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The transfer of passive immunity in calves born at pasture

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ABSTRACT

Calf and dam separation is an area of growing public interest, and timely separation is also a practical challenge for pastoral farmers to achieve for all calves. Very few studies have investigated the success of leaving calves with their dams in pastoral conditions, so this observational study assessed serum total protein (STP) in calves born at pasture and left to suckle from their dams for up to 24 h. It also investigated failure of transfer of passive immunity (FPT) once calves had been provided colostrum from the farmer and some factors that may contribute to the risk of FPT. Over 2 years, 8 farms (4 in the North Island, 4 in South Island of New Zealand) were involved in an observational study where cows and calves were observed for 24 h a day for 2 wk per farm. Observers recorded the time from birth to first suckling, number of suckling events, time of calf removal from the dam, and ambient temperature. Calves were blood sampled on arrival at housing, before receiving colostrum from the farmer (d 1), and again 2 d later (d 3) to test for STP concentration. On d 1, 689 calves had blood samples collected, at a median of 11.5 (interquartile range 5.6 to 19.2) hours postbirth. Of these, 283 calves [41.1%; 95% confidence interval (CI) 37.4 to 44.9%] had STP >52 g/L (proportion by farm ranged from 10 to 78%). On d 3, 680 blood samples were collected, of which 16.0% (95% CI 13.5 to 19.0) had FPT (STP ≤52 g/L) with proportion by farm ranging from 2.5 to 31.6%. The FPT risk at d 3 in calves that did not suckle before housing was 2.91 (95% CI 2.04 to 4.13) times the risk in calves that suckled. For every hour longer postbirth that it took for a calf to have its first suckling event, odds of FPT at d 3 increased by 1.21 (95% CI 1.08 to 1.36) times, and compared with calves that only suckled once, calves that suckled 2, 3–5, or >5 times had 0.42 (95% CI 0.15 to 0.99), 0.35 (95% CI 0.15 to 0.76), and 0.10 (95% CI 0.005 to 0.47) times the odds of FPT, respectively. For every 1-percentage-point increase in the Brix % of the colostrum, the odds of FPT decreased by 33% (95% CI 24 to 42). Calves that suckled in the paddock and were fed colostrum with ