Associations between on-farm cow welfare indicators and productivity and profitability on Canadian dairies: II. On tiestall farms

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ABSTRACT

The use of tiestall housing for dairy cows is often criticized due to the reduced freedom of movement it offers for the animals. Maximizing comfort is especially important in tiestall farms to ensure an acceptable level of cow welfare. Motivating dairy producers to make financial investments directly aimed toward the improvement of their animals' welfare can be challenging, especially when financial returns are uncertain. The aim of this study was to evaluate the existence of associations between on-farm animal welfare and indicators of farm productivity and profitability in tiestall farms. The prevalence of animal-, resource-, and management-based welfare indicators was collected on 100 Canadian tiestall farms during a cow comfort study. Records from the dairy herd improvement agency were retrieved and used to calculate the farms' productivity and profitability measures. Univariable and multivariable linear regressions were used to assess the associations between welfare indicators and milk production, milk quality, cow longevity, and economic margins calculated over replacement costs. Increased yearly average corrected milk production was associated with longer average lying time [$\beta = 272$; 95% confidence interval (CI): 94, 450] and a higher proportion of cows fitting the tie-rail height ($\beta = 6$; 95% CI: 1, 11). Lower yearly average somatic cell count was associated with lower percentages of stalls mostly soiled with manure ($\beta = -3.7$; 95% CI: -1.9, -5.4) and a lower proportion of cows with body condition score ≤ 2 ($\beta = -5.1$; 95% CI: -2.3, -8.3). The average margin per cow over replacement costs was positively associated with average lying time ($\beta = 147$; 95% CI: 27, 267), percent of stall not soiled

with manure ($\beta = 7.2$; 95% CI: 3.0, 11.3), and the frequency of scheduled hoof trimming per year. Some of the relationships found included interactions between animal- and management-based welfare measures. For example, the relationship between lameness prevalence and average milk production was modified through the milk production genetic index. Overall, the results show that improved cow comfort and welfare on tiestall farms is associated with increased productivity, cow longevity, and profitability when estimated through margins calculated over the replacement costs. Producers should aim to optimize all aspects of stall comfort to enhance their cows' productivity.

Key words: productivity, profitability, welfare indicator, comfort, tiestall

INTRODUCTION

The use of tiestall housing for dairy cattle is still widespread across the world. Approximately 70% and 39% of dairy herds use this type of housing for their lactating cows in Canada and the United States, respectively (AAFC, 2016; USDA, 2016). However, the use of tiestalls is often questioned in terms of animal welfare due to the limited freedom of movement it provides to the animals, especially when they are not granted outdoor access (Vučemilo et al., 2012; Popescu et al., 2013). In this context, maximizing the animals' welfare, including stall comfort, is especially important to satisfy new industry standards and consumer concerns. Yet, a cow comfort study done on Canadian tiestall farms found that the majority of cows were housed in smaller stalls than recommended, which lead to increased odds of lesions and lameness (Bouffard et al., 2017). Because lameness is known to cause animals pain and distress, and a producer's ability to detect lame cows in tiestalls is reduced compared with other types of housing, good cow comfort in tiestalls is essential (Whay et al., 1998; Higginson Cutler et al., 2017). Therefore, finding ways to encourage and motivate tiestall dairy producers to make management decisions and financial investments

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directly aimed toward the improvement of their animals' comfort and welfare is necessary.

Studies and surveys have shown that animal welfare is a priority for dairy farmers, but recent Canadian research stated that a lack of funds and time were the 2 greatest obstacles preventing producers from making changes aimed specifically at improving animal welfare (Kauppinen et al., 2013; Hansson and Lagerkvist, 2016; Nash et al., 2018). To reduce the obstacles posed by a lack of funds, economic advantages arising from improved welfare and comfort are important. A premium could be paid for milk produced on farms with improved animal welfare, but this market is likely too small (Bennett et al., 2012; Christensen et al., 2012; Wolf et al., 2015). Therefore, it is important to know the potential effects of better on-farm animal welfare on the direct productivity and profitability of farms. Improved welfare may not only be associated with greater milk production but also with better cow longevity, which could mean greater profitability for the farm (Langford and Stott, 2012). The potential financial benefits from enhanced productivity and profitability could alleviate the obstacles posed by a lack of funds for tiestall dairy producers, and therefore motivate them to make the appropriate changes to their management and housing.

