibility criteria in the study together with an overview of further analysis steps in the study.

Table 2
Words used to identify clinical mastitis reports and other cow's treatments (subclinical mastitis, dry cow treatments, preventive treatments).

Case reported	Words
Clinical mastitis	masti, flock, mammite, mamitte, mastit, coli, staph, vlok, strep, aureus, hard, flok, clot, swollen, grum, enflure, blood, sang, arcanobact, entero, lait texture anormal, positif, enflé, rosee, moins beau, mamite, open, tube, ambiental, tacto, tactar, pomo, texture bizarre
Other treatments	sub, no, vac, lysigin, idocolina, estreptopendiben, hardware, négatif, feet, foot, leg, eye, breath, DCT, dry cow, velage, sabot

Table 3
A conceptual overview of the cross-tabulation of the 4 possible outcomes

	Milk diversion positive	Milk diversion negative
Farmer-reported clinical case positive	A	B
Farmer-reported clinical case negative	C	D

Table 4
Medians of the 5%, 50%, and 95% percentile of the 300 fitted models for the different prevalence parameters of population 1 (cows with lower milk production) and population 2 (cows with higher milk production) in the model for differing milk-diversion-day thresholds and differing priors reflecting poor farmer clinical mastitis reporting (mode of sensitivity 51% and mode of specificity 99%) and good farmer clinical mastitis reporting (mode of sensitivity 90% and mode of specificity 99%).

Milk-diversion-day threshold	Prevalence population 1	Prevalence population 2
Set of models assuming poor clinical mastitis reporting quality		
DIV[a] ≥ 1	0.011 | 0.019 | 0.028	0.022 | 0.031 | 0.040
DIV ≥ 2	0.011 | 0.020 | 0.028	0.022 | 0.032 | 0.040
DIV ≥ 3	0.011 | 0.019 | 0.028	0.021 | 0.030 | 0.039
DIV ≥ 4	0.010 | 0.019 | 0.027	0.020 | 0.029 | 0.038
DIV ≥ 5	0.009 | 0.018 | 0.026	0.019 | 0.028 | 0.037
DIV ≥ 6	0.009 | 0.017 | 0.025	0.019 | 0.028 | 0.036
DIV ≥ 7	0.008 | 0.016 | 0.024	0.019 | 0.027 | 0.035
DIV ≥ 8	0.008 | 0.015 | 0.023	0.019 | 0.026 | 0.035
DIV ≥ 9	0.009 | 0.016 | 0.023	0.019 | 0.027 | 0.035
DIV ≥ 10	0.008 | 0.015 | 0.022	0.020 | 0.028 | 0.036
Set of models assuming good clinical mastitis reporting quality		
DIV ≥ 1	0.005 | 0.010 | 0.014	0.013 | 0.018 | 0.023
DIV ≥ 2	0.005 | 0.010 | 0.014	0.013 | 0.019 | 0.023
DIV ≥ 3	0.005 | 0.010 | 0.014	0.013 | 0.018 | 0.023
DIV ≥ 4	0.005 | 0.009 | 0.014	0.012 | 0.018 | 0.022
DIV ≥ 5	0.005 | 0.009 | 0.013	0.012 | 0.017 | 0.022
DIV ≥ 6	0.005 | 0.009 | 0.013	0.012 | 0.017 | 0.022
DIV ≥ 7	0.005 | 0.008 | 0.013	0.012 | 0.016 | 0.021
DIV ≥ 8	0.004 | 0.008 | 0.013	0.012 | 0.016 | 0.021
DIV ≥ 9	0.005 | 0.009 | 0.013	0.013 | 0.017 | 0.021
DIV ≥ 10	0.005 | 0.008 | 0.012	0.013 | 0.017 | 0.022

[a] DIV = milk-diversion-day threshold in number of days when milk was diverted from the bulk tank.

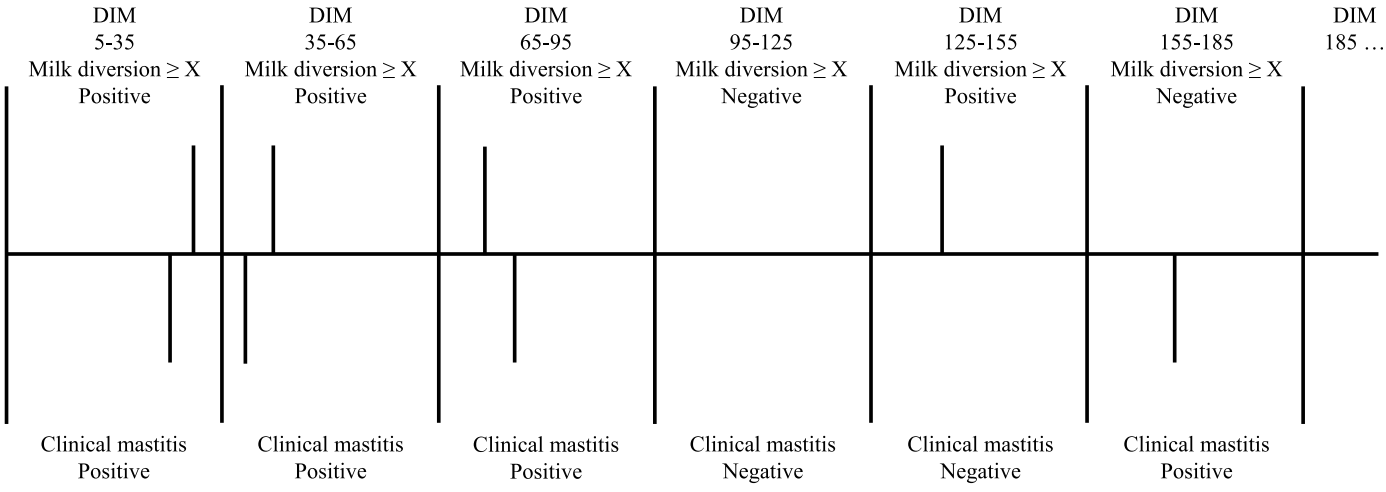

Fig. 2. Illustration of the aggregation procedure used to align milk diversions with reported clinical mastitis cases as indicated by a time series divided into 30-day observation time units, with black vertical lines above the central line (i.e. milk diversion higher than milk-diversion-day threshold X within the 30-day observation time unit) and black vertical lines below the central line (i.e. reported clinical mastitis case within the 30-day observation time unit).

Table 5
Medians of the 5%, 50%, and 95% percentile of the 300 fitted models for the different parameters in the model at differing milk-diversion-day thresholds and for differing priors reflecting poor farmer clinical mastitis reporting (mode of sensitivity 51% and mode of specificity 99%) and good farmer clinical mastitis reporting (mode of sensitivity 90% and mode of specificity 99%).