Very little information is currently available on the associations between cow welfare and farm productivity and profitability, especially in tiestall farms. We previously investigated the association between the results of a mandatory welfare assessment and herd productivity of a sample of tiestall farms (Villettaz Robichaud et al., 2018). Overall, the results indicated that meeting the benchmarks, such as the ones for lameness prevalence and appropriate placement of the electric trainers, during the on-farm assessment was partially associated with better herd productivity and farm profitability. However, these results also highlighted the limitations of using dichotomous thresholds for cow welfare indicators to determine their associations with herd performance. The success of a farm in terms of animal welfare was based on whether or not the thresholds set by the assessment scheme were met. However, many of the thresholds were met by either very few or almost all tiestall farms, which limited our ability to test them due to lack of variability in the data. To encourage tiestall dairy producers to prioritize animal welfare-oriented decisions, it is necessary to investigate the associations between the prevalence of on-farm animal welfare indicators and farm productivity and profitability. Our objective was to evaluate the associations between animal-, management-, and resource-based welfare indicators measured on a continuous basis with

farm productivity and profitability in Canadian tiestall dairies.

MATERIALS AND METHODS

The institutional research ethics boards and animal care committees of the Université Laval (Québec, Québec, Canada) and the University of Guelph (Guelph, Ontario, Canada) approved all procedures.

Herd and Animal Selection

This study was part of a larger Canadian study that investigated cow comfort on commercial dairy farms involving both tiestall and freestall farms. For this part of the study, a total of 100 tiestall dairy farms were visited between January 2011 and April 2012. These farms were situated in the highest milk producing provinces of Canada where tiestall housing is highly prevalent: Ontario ($n = 40$) and Québec ($n = 60$). The general characteristics of the farms are shown in Table 1. Participation in the study was voluntary, and to participate, the herds needed to meet several inclusion criteria: having a minimum of 40 Holstein cows in lactation, having an average milk production of $\geq 7,000$ kg per cow per year, and having used their current cow housing for at least 1 yr (Vasseur et al., 2015). The complete list of inclusion criteria is presented in detail in a companion publication related to the freestall farms involved in the larger cow comfort study (Villettaz Robichaud et al., 2019). Although the farms' selection process was not truly random due to the inclusion criteria, the final sample was representative of the Canadian tiestall dairy industry based on average milk production, herd size, and other farm characteristics (AAFC, 2016). Additionally, because both the animal welfare and productivity data were gathered at the same time, the lapse of time between data collection and analysis should not have influenced the results of this study.

Forty lactating cows were purposively selected on each farm for the animal-based data collection. The cows' selection was based on parity, with the proportion of primiparous cows in the sample reflecting the overall proportion in the herd, and DIM, with cows selected between 10 and 120 DIM, when possible. The overall average difference between the proportion of primiparous cows sampled (36%) and the actual proportion of primiparous cows (33%) in the respective herds was 3%. Because none of the farms included in the study had 40 cows between 10 and 120 DIM, the range was extended beyond 120 DIM until 40 cows were selected. The mean DIM of all the cows evaluated was

Table 1. Production characteristics and animal welfare indicators of the 100 tiestall dairy farms enrolled in Ontario and Québec, Canada

Item	n	Mean	SD
No. of milking cows	100	65	16
Milk production genetic index	100	165	197
Corrected milk production/yr, kg	100	9,160	926
SCC genetic rating	100	2.97	0.03
SCC/yr ($\times 1,000$)	99	246	91
Age at first calving, mo	100	26.5	1.7
Dry period length, d	100	70	16
Primiparous in lactation, %	99	32	7
Culling rate, ¹ %	100	34	10
Cows in 3+ lactation, %	100	40	9
Margin per cow, ² \$/yr	99	5,990	688
Margin per kg of quota, ² \$/yr	99	5,919	270
Cows with well-placed trainer, ³ %	100	96	8
Cows with hock lesion, ³ %	100	55	19
Cows with knee lesion, ³ %	100	43	22
Cows with neck lesion, ³ %	100	30	25
Cows with dirty flank, ³ %	100	10	12
Cows with dirty udder, ³ %	100	4	6
Cows with dirty leg, ³ %	100	4	6
Cows with BCS ≤ 2 , ³ %	100	4	5
Cows with BCS ≥ 4 , ³ %	100	1	3
Cows with docked tail, ³ %	99	3	13
Lameness prevalence, ³ %	100	24	15
Average lying time, ³ h	100	12.4	0.9
Average lying time SD, ³ min	100	145	22
Stalls with very wet bedding, %	100	4	9
Stalls mostly soiled with manure, %	100	2	8
Stalls not soiled with manure, %	100	50	27
Average chain length, cm	98	69	19
Cows fitting in the average stall width, ³ %	100	31	24
Cows fitting in the average bed length, ³ %	100	44	31
Cows fitting in the average tie rail height, ³ %	88	16	29

¹Culling for any other reasons than sold for milk production.

²Calculated on replacement costs.

³Estimated using the 40 cows per herd.

145 $\pm$ 96 (SD) d, thus providing a sample of every stage of lactation.

Data Collection and Handling

Each farm was visited by 2 trained observers ($n = 10$) to collect all the animal-, management-, and resource-based measures (Vasseur et al., 2013). Detailed standard protocols that included written descriptions and pictures were used to score lesions, cleanliness, BCS, lameness, and stall characteristics, to ensure high repeatability found between all observers (Gibbons et al., 2012; Vasseur et al., 2013; Nash et al., 2016). The standard protocols used to score lesions, cleanliness, BCS, and stall characteristics are explained in detail in the companion publication related to freestall farms (available at: <https://www.dairyresearch.ca/animal-comfort-tool.php>). Each farm's lameness prevalence was calculated using the in-stall lameness score assessed for the 40 selected cows. Individual video recordings were

taken for each animal and used a posteriori to score each animal using an in-stall lameness scoring method (Gibbons et al., 2014; Palacio et al., 2017). Briefly, the in-stall scoring method consisted of evaluating the presence or absence of 4 indicators of lameness: when the cow voluntarily took a standing pose, weight shifting from one foot to another, uneven weight bearing, and standing on the edge of the stall. When the cow was moved from side to side, the presence or absence of uneven movement was evaluated. If 2 or more indicators were present, the animal was considered lame (Leach et al., 2009; Palacio et al., 2017). Lying behavior of the selected cows was recorded using Hobo G Acceleration loggers (Hobo Pendant G Acceleration Data Logger, Onset Computer Corp., Pocasset, MA) fitted to one of their hind legs using CoFlex bandage wrap (CoFlex, Andover Coated Products Inc., Salisbury, MA) and programmed to record the cows' position at 1-min intervals for 4 d (Ito et al., 2009; Ledgerwood et al., 2010; Vasseur et al., 2012). The SD of the average lying time

within each farm was calculated using the SD for the 4 d average lying time of the individual selected cows.

For each farm, resource- and management-based measures were collected using a questionnaire administered by a trained observer during the farm visits, in-barn measures, and DHIA data. The questionnaire contained 68 questions covering a wide variety of subjects. In the barn, the presence and placement of electric stall trainers was recorded. The placement was deemed appropriate if the trainer had a height adjustment and was placed above the backbone of the cow without contact when she was standing with her hind leg close to the rear curb of the stall, or if no trainer was present. The dryness of the bedding and the level of manure contamination of the stalls were scored for 6 stalls on each farm using a standardized protocol available at <https://www.dairyresearch.ca/animal-comfort-tool.php>. The type of stall used to house the lactating cows was noted and categorized in 4 types: tie-rail and chain, 2-bar obstruction, 4-bar obstruction, and other (Nash et al., 2016). The length of the tie-chain was also noted. The proportion of cows fitting in their assigned stall in terms of stall width, bed length, and tie-rail height was calculated by comparing the stall and cow dimensions collected during the in-barn assessment for the 40 selected animals with the recommended dimensions for tiestall housing (Anderson, 2014).

The productivity indicators included in this study for each farm were average yearly fat- and protein-corrected milk production (kg), yearly SCC, culling rate (%), and percentage of cows in third lactation or greater (%). They were based on the data collected by the regional DHIA programs during the 12 mo before the on-farm visit. A cow was considered culled if she left the herd for any reason other than being sold to another farm for milk production. Each farm's overall profitability was assessed through yearly economic margins per cow and per kilogram of dairy fat production quota and calculated over the replacement costs. These margins were calculated exclusively over the replacement costs, and therefore did not include costs or added value related to animal welfare such as feed or veterinary services because these were not available. The details of the margin calculations can be found in the companion publication related to the freestall farms (Villettaz Robichaud et al., 2019).