Milk-diversion-day threshold	Se_{MD} [b]	Se_{RCM} [c]	Sp_{MD} [d]	Sp_{RCM} [e]	Covariance sensitivity	Covariance specificity
Set of models assuming poor clinical mastitis reporting quality						
DIV[a] ≥ 1	0.542 | 0.687 | 0.830	0.470 | 0.503 | 0.536	0.903 | 0.909 | 0.916	0.988 | 0.993 | 0.996	0.033 | 0.087 | 0.152	0.002 | 0.005 | 0.009
DIV ≥ 2	0.538 | 0.680 | 0.823	0.470 | 0.503 | 0.536	0.949 | 0.956 | 0.962	0.988 | 0.993 | 0.997	0.033 | 0.085 | 0.149	0.002 | 0.005 | 0.009
DIV ≥ 3	0.522 | 0.656 | 0.809	0.471 | 0.504 | 0.537	0.959 | 0.965 | 0.972	0.988 | 0.993 | 0.996	0.036 | 0.091 | 0.154	0.002 | 0.005 | 0.010
DIV ≥ 4	0.490 | 0.623 | 0.779	0.470 | 0.504 | 0.536	0.963 | 0.969 | 0.975	0.988 | 0.992 | 0.996	0.037 | 0.091 | 0.148	0.002 | 0.006 | 0.010
DIV ≥ 5	0.449 | 0.578 | 0.734	0.470 | 0.504 | 0.536	0.968 | 0.974 | 0.980	0.987 | 0.992 | 0.996	0.038 | 0.088 | 0.143	0.002 | 0.006 | 0.010
DIV ≥ 6	0.404 | 0.532 | 0.694	0.470 | 0.503 | 0.537	0.971 | 0.976 | 0.982	0.987 | 0.991 | 0.995	0.038 | 0.088 | 0.139	0.002 | 0.006 | 0.010
DIV ≥ 7	0.327 | 0.448 | 0.596	0.470 | 0.504 | 0.537	0.973 | 0.978 | 0.983	0.987 | 0.991 | 0.994	0.032 | 0.073 | 0.121	0.002 | 0.006 | 0.009
DIV ≥ 8	0.275 | 0.392 | 0.553	0.470 | 0.504 | 0.537	0.976 | 0.981 | 0.985	0.987 | 0.990 | 0.994	0.028 | 0.065 | 0.111	0.002 | 0.006 | 0.009
DIV ≥ 9	0.232 | 0.343 | 0.488	0.471 | 0.504 | 0.537	0.980 | 0.984 | 0.988	0.987 | 0.990 | 0.994	0.025 | 0.059 | 0.099	0.002 | 0.005 | 0.008
DIV ≥ 10	0.156 | 0.262 | 0.397	0.470 | 0.503 | 0.536	0.983 | 0.986 | 0.990	0.987 | 0.990 | 0.993	0.018 | 0.044 | 0.078	0.002 | 0.005 | 0.007
Set of models assuming good clinical mastitis reporting quality						
DIV ≥ 1	0.766 | 0.843 | 0.910	0.872 | 0.893 | 0.912	0.900 | 0.905 | 0.910	0.988 | 0.993 | 0.996	0.015 | 0.034 | 0.057	0.002 | 0.005 | 0.009
DIV ≥ 2	0.761 | 0.839 | 0.909	0.872 | 0.893 | 0.912	0.946 | 0.951 | 0.955	0.988 | 0.993 | 0.996	0.014 | 0.033 | 0.056	0.002 | 0.005 | 0.010
DIV ≥ 3	0.746 | 0.829 | 0.900	0.872 | 0.893 | 0.912	0.956 | 0.961 | 0.965	0.988 | 0.993 | 0.996	0.015 | 0.034 | 0.056	0.002 | 0.005 | 0.010
DIV ≥ 4	0.699 | 0.793 | 0.871	0.872 | 0.893 | 0.912	0.961 | 0.965 | 0.969	0.987 | 0.992 | 0.996	0.015 | 0.033 | 0.055	0.002 | 0.006 | 0.010
DIV ≥ 5	0.646 | 0.748 | 0.836	0.873 | 0.894 | 0.912	0.966 | 0.970 | 0.974	0.987 | 0.991 | 0.995	0.014 | 0.032 | 0.052	0.002 | 0.006 | 0.010
DIV ≥ 6	0.580 | 0.696 | 0.791	0.873 | 0.894 | 0.913	0.969 | 0.973 | 0.977	0.987 | 0.991 | 0.995	0.014 | 0.030 | 0.050	0.002 | 0.006 | 0.010
DIV ≥ 7	0.457 | 0.594 | 0.710	0.873 | 0.894 | 0.913	0.972 | 0.976 | 0.980	0.987 | 0.991 | 0.995	0.011 | 0.025 | 0.043	0.003 | 0.006 | 0.009
DIV ≥ 8	0.394 | 0.529 | 0.645	0.873 | 0.894 | 0.913	0.975 | 0.979 | 0.982	0.987 | 0.991 | 0.994	0.010 | 0.023 | 0.039	0.003 | 0.006 | 0.009
DIV ≥ 9	0.331 | 0.464 | 0.584	0.873 | 0.894 | 0.913	0.979 | 0.982 | 0.985	0.988 | 0.991 | 0.995	0.008 | 0.020 | 0.035	0.002 | 0.005 | 0.007
DIV ≥ 10	0.210 | 0.343 | 0.469	0.873 | 0.894 | 0.913	0.982 | 0.985 | 0.987	0.988 | 0.991 | 0.994	0.006 | 0.014 | 0.027	0.002 | 0.005 | 0.007

[a] DIV = milk-diversion-day threshold in number of days when milk was diverted from the bulk tank;
[b] Se_{MD} = sensitivity, milk diversion;
[c] Se_{RCM} = sensitivity, reported clinical mastitis;
[d] Sp_{MD} = specificity milk diversion;
[e] Sp_{RCM} = specificity reported clinical mastitis.

gap of 30 milking days or more occurred within a lactation, we removed the rest of the lactation (reducing the dataset from 3,451 cow lactations to 3,443 cow lactations). The resulting dataset had records from 27 June 2018 until 25 July 2019. From every lactation, we removed the first 5 DIM, as such milk is usually not used for consumption and data before 5 DIM were also mostly unavailable. Missing daily observations occurred when a cow did not visit the AMS on a specific day. Missing values were regarded as diversions when the last known value was a milk diversion and the next known value was also a milk diversion, and as non-diverted otherwise.

2.2. Test methods and case identification

The first test method is RCM in which farmers actively reported clinical mastitis in their management system. To identify RCM cases, search queries were specified to collect cases in the DelPro database. A case of mastitis was reported as clinical mastitis, mastitis, or signs of mastitis (e.g. flocks or clots in the milk). A case of RCM was considered as either when directly reported as clinical mastitis by the farmer or when the case was not specifically indicated by the farmer as clinical mastitis but the farmer's remarks contained any of the words or parts thereof in Table 2 for a cow.

Each unique farmers' remark was manually screened and translated to English using translation software (Google Translate) when we constructed the queries. From the resulting management program records, we excluded the treatment of subclinical mastitis or treatments without any reported clinical mastitis or signs of mastitis from the results of the query above. We also excluded registrations with remarks indicating dry cow treatments, preventive treatments such as vaccinations, or other diseases using the other treatments in Table 2.

The resulting reported clinical mastitis cases were regarded as separate episodes when there was an interval of at least 8 days between two clinical mastitis observations (International Dairy Federation, 2011).

The second test method was milk diversion in which milk was diverted from the bulk tank with consumable milk for multiple consecutive days. Identifying a milk diversion case, 10 different thresholds for the duration of a milk diversion episode were applied, i.e. with thresholds ranging from 1 or more milk diversion days to 10 or more milk diversion days, as we determined that 90% of the milk