Statistical Analyses

The statistical software Stata 13 (StataCorp LP, College Station, TX) was used to analyze the data. The details of the statistical analysis have been presented in a companion publication related to the freestall

farms included in the larger cow comfort study (Villettaz Robichaud et al., 2019). Descriptive statistics were generated and herd prevalence was estimated for each animal-based measure using the data collected on the 40 selected cows.

Univariable linear regression models with a cut-off value of $P < 0.2$ and backward manual selection multivariable linear regression models were used to analyze the association between the farm characteristics; animal-, management-, and resource-based measures; and the indicators of farm productivity and profitability mentioned above. The level of significance was set at $\alpha = 0.05$ for a variable to be retained in the final models. Biologically plausible interactions between predictors were tested and kept in the multivariable models only if statistically significant. Confounding variables were identified based on the causal diagram and were kept in the models if their removal resulted in a change of 20% or greater on the coefficients of other significant variables. The farms' characteristics and the animal-, management-, and resource-based measures tested as continuous covariates for each statistical model are presented in Table 1. Categorical predictors were also tested in each model and included whether or not the farm fed TMR, the province where the farm was located, the type of tiestall used on the farm, and the frequency of scheduled hoof trimming.

RESULTS

Characteristics of Farms Enrolled

The characteristics of the farms enrolled in this study are presented in Table 1. Approximately half (53%) of the farms fed TMR to their lactating cows. Tie-rails with chains was the type of stall most commonly used (89% of farms). The other type of stalls used were a 2-bar design (4% of farms), 6-bar design (5% of farms), and others which included yoke (1 farm) and stanchion (1 farm). Eighteen farms hoof trimmed their cows once per year, 64 did so twice per year, and 17 farms had routinely scheduled hoof trimming 3 or more times per year. The herd prevalence of the animal-based welfare indicators was estimated using the data collected on the 40 selected cows and varied greatly between measures and between farms (Table 1). Hock lesions were the most prevalent animal-based welfare indicator, and the proportion of cows with $\text{BCS} \geq 4$ was the least prevalent. Some moderately strong ($\rho > 0.60$) correlations were found between the animal-based measures for hock and knee lesions, and between the percentage of cows with a dirty flank, dirty leg, and dirty udder (Table 2). Some correlations ($\rho > 0.45$) were also found

Table 2. Correlation coefficient between prevalence levels of the animal-based welfare measures estimated using 40 cows per herd on 100 tiestall dairy farms in Ontario and Québec, Canada

Item	Hock	Knee	Neck	Flank	Udder	Leg	BCS ≤ 2	BCS ≥ 4	Lameness	Lying time
Hock lesions	1									
Knee lesions	0.66	1								
Neck lesions	0.36	0.54	1							
Flank cleanliness	-0.08	-0.01	0.05	1						
Udder cleanliness	0.04	0.04	0.10	0.62	1					
Leg cleanliness	-0.04	-0.11	-0.06	0.74	0.56	1				
BCS ≤ 2	-0.16	-0.21	-0.25	0.25	0.12	0.32	1			
BCS ≥ 4	-0.33	-0.27	-0.22	-0.04	-0.10	-0.03	0.18	1		
Lameness prevalence	0.47	0.55	0.52	-0.20	-0.13	-0.19	-0.30	-0.29	1	
Average lying time	-0.36	-0.28	-0.22	-0.03	0.03	-0.05	0.10	0.27	-0.24	1
Average lying time SD	-0.03	-0.01	-0.23	0.17	0.05	0.11	0.06	0.16	-0.05	-0.13

between lameness prevalence and hock, knee, and neck lesion prevalence.

had a greater effect on average yearly SCC in herds with a lower (better) average SCC genetic rating.

Milk Production and Yearly SCC

Higher milk production was associated with a longer average daily lying time and a higher percentage of cows fitting in the average tie-rail height (Table 3). Lower average milk production was associated with a higher proportion of cows with a docked tail and a greater age at first calving. The percentage of lame cows interacted with the average milk production genetic index in its association with average milk production (Table 3). The increase in milk production with increasing genetic index was steeper in herds with a lower lameness prevalence (Figure 1).