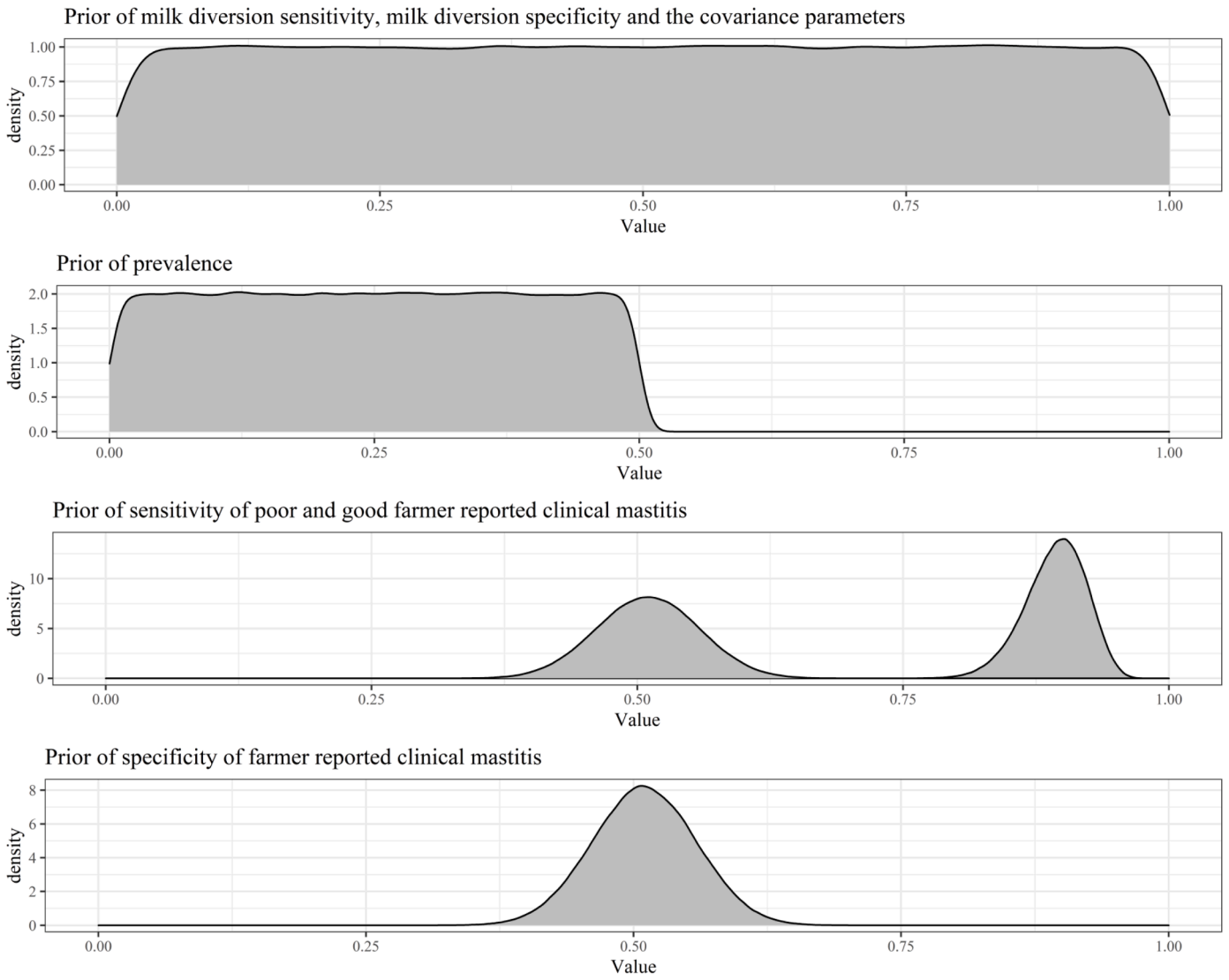

Fig. A1. Graphs indicating the form of the prior distributions for all the parameters in models as used in this study.

diversion periods were equal to or shorter than 10 days and we wanted to include every possible threshold.

Next, an aggregation procedure, shown in Fig. 2, was applied to align in time the classification of the milk diversion variable and the farmer-RCM case variable, because a milk diversion could have occurred earlier or later than the clinical mastitis registration. To account for differences in DIM between the milk diversion episode and the RCM case, individual cow milkings during a lactation were grouped into observation time units of 30 DIM (i.e. 5–35, 35–65, 65–95, and so forth up to 315 DIM). For each 30-day observation time unit, when 10 or more milkings were recorded, it was noted whether there was a recorded clinical mastitis case as well as a start of a milk diversion episode. The minimum number of milkings within the 30-day observation time units was chosen due to the maximum milk diversion threshold of 10 days or more.

2.3. Analysis

Using the collected data, the diagnostic properties of milk diversion and reported cases of clinical mastitis were evaluated using Bayesian latent class analysis. We used a two-test multiple-population model (Hui and Walter, 1980) for each milk diversion threshold. To obtain sub-populations, we divided the data into two equally sized subpopulations using the median of mean daily milk yield of each lactation during 21–50 DIM of the cow. The milk yield variable was chosen as differences in clinical mastitis incidence can be expected between cows with high versus low milk yields, as a high milk yield is a risk factor for clinical mastitis (Barnouin et al., 2005; Suriyasathaporn et al., 2000; Waage et al., 1998). Furthermore, higher parity cows tend to have higher milk production and a higher parity is also a cow risk factor for clinical mastitis incidence (Steeneveld et al., 2008).

It was not possible to include all 30-DIM windows in one analysis because of autocorrelation between the periods belonging to the same lactation could occur and bias our estimates of the diagnostic properties. Instead, we randomly sampled 1 30-DIM window from each lactation to include in the analysis.

During preliminary analysis, we found that the estimated specificity and sensitivity parameters differed widely between the different Bayesian Latent Class Analysis models when we fitted the models on different randomly sampled datasets. This was due to a limited number of cases of milk diversion negative–reported clinical positive cases (B in Table 3 that indicates the cross tabulation) in the dataset. Therefore, the effect on the estimated parameters could be sizable when we randomly sampled 30d periods and this explained the variation in estimated parameters. Randomly sampling a large number of times would allow us to incorporate the uncertainty of artificially sampling lactations, attain more robust results, and give insight into the overall distribution of the

Table B1
Twenty-fifth percentile of the 5%, 50%, and 95% percentile of the 300 fitted models for the different prevalence parameters of population 1 (cows with lower milk production) and population 2 (cows with higher milk production) in the model for differing milk-diversion-day thresholds and differing priors reflecting poor farmer clinical mastitis reporting (mode of sensitivity 51% and mode of specificity 99%) and good farmer clinical mastitis reporting (mode of sensitivity 90% and mode of specificity 99%).

Milk-diversion-day threshold	Prevalence population 1	Prevalence population 2
Set of models assuming poor clinical mastitis reporting quality		
DIV[a] ≥ 1	0.009 | 0.017 | 0.025	0.018 | 0.028 | 0.036
DIV ≥ 2	0.009 | 0.017 | 0.025	0.018 | 0.028 | 0.036
DIV ≥ 3	0.009 | 0.017 | 0.025	0.017 | 0.027 | 0.036
DIV ≥ 4	0.007 | 0.016 | 0.024	0.017 | 0.026 | 0.034
DIV ≥ 5	0.007 | 0.014 | 0.022	0.016 | 0.025 | 0.033
DIV ≥ 6	0.007 | 0.014 | 0.022	0.016 | 0.024 | 0.033
DIV ≥ 7	0.006 | 0.013 | 0.021	0.016 | 0.023 | 0.032
DIV ≥ 8	0.006 | 0.012 | 0.020	0.015 | 0.023 | 0.031
DIV ≥ 9	0.007 | 0.013 | 0.020	0.015 | 0.023 | 0.031
DIV ≥ 10	0.007 | 0.012 | 0.019	0.015 | 0.023 | 0.032
Set of models assuming good clinical mastitis reporting quality		
DIV ≥ 1	0.004 | 0.009 | 0.013	0.010 | 0.016 | 0.021
DIV ≥ 2	0.004 | 0.009 | 0.013	0.010 | 0.016 | 0.021
DIV ≥ 3	0.004 | 0.009 | 0.013	0.010 | 0.016 | 0.021
DIV ≥ 4	0.004 | 0.008 | 0.012	0.010 | 0.015 | 0.020
DIV ≥ 5	0.003 | 0.007 | 0.012	0.010 | 0.015 | 0.020
DIV ≥ 6	0.004 | 0.007 | 0.012	0.010 | 0.015 | 0.020
DIV ≥ 7	0.003 | 0.007 | 0.011	0.010 | 0.014 | 0.019
DIV ≥ 8	0.003 | 0.007 | 0.011	0.010 | 0.014 | 0.019
DIV ≥ 9	0.004 | 0.007 | 0.011	0.010 | 0.015 | 0.019
DIV ≥ 10	0.004 | 0.007 | 0.010	0.010 | 0.015 | 0.020

[a] DIV = milk-diversion-day threshold in number of days when milk was diverted from the bulk tank.

sensitivity and specificity parameters. Therefore, we created 300 randomly sampled datasets. To check whether this was sufficient, we compared it to the model results at 200 randomly sampled datasets and determined that the differences in estimated median sensitivity and specificity parameters between the 200 and 300 fits were less than 0.02 for all milk diversion thresholds and 2 prior groups.

Furthermore, we used a model in which the milk diversion and reported cases of clinical mastitis were conditionally dependent. In a standard Bayesian latent class analysis, conditional independence is assumed (Kostoulas et al., 2017), which would mean that the farmer was no more likely to divert milk when the farmer-RCM, and vice versa, regardless of whether the cow actually suffered from clinical mastitis. This is unrealistic, as both milk diversion and RCM rely on the same mechanism for the detection of clinical mastitis.

The model used a cross-tabulation (see Table 3) as a basis for each of the two milk production subpopulations.

Each outcome combination (A, B, C, D) was modelled using a multinomial distribution with four possible outcomes, with four separate probabilities ($P_{i,a}$, $P_{i,b}$, $P_{i,c}$, $P_{i,d}$). These probabilities were specific to each population i (two milk production groups) and were functions of population-specific prevalence (the proportion of the positive samples in the total population) parameters, sensitivity (the proportion of the rightly identified positive samples in the total number of positive samples) parameters of recorded clinical mastitis cases (Se_{RCM}) and milk diversion (Se_{MD}), and specificity (the proportion of the rightly identified negative samples in the total number of negative samples) parameters of recorded clinical mastitis cases (Sp_{RCM}) and milk diversion (Sp_{MD}). The associations between sensitivity and specificity parameters were estimated by fitting two covariance parameters (covSE and covSP) and specifying the association between the sensitivities and the specificities, in accordance with the fixed-effects model described by Dendukuri and Joseph (2001). The exact model is defined below:

$$P_{i,a} = prevalence_i * (SE_{MD} * SE_{RCM} + covSE) + (1 - prevalence_i) * ((1 - SP_{MD}) * (1 - SP_{RCM}) + covSP) \quad (1)$$

$$P_{i,b} = prevalence_i * (SE_{MD} * (1 - SE_{RCM}) - covSE) + (1 - prevalence_i) * ((1 - SP_{MD}) * SP_{RCM} - covSP) \quad (2)$$

$$P_{i,c} = prevalence_i * ((1 - SE_{MD}) * SE_{RCM} - covSE) + (1 - prevalence_i) * (SP_{MD} * (1 - SP_{RCM}) - covSP) \quad (3)$$

$$P_{i,\,d} = prevalence_i * ((1 - SE_{MD}) * (1 - SE_{RCM}) + covSE) + (1 - prevalence_i) * (SP_{MD} * SP_{RCM} + covSP) \quad (4)$$

Furthermore, the covariance parameters were constrained as follows:

$$0 \leq covSE \leq \min(SE_{MD}, SE_{RCM}) - SE_{MD} * SE_{RCM} \quad (5)$$

$$0 \leq covSP \leq \min(SP_{MD}, SP_{RCM}) - SP_{MD} * SP_{RCM} \quad (6)$$

The constraints in (5) and (6) were implemented to ensure that $SE_{MD} * SE_{RCM} + covSE$ and $SP_{MD} * SP_{RCM} + covSP$ could not be higher than SE_{MD}, SE_{RCM} and SP_{MD}, SP_{RCM} individually. The reason for these constraints is that multiplying sensitivities or specificities, which are essentially probabilities, would create joint probabilities that could not be higher than the probabilities of the events separately (e.g. the probability that the farmer-reported status and the milk diversion indicator are both correct cannot exceed the probability that the farmer-reported status is correct). This constraint was imposed by estimating a transformed covariance parameter (transformed covSE, covSP) taking values from 0 to 1 using a beta(1; 1) distribution and multiplying this by the upper bound of the constraints described above to form covSE and covSP, which were used in (1), (2), (3), and (4).

Bayesian statistics necessitates the use of prior distributions for all parameters. Moreover, the conditionally dependent model implies that informative priors for the sensitivity and specificity of one of either milk diversion or RCM are required (Branscum et al., 2005). The models were fitted using non-informative priors, namely, beta(1; 1) for milk diversion sensitivity, milk diversion specificity, and the transformed covariance parameters between the sensitivities and specificities of milk diversion and recorded clinical mastitis cases. These priors were chosen as we had

Table B2
Twenty-fifth percentile of the 5%, 50%, and 95% percentile of the 300 fitted models for the different parameters in the model at differing milk-diversion-day thresholds and for differing priors reflecting poor farmer clinical mastitis reporting (mode of sensitivity 51% and mode of specificity 99%) and good farmer clinical mastitis reporting (mode of sensitivity 90% and mode of specificity 99%).