Higher average SCC per year was associated with a higher percentage of cows with BCS ≤ 2 and the prevalence of stalls mostly soiled with manure (Table 4). The type of tiestall used was significantly associated with the average SCC per year, with farms using a 2-bar stall design having an average SCC 202,760 cells/mL higher compared with farms using stalls with a tie-rail and chains (Table 4). The average SCC was also associated with an interaction between the genetic rating for SCC and the percentage of cows with a dirty leg (Figure 2). The prevalence of animals with dirty legs

Culling and Longevity

The culling rate was calculated for each farm using the number of cows that left the production herd for any reason other than being sold for milk production purposes. Culling rate was significantly associated with the animal-based welfare indicators of neck lesion prevalence and proportion of cows with BCS ≤ 2 (Table 5). For every 1% increase in prevalence of neck lesion, the culling rate decreased by 0.08%. The proportion of cows with BCS ≤ 2 interacted with the average dry period length in its association with culling rate. In farms with longer dry periods, the effect of the proportion of cows with BCS ≤ 2 on culling rate was smaller (Figure 3). Reduced prevalence of cows with BCS ≤ 2 was associated with lower culling rates, but only if the dry period was < 83 d. An increase in culling rate was also associated with a higher percentage of stalls with very wet bedding (Table 5).

The percentage of the herd that was in their third lactation or greater was significantly higher on farms with a higher prevalence of neck lesions (Table 6). On the contrary, farms with higher average milk production genetic indexes and farms with a greater SD of

Table 3. Multivariable linear regression model investigating the associations between average corrected milk production (kg) and farms' management practices and animal welfare indicators on 87 tiestall farms in Québec and Ontario, Canada

Model/predictor	β	95% CI	P-value
Milk production genetic index	3.90	2.547, 5.254	< 0.001
Age at first calving, d	-4.76	-7.495, -2.030	0.001
Average lying time, ¹ h	272.58	94.498, 450.657	0.003
Cows with docked tail, ¹ %	-21.69	-32.415, -10.966	< 0.001
Cows fitting in the average tie rail height, ¹ %	5.85	0.993, 10.708	0.019
Lameness prevalence, ¹ %	20.72	8.218, 33.213	0.001
Lameness prevalence $\times$ milk genetic index	-0.07	-0.119, -0.021	0.006

¹Estimated using the 40 cows per herd.

Figure 1. Effect of the interaction between the estimated percentage of lame cows (%) and the average milk production genetic index on the average corrected milk production per year (kg) on 87 tiestall farms in Québec and Ontario, Canada.

Figure 2. Effect of the interaction between the estimated percentage of cows with a dirty leg (%) and the average SCC genetic rating on the average SCC ($\times 1,000$ cells) per year on 100 tiestall farms in Québec and Ontario, Canada.

lying time were significantly associated with a lower percentage of cows in their third lactation or higher (Table 6).

Farm Profitability Margins

The yearly margin per cow calculated over the replacement costs was positively associated with the average lying time, the percentage of stalls not soiled with manure, and the frequency of scheduled hoof trimming per year (Table 7). It was also negatively associated with the percentage of stalls with very wet bedding and with increasing dry period length (Table 7). The yearly margin per cow was significantly associated with the combined effect of the farms' estimated lameness prevalence and average milk production genetic index (Figure 4). The increase in margin per cow calculated over replacement costs with increasing milk genetic

index was much steeper in farms with lower lameness prevalence.

The yearly margin per kilogram of dairy fat production quota, calculated over replacement costs, was negatively associated with the percentage of cows with BCS ≤ 2 and the percentage of stalls with very wet bedding (Table 8).

DISCUSSION

The objective of this study was to evaluate the associations between the on-farm prevalence of several animal-, management-, and resource-based welfare indicators and measures of farm productivity. The on-farm prevalence of animal-based indicators was estimated using the data collected on 40 cows selected for each herd. Our results indicate that good cow comfort and welfare on tiestall farms is associated with improved

Table 4. Multivariable linear regression model investigating the associations between average SCC production ($\times 1,000$) and farms' management practices and animal welfare indicators on 100 tiestall farms in Québec and Ontario, Canada