Milk-diversion-day threshold	Se_{MD} [b]	Se_{RCM} [c]	Sp_{MD} [d]	Sp_{RCM} [e]	Covariance sensitivity	Covariance specificity
Set of models assuming poor clinical mastitis reporting quality						
DIV[a] ≥ 1	0.511 | 0.643 | 0.794	0.468 | 0.501 | 0.534	0.900 | 0.907 | 0.913	0.987 | 0.992 | 0.996	0.025 | 0.071 | 0.136	0.001 | 0.004 | 0.008
DIV ≥ 2	0.506 | 0.631 | 0.784	0.468 | 0.501 | 0.534	0.947 | 0.954 | 0.960	0.987 | 0.992 | 0.996	0.026 | 0.072 | 0.135	0.002 | 0.004 | 0.008
DIV ≥ 3	0.486 | 0.609 | 0.764	0.468 | 0.501 | 0.534	0.957 | 0.963 | 0.970	0.987 | 0.992 | 0.996	0.027 | 0.074 | 0.136	0.002 | 0.004 | 0.008
DIV ≥ 4	0.447 | 0.566 | 0.724	0.468 | 0.501 | 0.535	0.961 | 0.967 | 0.973	0.986 | 0.991 | 0.995	0.028 | 0.074 | 0.134	0.002 | 0.005 | 0.009
DIV ≥ 5	0.399 | 0.521 | 0.673	0.469 | 0.502 | 0.535	0.965 | 0.971 | 0.977	0.986 | 0.991 | 0.995	0.029 | 0.074 | 0.130	0.002 | 0.005 | 0.009
DIV ≥ 6	0.352 | 0.457 | 0.599	0.469 | 0.502 | 0.535	0.969 | 0.975 | 0.980	0.986 | 0.990 | 0.994	0.029 | 0.072 | 0.125	0.002 | 0.005 | 0.008
DIV ≥ 7	0.258 | 0.366 | 0.493	0.468 | 0.501 | 0.534	0.971 | 0.976 | 0.981	0.986 | 0.990 | 0.993	0.026 | 0.064 | 0.110	0.002 | 0.005 | 0.008
DIV ≥ 8	0.206 | 0.314 | 0.441	0.468 | 0.501 | 0.534	0.974 | 0.978 | 0.983	0.986 | 0.989 | 0.993	0.022 | 0.055 | 0.098	0.002 | 0.005 | 0.008
DIV ≥ 9	0.167 | 0.262 | 0.382	0.469 | 0.501 | 0.535	0.978 | 0.982 | 0.986	0.986 | 0.989 | 0.993	0.020 | 0.050 | 0.087	0.002 | 0.004 | 0.007
DIV ≥ 10	0.099 | 0.182 | 0.282	0.469 | 0.502 | 0.535	0.981 | 0.984 | 0.988	0.986 | 0.989 | 0.992	0.014 | 0.035 | 0.065	0.002 | 0.004 | 0.006
Set of models assuming good clinical mastitis reporting quality						
DIV ≥ 1	0.726 | 0.812 | 0.885	0.871 | 0.892 | 0.911	0.897 | 0.902 | 0.907	0.986 | 0.992 | 0.996	0.013 | 0.032 | 0.055	0.001 | 0.004 | 0.008
DIV ≥ 2	0.719 | 0.805 | 0.881	0.871 | 0.892 | 0.911	0.944 | 0.949 | 0.953	0.987 | 0.992 | 0.996	0.013 | 0.032 | 0.055	0.002 | 0.004 | 0.008
DIV ≥ 3	0.706 | 0.797 | 0.873	0.871 | 0.893 | 0.911	0.954 | 0.959 | 0.963	0.987 | 0.992 | 0.996	0.014 | 0.032 | 0.055	0.002 | 0.004 | 0.008
DIV ≥ 4	0.635 | 0.751 | 0.836	0.872 | 0.893 | 0.912	0.958 | 0.963 | 0.967	0.986 | 0.991 | 0.995	0.014 | 0.031 | 0.052	0.002 | 0.005 | 0.009
DIV ≥ 5	0.566 | 0.696 | 0.797	0.872 | 0.893 | 0.912	0.964 | 0.968 | 0.972	0.986 | 0.990 | 0.995	0.013 | 0.029 | 0.049	0.002 | 0.005 | 0.009
DIV ≥ 6	0.508 | 0.644 | 0.743	0.873 | 0.893 | 0.912	0.968 | 0.972 | 0.976	0.986 | 0.990 | 0.995	0.012 | 0.028 | 0.046	0.002 | 0.005 | 0.008
DIV ≥ 7	0.380 | 0.528 | 0.642	0.873 | 0.894 | 0.912	0.970 | 0.974 | 0.978	0.986 | 0.990 | 0.994	0.010 | 0.022 | 0.039	0.002 | 0.005 | 0.008
DIV ≥ 8	0.303 | 0.456 | 0.575	0.873 | 0.894 | 0.912	0.974 | 0.977 | 0.980	0.986 | 0.990 | 0.994	0.008 | 0.019 | 0.034	0.002 | 0.005 | 0.008
DIV ≥ 9	0.251 | 0.391 | 0.510	0.873 | 0.894 | 0.912	0.978 | 0.981 | 0.984	0.986 | 0.990 | 0.994	0.007 | 0.016 | 0.030	0.002 | 0.004 | 0.007
DIV ≥ 10	0.153 | 0.273 | 0.385	0.873 | 0.894 | 0.912	0.981 | 0.983 | 0.986	0.987 | 0.990 | 0.993	0.004 | 0.011 | 0.022	0.002 | 0.004 | 0.006

[a] DIV = milk-diversion-day threshold in number of days when milk was diverted from the bulk tank;
[b] Se_{MD} = sensitivity, milk diversion;
[c] Se_{RCM} = sensitivity, reported clinical mastitis;
[d] Sp_{MD} = specificity milk diversion;
[e] Sp_{RCM} = specificity reported clinical mastitis.

Table B3
Seventy-fifth percentile of the 5%, 50%, and 95% percentile of the 300 fitted models for the different prevalence parameters of population 1 (cows with lower milk production) and population 2 (cows with higher milk production) in the model for differing milk-diversion-day thresholds and differing priors reflecting poor farmer clinical mastitis reporting (mode of sensitivity 51% and mode of specificity 99%) and good farmer clinical mastitis reporting (mode of sensitivity 90% and mode of specificity 99%).

Milk-diversion-day threshold	Prevalence population 1	Prevalence population 2
Set of models assuming poor clinical mastitis reporting quality		
DIV[a] ≥ 1	0.012 | 0.022 | 0.031	0.026 | 0.036 | 0.045
DIV ≥ 2	0.012 | 0.022 | 0.031	0.027 | 0.036 | 0.044
DIV ≥ 3	0.013 | 0.023 | 0.031	0.025 | 0.035 | 0.044
DIV ≥ 4	0.012 | 0.022 | 0.031	0.024 | 0.033 | 0.042
DIV ≥ 5	0.011 | 0.021 | 0.030	0.023 | 0.032 | 0.041
DIV ≥ 6	0.011 | 0.020 | 0.029	0.022 | 0.032 | 0.040
DIV ≥ 7	0.010 | 0.019 | 0.028	0.022 | 0.031 | 0.040
DIV ≥ 8	0.010 | 0.019 | 0.027	0.022 | 0.030 | 0.039
DIV ≥ 9	0.011 | 0.018 | 0.026	0.023 | 0.031 | 0.040
DIV ≥ 10	0.010 | 0.018 | 0.025	0.025 | 0.033 | 0.041
Set of models assuming good clinical mastitis reporting quality		
DIV ≥ 1	0.006 | 0.011 | 0.016	0.016 | 0.021 | 0.026
DIV ≥ 2	0.006 | 0.011 | 0.016	0.016 | 0.021 | 0.026
DIV ≥ 3	0.006 | 0.011 | 0.016	0.016 | 0.021 | 0.026
DIV ≥ 4	0.006 | 0.011 | 0.015	0.015 | 0.020 | 0.025
DIV ≥ 5	0.005 | 0.010 | 0.015	0.014 | 0.020 | 0.025
DIV ≥ 6	0.005 | 0.010 | 0.015	0.014 | 0.019 | 0.024
DIV ≥ 7	0.005 | 0.010 | 0.014	0.014 | 0.019 | 0.024
DIV ≥ 8	0.005 | 0.009 | 0.014	0.014 | 0.019 | 0.024
DIV ≥ 9	0.005 | 0.010 | 0.014	0.015 | 0.019 | 0.024
DIV ≥ 10	0.005 | 0.009 | 0.014	0.015 | 0.020 | 0.024

[a] DIV = milk-diversion-day threshold in number of days when milk was diverted from the bulk tank.

no prior information on the sensitivity and specificity of milk diversion or on the association between milk diversion and the reporting of clinical mastitis. For prevalence, we set a uniform prior that could contain values from 0 to 0.5 (uniform(0; 0.5)), as we assumed that the prevalence of clinical mastitis could not exceed 50%. This was done to avoid the label switching problem (Stephens, 2000), in which a healthy case would be defined as a positive case (i.e. the number 1) by the model rather than a positive case being defined as a clinical mastitis case, with this definition switching between runs. Such switching between runs leads to erroneous results. For the sensitivity and specificity of farmer-recorded clinical mastitis cases, we set informative priors. We used the epi.betabuster function of the epiR (Stevenson et al., 2013) in R 3.6.1 (R Core Team, 2018) to obtain parameters for these informative prior (beta) distributions using a mode and a probability that the parameter is higher or lower than a set value. Specifically, for the specificity of farmer-RCM, it was assumed that the farmer rarely misidentified a non-clinical mastitis case as a clinical case, since clinical mastitis is visible. As a result, the prior for the specificity of farmer-RCM was set to a mode of 99% and a confidence of 90% that the specificity would exceed 90%. This resulted in a beta(11.049;1.101505) distribution. For sensitivity, limited information is available on the diagnostic abilities of farmers to detect clinical mastitis. Due to the limited information on larger groups of people, we created two sets of models using two different sensitivity priors to reflect two scenarios (Wolff et al., 2012), scenario 1 is as a poor clinical mastitis reporting-quality, and scenario 2 is a good clinical mastitis reporting-quality. In a study of sensitivity in reporting clinical mastitis cases per Nordic country, Wolff et al. (2012) found that Finland had the lowest sensitivity of 0.51 (CI: 0.43–0.59) and Denmark had the highest sensitivity of 0.90 (CI: 0.87–0.93). For the set of models assuming poor clinical mastitis reporting quality, we assumed a mode of 51% and a confidence of 95% that the sensitivity would exceed 43%, in line with the reported sensitivity for Finland (Wolff et al., 2012). This resulted in a beta(53.82; 51.74863) distribution. For the set of models assuming good clinical mastitis reporting quality, we assumed a mode of 90% and a confidence of 95% that the sensitivity would exceed 87% (Wolff et al., 2012). This resulted in a beta(100; 12) distribution. All prior distributions are visualized in Appendix A. The posterior distributions of the sensitivity and specificity of both indicators at each threshold for milk diversion duration were estimated using Markov chain Monte Carlo methods.

The models (300 datasets times 10 milk diversion thresholds times 2 reporting quality scenarios = 6000 models) were estimated using JAGS (Plummer, 2003), with RJAGS (Plummer, 2013) as an interface with an adaptation phase of 5,000 samples and a burn-in of 100,000 samples without thinning. This number of samples for burn-in was chosen as a substantial number of models did not converge with lower burn-in. Thinning was not performed as it is not necessarily useful as we were not constrained by computer memory limitations (Link and Eaton, 2012). This number of samples for burn-in was chosen as a substantial number of models did not converge with lower burn-in. Next, 100,000 samples were drawn from each model. Two Markov chains were run for each model to determine whether both chains independently converged on the same distributions. This was checked by using the Gelman–Rubin convergence diagnostic (Gelman and Rubin, 1992) with a confidence interval of 0.95 where it was tracked when the diagnostic was equal or above 1.01. If this was the case for any of the 6000 models, this model was rerun with another random seed until it converged according to the Gelman–Rubin convergence diagnostic (Gelman and Rubin, 1992). This measure was chosen as it returns a single value that can be compared to a value (1.01) for each and it uses multiple independent chains to determine convergence and it is used by others in the context of Bayesian Latent Class analysis (Kostoulas et al., 2017; Mahmmod et al., 2013b, 2013a).

To summarize the results of the 300 models, we calculated the median (and the 25th and 75th percentiles in Appendix B) of summary statistics (the 95% credible interval and the median) of each model parameter in the 300 models and reported them as such in the Results section.

3. Results

Table 4 gives the median population-specific prevalence parameters of the 300 models at different thresholds for milk diversion duration and the two milk production level subpopulations. The estimated ("true") prevalence of clinical mastitis decreased when the milk-diversion-day threshold increased in all scenarios. Table 5 shows the median sensitivity and specificity of milk diversion and RCM of the 300 models, while the summary statistics of the 25th and 75th percentiles of the 300 models can be found in Appendix B. Se_{MD} generally decreased with increasing milk-diversion-day threshold in both poor and good clinical mastitis reporting-quality scenarios, while Sp_{MD} increased with an increasing milk-diversion-day threshold. Se_{MD} and Se_{RCM} were similar at 1–7 (50th percentile of Se_{MD} within 10% of Se_{RCM} or higher) milk diversion days in the poor reporting-quality scenario and at 1–4 milk diversion days in the good reporting-quality scenario. The 95% credible interval of Se_{MD} ranged from 0.542–0.830 to 0.156 - 0.397 in the poor clinical mastitis reporting quality models for the 1 or more milk diversion days and 10 or more milk diversion days threshold respectively, and from 0.766–0.910 to 0.210–0.469 in the good clinical mastitis reporting quality models. The 95% credible interval of Se_{RCM} ranged from 0.470–0.536 to 0.471–0.537 in the poor clinical mastitis reporting quality models and from 0.872–0.912 to 0.873–0.913 in the good clinical mastitis reporting quality models. At more than 4 and 7 milk diversion days, Se_{MD} decreased substantially for the good and poor reporting-quality scenarios. However, Sp_{MD} was low at thresholds shorter than 7 days of milk diversion relative to Sp_{MD} at higher thresholds. Sp_{MD} was not substantially greater than Sp_{RCM} at any milk-diversion-day threshold in any scenario, although Sp_{MD} did come relatively close to approximately 0.990 and close to Sp_{RCM} (50th percentile of Sp_{MD} in Table 5 was more than 98% at a milk-diversion-day threshold of 8 to 10 or more milk

Table B4
Seventy-fifth percentile of the 5%, 50%, and 95% percentile of the 300 fitted models for the different parameters in the model at differing milk-diversion-day thresholds and for differing priors reflecting poor farmer clinical mastitis reporting (mode of sensitivity 51% and mode of specificity 99%) and good farmer clinical mastitis reporting (mode of sensitivity 90% and mode of specificity 99%).

Milk-diversion-day threshold	Se_{MD} [b]	Se_{RCM} [c]	Sp_{MD} [d]	Sp_{RCM} [e]	Covariance sensitivity	Covariance specificity
Set of models assuming poor clinical mastitis reporting quality						
DIV[a] ≥ 1	0.578 | 0.730 | 0.864	0.471 | 0.504 | 0.537	0.905 | 0.912 | 0.919	0.990 | 0.994 | 0.997	0.045 | 0.108 | 0.168	0.002 | 0.005 | 0.010
DIV ≥ 2	0.575 | 0.726 | 0.859	0.472 | 0.505 | 0.538	0.951 | 0.957 | 0.964	0.990 | 0.994 | 0.997	0.045 | 0.108 | 0.169	0.002 | 0.006 | 0.010
DIV ≥ 3	0.562 | 0.706 | 0.843	0.473 | 0.506 | 0.539	0.961 | 0.967 | 0.974	0.989 | 0.994 | 0.997	0.050 | 0.115 | 0.171	0.002 | 0.006 | 0.011
DIV ≥ 4	0.529 | 0.676 | 0.821	0.472 | 0.505 | 0.538	0.965 | 0.971 | 0.978	0.989 | 0.993 | 0.996	0.050 | 0.114 | 0.165	0.002 | 0.007 | 0.011
DIV ≥ 5	0.499 | 0.642 | 0.793	0.472 | 0.505 | 0.538	0.969 | 0.975 | 0.982	0.988 | 0.993 | 0.996	0.052 | 0.111 | 0.160	0.003 | 0.007 | 0.011
DIV ≥ 6	0.448 | 0.586 | 0.757	0.472 | 0.506 | 0.539	0.973 | 0.978 | 0.984	0.988 | 0.992 | 0.996	0.053 | 0.107 | 0.153	0.003 | 0.007 | 0.011
DIV ≥ 7	0.375 | 0.514 | 0.703	0.472 | 0.505 | 0.538	0.975 | 0.980 | 0.985	0.988 | 0.992 | 0.995	0.044 | 0.093 | 0.136	0.003 | 0.007 | 0.010
DIV ≥ 8	0.329 | 0.457 | 0.661	0.472 | 0.505 | 0.538	0.978 | 0.983 | 0.987	0.988 | 0.991 | 0.995	0.039 | 0.083 | 0.124	0.003 | 0.007 | 0.010
DIV ≥ 9	0.285 | 0.409 | 0.614	0.472 | 0.505 | 0.538	0.981 | 0.985 | 0.990	0.988 | 0.991 | 0.995	0.034 | 0.072 | 0.111	0.003 | 0.006 | 0.009
DIV ≥ 10	0.201 | 0.320 | 0.570	0.472 | 0.505 | 0.538	0.984 | 0.988 | 0.991	0.988 | 0.991 | 0.994	0.022 | 0.052 | 0.088	0.003 | 0.006 | 0.008
Set of models assuming good clinical mastitis reporting quality						
DIV ≥ 1	0.806 | 0.871 | 0.930	0.872 | 0.893 | 0.912	0.903 | 0.908 | 0.912	0.990 | 0.994 | 0.997	0.016 | 0.035 | 0.058	0.002 | 0.006 | 0.010
DIV ≥ 2	0.797 | 0.868 | 0.928	0.872 | 0.893 | 0.912	0.948 | 0.953 | 0.957	0.990 | 0.994 | 0.997	0.016 | 0.035 | 0.058	0.002 | 0.006 | 0.011
DIV ≥ 3	0.789 | 0.859 | 0.921	0.873 | 0.894 | 0.912	0.959 | 0.963 | 0.967	0.990 | 0.994 | 0.997	0.016 | 0.036 | 0.058	0.002 | 0.007 | 0.011
DIV ≥ 4	0.750 | 0.828 | 0.902	0.873 | 0.894 | 0.913	0.963 | 0.967 | 0.971	0.989 | 0.993 | 0.996	0.016 | 0.035 | 0.057	0.003 | 0.007 | 0.012
DIV ≥ 5	0.697 | 0.790 | 0.873	0.873 | 0.894 | 0.913	0.968 | 0.972 | 0.975	0.989 | 0.993 | 0.996	0.016 | 0.034 | 0.055	0.003 | 0.008 | 0.012
DIV ≥ 6	0.640 | 0.741 | 0.839	0.874 | 0.894 | 0.913	0.971 | 0.975 | 0.979	0.989 | 0.992 | 0.996	0.015 | 0.032 | 0.053	0.003 | 0.007 | 0.011
DIV ≥ 7	0.534 | 0.653 | 0.759	0.874 | 0.894 | 0.913	0.974 | 0.977 | 0.981	0.988 | 0.992 | 0.995	0.013 | 0.028 | 0.047	0.003 | 0.007 | 0.010
DIV ≥ 8	0.469 | 0.595 | 0.708	0.874 | 0.895 | 0.913	0.977 | 0.980 | 0.983	0.989 | 0.992 | 0.995	0.012 | 0.026 | 0.044	0.004 | 0.007 | 0.010
DIV ≥ 9	0.400 | 0.524 | 0.651	0.874 | 0.894 | 0.913	0.981 | 0.983 | 0.986	0.989 | 0.992 | 0.995	0.010 | 0.023 | 0.039	0.003 | 0.006 | 0.009
DIV ≥ 10	0.278 | 0.409 | 0.534	0.874 | 0.894 | 0.913	0.984 | 0.986 | 0.988	0.989 | 0.992 | 0.995	0.007 | 0.017 | 0.031	0.004 | 0.006 | 0.008