Model/predictor	β	95% CI	P-value
Milk production genetic index	-0.10	-0.171, -0.024	0.010
SCC genetic rating	766.42	210.08, 1322.76	0.007
Stalls mostly soiled with manure, %	3.68	1.946, 5.410	<0.001
Type of stall ¹			
Tie-rail and chain	Referent	—	—
2-Bar	202.76	129.747, 275.774	<0.001
6-Bar	17.05	-48.928, 83.011	0.609
Other ²	-5.58	-108.651, 97.488	0.915
Cows with dirty leg, ³ %	209.38	51.983, 394.142	0.019
Cows with BCS ≤ 2 , ³ %	5.05	2.346, 8.282	0.001
Cows with dirty leg $\times$ SCC genetic rating	-69.74	-128.324, -11.155	0.020

¹Tie-rail and chain: n = 89; 2-bar: n = 4; 6-bar: n = 5; other: n = 2.

²Other included stanchion and yoke.

³Estimated using the 40 cows per herd.

Table 5. Multivariable linear regression model investigating the associations between culling rate (%) and farms' management practices and animal welfare indicators on 100 tiestall farms in Québec and Ontario, Canada

Model/predictor	β	95% CI	P-value
Dry period length, d	-0.02	-0.160, 0.122	0.790
Cows with neck lesion, ¹ %	-0.08	-0.158, -0.001	0.047
Cows with BCS ≤ 2 , ¹ %	2.61	0.856, 4.365	0.004
Stalls with very wet bedding, %	0.47	0.247, 0.686	<0.001
Cows with BCS $\leq 2 \times$ dry period length	-0.03	-0.057, -0.006	0.015

¹Estimated using the 40 cows per herd.

milk production and cow longevity at the farm level, which is reflected in greater economic margins over replacement costs. Improved lying time and lying surface comfort, and reduced prevalence of cows with a BCS ≤ 2 were all significantly associated with improved farm productivity indicators or profitability margins. Many animal-based welfare measures also had combined effects with resource-based measures in their associations with farm productivity and profitability.

No strong correlations between the animal-based welfare indicators were found. Unsurprisingly, the highest positive correlations were found between the prevalence of leg and neck lesions and lameness prevalence, and among the cleanliness measures. The correlations between the lesions and lameness prevalence were expected because they share important risk factors such as stall dimensions and stall base (Potterton et al., 2011; Brenninkmeyer et al., 2013; Nash et al., 2016). The correlations between the cleanliness measures were also expected because their common farm-level risk factors include stall base and bedding quality (Norrington et al., 2008; Hauge et al., 2012; Bouffard et al., 2017). Overall, the animal-based measures with the highest prevalence of problems were leg lesions and lameness. Within the resource-based measures, on average only 16% of cows fitted the average tie-rail height and 44% fitted the average stall width. It is important to emphasize that the farms' participation in this study was voluntary and that numerous selection criteria were applied for both the farms and the animals assessed. None of the farms included in this study gave outdoor access to their lactating animals, as this was one of the enrollment criteria. Therefore, the results of this study may

have limited applicability to farms that provide regular outdoor access to their animals or that have characteristics greatly different from the farms enrolled in this study.

The level of comfort of the resting area is known to greatly affect lying time and other animal-based welfare measures (Krawczel and Grant, 2009; Tucker et al., 2009; Bouffard et al., 2017). In this study, the overall average lying time was 12 h/d (range: 10.3 to 14.4 h/d), which is similar to previously published data from tiestall farms (Tucker et al., 2009; von Keyserlingk et al., 2012). Published studies investigating the relationship between lying time and milk production have shown mixed results on the existence of an association, and most of this research has been conducted in freestall housing (Grant, 2007; Bewley et al., 2010; Watters et al., 2013). In the current study, the farms' yearly milk production per cow was positively associated with the average daily lying time, with an increase of 273 kg of fat- and protein-corrected milk per year for each 1 h increase in average lying time. Similarly, Grant (2007) found that in freestall housing, each 1 h increase in lying time resulted in an increase of 1.7 kg of milk production per day. Because in tiestall housing cows are either lying down or standing in their stall, their movements are restricted to this space and the comfort of the stall has a constant effect on their behavior and welfare (Cook, 2002). This may partly explain the strong association that was found in this study between lying time and milk production. In addition, a positive association was found between the proportion of cows that fit the tie-rail height and the average corrected milk production. Cows were considered to fit the tie-rail height based

Table 6. Multivariable linear regression model investigating the associations between the average prevalence of cows in their third or greater lactation (%) and farms' management practices and animal welfare indicators on 100 tiestall farms in Québec and Ontario, Canada

Model/predictor	β	95% CI	P-value
Milk production genetic index	-0.02	-0.023, -0.009	<0.001
Cows with neck lesion, ¹ %	0.09	0.026, 0.144	0.005
Average lying time SD, ¹ min	-0.10	-0.163, -0.027	0.007

¹Estimated using the 40 cows per herd.