[a] DIV = milk-diversion-day threshold in number of days when milk was diverted from the bulk tank;
[b] Se_{MD} = sensitivity, milk diversion;
[c] Se_{RCM} = sensitivity, reported clinical mastitis;
[d] Sp_{MD} = specificity milk diversion;
[e] Sp_{RCM} = specificity reported clinical mastitis.

diversion days and 9 to 10 or more milk diversion days for the poor and good mastitis reporting-quality scenarios, respectively). The 95% credible interval of Sp_{MD} in Table 5 ranged from 0.903-0.916 to 0.983–0.990 in the poor clinical mastitis reporting quality models, and from 0.900 - 0.910 to 0.982–0.987 in the good clinical mastitis reporting quality models. The 95% credible interval of Sp_{RCM} ranged from 0.987–0.993 to 0.988–0.996 in the poor clinical mastitis reporting quality models and from 0.987–0.994 to 0.988–0.996 in the good clinical mastitis reporting quality models. The covariance between Sp_{MD} and Sp_{RCM} did not differ substantially between all models. In contrast, the covariance between Se_{MD} and Se_{RCM} differed and was substantially greater in the poor reporting-quality scenario, both in median level as well as the variation indicated in the 95% credible interval. A high covariance between sensitivities indicates that farmers tended to divert milk when they reported clinical mastitis, and vice versa, regardless of whether the cow actually had mastitis. Furthermore, in both scenarios, the covariance between sensitivity parameters decreased when the milk-diversion-day threshold increased.

4. Discussion

To our knowledge, this is the first study investigating the accuracy of milk diversion as a mastitis indicator in relation to the accuracy of farmers' registration of clinical mastitis. Obtaining insight into the accuracy of milk diversion is useful as it is commonly available in AMS management software data and it could be an appropriate indicator of farmer-RCM cases, especially when there is no such data or data of low reporting quality. We used different thresholds on consecutive days of diverted milk and found that milk diversion is similar in sensitivity to farmer-RCM cases at a milk-diversion-day threshold duration of 1 to 4 days. However, at a milk-diversion-day threshold of 1 to 4 days, it can be questioned whether specificity is high enough to warrant the use of the threshold. A milk diversion specificity of more than 98% can be reached at a milk-diversion-day threshold of 8 to 10 or more milk diversion days and 9 to 10 or more milk diversion days for the poor and good mastitis reporting-quality scenarios, respectively. A high sensitivity of milk diversion relative to reported clinical cases can be reached at lower milk-diversion-day thresholds, but at the cost of lower specificity. There is, as always, a tradeoff between sensitivity and specificity when changing the

milk-diversion-day threshold. Generally, we saw adequate tradeoffs between specificity and sensitivity at a general threshold of 4 to 7 days, depending on the knowledge on the farmer recording ability.

Choosing an optimal milk-diversion-day threshold would depend on the usual length of treatment regimen and the aim of using milk diversion as a proxy for clinical mastitis. Some studies of extended intramammary treatment use treatment durations of 1.5–5 days (Swinkels et al., 2014) or 2–8 days (Oliver et al., 2004) without considering withdrawal time. In practice, antibiotic treatments of clinical mastitis cases are recommended to take longer than 3 days (Pyörälä, 2009) and, including withdrawal times, even longer milk-diversion-day thresholds could apply. In these cases, our found threshold of 4–7 days would be approximately in the range of the above treatment durations. However, these milk-diversion-day durations may also be regional or herd specific, depending on the recommendations for antibiotic usage. For example, differences between conventional and organic farms in terms of number of cases treated with antibiotics has been found in some countries (Bennedsgaard et al., 2003), but not in others (Fall and Emanuelson, 2009), which could also influence the milk-diversion-day threshold. Hence, the diagnostic properties of milk diversion to detect clinical mastitis at specific thresholds depend on the treatment regiments used, which may be farm specific. Future work could seek specific milk-diversion-duration thresholds for different farm types, times, or even types of uses.

Milk diversion will never be a perfect indicator of clinical mastitis as: 1) clinical mastitis observations do not always lead to treatments leading to milk diversion; 2) milk diversion may occur for other reasons than clinical mastitis (e.g. subclinical mastitis or other diseases); and 3) clinical mastitis is not always detected by farmers and thus may not be treated. Addressing the first point, it should be noted that most cows with registered (clinical) mastitis in the United States received antibiotic treatment (85.6%) (APHIS, 2016). As such, assuming that farmers follow milk withdrawal guidelines, milk diversion would work in most clinical cases. Addressing the second point, antibiotic treatments of other diseases in dairy cows during lactation are less frequent than treatments due to udder health, at least in Denmark, Sweden, and the Netherlands (Høg et al., 2019; Kuipers et al., 2016; Växa Sverige, 2020). Nonetheless, the relative proportions of treatments due to mastitis and due to other diseases are likely to differ between countries due to different farm practices. Nevertheless, the influence of other reasons for diverting milk may be limited. To address this, we have tried to implement a model with cohort-specific parameters (Bermingham et al., 2015) for the different countries in our data, but the model did not converge and we could not find more information to incorporate into our prior distributions to combat the lack of identifiability. Addressing the third point, milk diversion would only work when clinical mastitis is detected by the farmer. Clinical mastitis is not always detected because farmers may miss signs of clinical mastitis, although this seems rare when it comes to clots in the milk (Rasmussen, 2005). In AMS, clinical mastitis is not always detected because not all clinical mastitis cases lead to alerts and not all alerts are followed up by farmers, as illustrated by a study finding that only 3.5% of alerts were followed up by farmers (Hogeveen et al., 2013). Milk diversion, therefore, cannot be used to indicate undetected clinical mastitis, only observed but unreported clinical mastitis. These unreported cases might for instance occur when a cow is not treated for mastitis, but culled without a reported reason. In general, milk diversion or withdrawal is initiated in connection with the start of antibiotic treatment to avoid antibiotic residue in the bulk tank and, when clinical mastitis is treated, it is likely reported, as milk diversion is similar in sensitivity and specificity to the RCM status found here.

We used informative priors for the sensitivity and specificity of farmer-RCM and herd prevalence in our analyses, but weakly informative priors for all other parameters. The priors for farmer-recorded parameters was based on the sensitivity of farmer-RCM reported by Wolff et al. (2012) and was used to create two models with different assumptions as to farmer attitude toward detecting and reporting clinical mastitis when clinical mastitis can be observed. These priors may not have been correct for all regions, as the information for determining the priors came from countries not included in the dataset; we had no choice in this matter, as we were extremely limited in the available information about farmer attitude toward detecting and reporting clinical mastitis. Therefore, we used the lowest and highest sensitivity cases presented by Wolff et al. (2012) as the scenarios of the sensitivity of farmer-RCM to obtain an approximation of the diagnostic properties of RCM under two substantially different scenarios in the different countries.

Changing the priors for farmer-RCM affected all other parameters. This can be explained by the need to estimate 8 parameters (2 sensitivity, 2 specificity, 2 prevalence, and 2 covariance parameters) with 8 data points (4 possible test combinations for 2 populations), essentially forcing the model to estimate a relatively large number of parameters for a limited number of data points. The use of the conditionally dependent model increases the need for prior information (Branscum et al., 2005; Kostoulas et al., 2017) as it increases the number of parameters to be estimated. This is why two scenarios for the sensitivity of farmer-RCM were explored in this study. Examining two different scenarios could be helpful, as a researcher may have indications of the data quality of specific farms and could use them in determining the milk-diversion-day threshold. In both scenarios, milk diversion was on par with RCM cases in terms of sensitivity and worse in terms of specificity when using a milk-diversion-day threshold of 1–4 days when the farmer's quality of clinical mastitis case reporting was good. Consequently, milk diversion at specific milk-diversion-day thresholds is a relatively good indicator of clinical mastitis but not as specific as farmer-reported cases, regardless of the farmer's quality of clinical mastitis reporting.

We also assumed in our Bayesian latent class analysis that the high- and low-producing populations would have equal diagnostic properties in terms of sensitivities and specificities for diagnosing clinical mastitis. Implicitly, we assumed that farmers who primarily have high-producing cows would have diagnostic skills similar to those of farmers with low-producing cows and that farmers who have both high- and low-producing cows would not have any preferential diagnostic and recording bias towards high-producing cows. However, this may not be the case, as the difference in prevalence of clinical mastitis between high- and low-producing cows could partly be because farmers with higher-producing cows are more eager to treat and report clinical mastitis (Nyman et al., 2007). Many factors could play a role in the potential preferential diagnostic biases of farmers; however, research into differences in the diagnostic ability of farmers is limited. We did not encounter any research that quantified the factors that affect preferential diagnostic and treatment bias in clinical mastitis. We could not make any distinction based on a mastitis indicator (e.g. SCC), as farmers might not apply the same diagnostic properties across groups, as they might check cows with a high mastitis indicator more thoroughly than cows with a low mastitis indicator. The division could not be made on the herd level, as it can be expected that the farmers' skill levels might differ between herds. Division on the region level resulted in a very unequal distribution of cases between populations and was therefore undesirable. Hence, we assumed that there were no differences in diagnostic properties, at least globally, between our milk-yield groups. Nevertheless, further research is needed to determine the size of these biases in diagnosing clinical mastitis and, possibly, to change this view.

To remove autocorrelation, we randomly sampled one 30 DIM time period within each lactation, ran the analysis, and repeated these steps 300 times. It excluded multiple observations from the same cow and therefore removed the cow level autocorrelation. The cow level autocorrelation could occur when the farmer has observed clinical mastitis prior in the lactation. Once a farmer has observed clinical mastitis, the farmer will pay more attention to that cow and have a higher sensitivity in detecting a new case during the same lactation. To gather overall diagnostic properties, we have chosen to take a random sample for each lactation. An interesting alternative would be to focus on the first, second, and third cases during a lactation separately to determine whether

the diagnostic measures change. It is generally unknown how the diagnostic abilities of farmers change and this work would investigate whether clinical mastitis history is one of the factors that influence diagnostic ability. However, this was not the aim of this study, but it might be an interesting research avenue to pursue in the future.

The good diagnostic properties of milk diversion indicate that milk diversion at certain thresholds can be used to indicate the clinical mastitis status. More specifically, milk diversion could be useful when analyzing large databases. The current ways of conducting research on clinical mastitis are to: 1) create very small databases in which the researchers detect clinical mastitis cases themselves using very precise definitions; 2) carrying out larger studies in which farmers are asked to keep track of their mastitis detection results for a certain period, potentially based on instructions from the researcher; or 3) create large databases in which all veterinary treatments are stored (e.g. as has been done in the Scandinavian countries). Option one would be very time consuming and costly and is typically used when high precision is required. In option two, the farmers might forget to record all the cases they detected or, despite the instructions given them about the definition of clinical mastitis, might deviate in their actual reporting. In option three, the clinical mastitis data are not perfect as not all clinical cases would be treated and recorded. Using milk diversion, uniform estimates can be made over a large number of dairy farmers, routinely, without any interference. This would create novel opportunities for "big data"-based research or very specific farm-based research.

5. Conclusions

Milk diversion may serve as a reasonable indicator of the clinical mastitis status of a cow. Overall, we would recommend a milk-diversion-day threshold of 4–7 days, as it gave very similar or minimally poorer sensitivity and specificity compared with those of recorded mastitis cases. The threshold should be determined according to the aim for which milk diversion will be used, information on the farmers' reporting quality, and the used treatment regimens. Using milk diversion as an indicator of clinical mastitis could be valuable in several areas, including estimating herd incidence rates of mastitis, evaluating farmer reporting quality, and possibly as a label in clinical mastitis detection algorithms.

CRediT authorship contribution statement

John Bonestroo: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Visualization, Investigation, Validation, Writing – review & editing, Project administration. **Nils Fall:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Visualization, Investigation, Validation, Writing – review & editing, Project administration, Supervision. **Mariska van der Voort:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Visualization, Investigation, Validation, Writing – review & editing, Project administration, Supervision. **Ilka Christine Klaas:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Visualization, Investigation, Validation, Writing – review & editing, Project administration, Funding acquisition, Supervision. **Henk Hogeveen:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Visualization, Investigation, Validation, Writing – review & editing, Project administration, Funding acquisition, Supervision. **Ulf Emanuelson:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Visualization, Investigation, Validation, Writing – review & editing, Project administration, Funding acquisition, Supervision.

Declaration of Competing Interest

John Bonestroo and Ilka C. Klaas are employed by DeLaval International AB. Mariska van der Voort, Nils Fall, Ulf Emanuelson, and Henk Hogeveen have no conflict of interest to report.

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Appendix A. The prior distributions used in the Bayesian latent class analysis

Fig. A1.

Appendix B. The 25th and 75th percentile results of the model fits

Table B1, Table B2, Table B3, Table B4.

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