Table 7. Multivariable linear regression model investigating the associations between economic margin per cow over replacement costs (\$) and farms' management practices and animal welfare indicators on 98 tiestall farms in Québec and Ontario, Canada

Model/predictor	β	95% CI	P-value
Milk production genetic index	2.08	1.096, 3.064	<0.001
Dry period length, d	-10.39	-17.300, -3.488	0.004
Lameness prevalence, ¹ %	14.46	5.177, 23.735	0.003
Stalls not soiled with manure, %	7.16	3.020, 11.297	0.001
Stalls with very wet bedding, %	-15.67	-28.563, -2.776	0.018
Average lying time, ¹ h	147.22	27.073, 267.364	0.017
Frequency of scheduled hoof trimming/yr ²			
Once	Referent	—	—
Twice	448.53	184.226, 712.827	0.001
Routinely (>twice)	595.84	247.163, 944.516	0.001
Lameness prevalence $\times$ milk genetic index	-0.03	-0.068, -0.001	0.043

¹Estimated using the 40 cows per herd.

²Once: n = 18; twice: n = 64; routinely: n = 17.

on current recommendation, which stipulates that the tie-rail height should be 0.8 times the height of the cow at the rump (Anderson, 2014). The tie-rail height can affect both feeding and standing behavior and has been documented to affect the prevalence of neck lesion and cow cleanliness (Zurbrigg et al., 2005; Anderson, 2014; Bouffard et al., 2017). Unfortunately, very little information is available in the current literature on the feeding behavior of cows kept in tiestalls, especially in relation to stall dimensions. The results of this study may indicate that cows that fit the recommendation for tie-rail height are more comfortable during feeding, which leads to an increase in feeding time and average milk production (Huzzey et al., 2006; Miller-Cushon and DeVries, 2017).

The association found between the farm's estimated lameness prevalence and corrected milk production was modified by the milk production genetic index, showing that higher average milk production on farms with low genetic index occurs when there is also a higher lame-

ness prevalence. These results could be explained by a combination of factors, including that animals with greater milk production genetic merit have an increased chance of being lame and that lameness is associated with milk loss (Green et al., 2002; Charfeddine and Pérez-Cabal, 2017). The negative association found between yearly milk production and the percentage of cows with docked tail was unexpected and does not seem to have been previously documented, especially in tiestall farms. Some studies have shown that tail docking in cattle does not improve cow cleanliness or milk quality and has the potential of causing chronic pain (Schreiner and Ruegg, 2002; Eicher et al., 2006). This association may also be a reflection of the producers' management style, which was not captured by the other variables tested. A new requirement of the Canadian dairy industry prohibits the use of tail docking as a standard management practice (DFC-NFACC, 2009; DFC-PLC, 2015).

Figure 3. Effect of the interaction between the estimated prevalence of cows with BCS ≤ 2 (%) and the average days dry on the culling rate (%) on 100 tiestall farms in Québec and Ontario, Canada.

Figure 4. Effect of the interaction between the average milk genetic index and the estimated lameness prevalence (%) on the economic margin per cow over replacement costs (\$) on 98 tiestall farms in Québec and Ontario, Canada.

Table 8. Multivariable linear regression model investigating the associations between economic margin per kilogram of quota over replacement costs (\$) and farms' management practices and animal welfare indicators on 99 tiestall farms in Québec and Ontario, Canada

Model/predictor	β	95% CI	P-value
Cows with BCS ≤ 2 , ¹ %	-15.20	-25.903, -4.502	0.006
Stalls with very wet bedding, %	-11.52	-17.303, -5.729	<0.001

¹Estimated using the 40 cows per herd.

In terms of milk quality, the yearly average SCC was positively associated with the proportion of stalls mostly soiled with manure and the percentage of cows with a BCS ≤ 2 . Similarly, other researchers have shown genetic correlations between BCS and milk quality, leading to increased susceptibility to mastitis and high SCC in cows with low BCS (Loker et al., 2012a,b). Farms using stalls with minor front obstruction (2-bar) also had significantly higher average SCC than farms using the other types of stalls included in this study, including tie-rail and chain. Previous research has shown a relationship between stall dimensions and cow cleanliness in tiestall farms, but none have been found that treated different stall designs separately (Cook, 2002; Zurbrigg et al., 2005). The association between herd average SCC and proportion of cows with dirty legs was modified by the average SCC genetic index. The decrease in average SCC with better SCC genetic index (lower) was steeper on farms with a lower proportion of cows with dirty legs. The relationship between cow hygiene and SCC is well documented, and the interaction found in this study highlights the importance of managing cow cleanliness to maximize the return of good genetics (Dohmen et al., 2010; Sant'anna and Paranhos da Costa, 2011).

Average culling rate was negatively associated with the prevalence of cows with neck lesions and positively associated with the proportion of stalls with very wet bedding. The lower culling rate in herds with a higher prevalence of neck lesions was expected because older cows are more likely to be injured (Zaffino Heyerhoff et al., 2014; Bouffard et al., 2017). The prevalence of cows with low BCS interacted with the average dry period length in its association with the farms' average culling rate. On farms that had no cows with low BCS, the average culling rate was not affected by the length of the dry period. The decrease in culling rate with longer dry periods intensified as the percentage of cows with low BCS increased if the dry period was shorter than 83 d. The interaction with low BCS suggests that the nutrition of the cows during the dry period may explain part of the effects of the dry period length.

The proportion of the milking herds composed of cows in their third lactation or greater was positively associated with the estimated prevalence of neck lesions

and negatively associated with greater within-farm estimated average lying time SD (40 cows sampled). As previously stated, older cows are more likely to present with body injuries, and so it is not surprising that farms with greater proportions of older cows also present higher prevalence of neck lesions (Rutherford et al., 2008). An individual cow's lying time is known to be affected by her characteristics, comfort, lameness, and health status (Ito et al., 2009; Kaufman et al., 2016; Maselyne et al., 2017). The negative association between the within-farm variation in lying time and the proportion of older cows might indicate a lack of comfort, which can lead to health issues on these farms.

The margin per cow, calculated exclusively on replacement costs, was associated with multiple measures of cow welfare. Some of these elements were also associated with either the average corrected milk production or the average culling rate. Most farms enrolled in this study routinely hoof-trimmed their animals twice per year, but overall it varied from once to 4 times per year. Previous research conducted on tiestall farms in Canada reported similar trimming frequencies (Cramer et al., 2009; Desrochers and Daigle, 2017). Greater margins per cow with increasing frequency of scheduled hoof trimming may indicate that routine hoof trimming allows hoof lesions to be found and treated more rapidly, which may in turn reduce their influence on milk production and cow longevity (Fjeldaas et al., 2006). The estimated lameness prevalence was also positively associated with the margin per cow. This may be explained by the fact that older cows are more likely to be lame, and that a greater number of older cows generally translates to a higher margin per cow, as per the calculation of the margin (Solano et al., 2015). In contrast, the margin per kilogram of dairy fat production quota was negatively associated only with the prevalence of cows with BCS ≤ 2 and the proportion of cows in stalls with very wet bedding. This indicates that both nutrition and cow comfort management need to be part of the integrated strategy to maximize cow welfare and productivity. Unfortunately, nutrition, bedding, and veterinary costs were not available for individual farms and therefore could not be factored into the margin calculations. The addition of these parameters could have influenced farm profitability results.

CONCLUSIONS

The results of this study indicate that improved cow comfort and welfare is associated with greater farm productivity and profitability margins calculated over the replacement costs. The numerous interactions found between the management-, animal-, and resource-based welfare indicators emphasizes the complexity of the association between animal well-being and farm profitability, especially in connection with the farm's management and culling strategy. To maximize the welfare of cows kept on tiestall farms, every aspect of the stall needs to provide the highest level of comfort for the animals. Minimizing the number of cows with low BCS and managing hoof health to reduce lameness also improves animal longevity and farm profitability. This study provides indications to dairy farmers using tiestall housing under the Canadian quota system that providing good cow comfort and welfare can benefit them financially both in terms of improved production and enhanced margins over replacement costs.

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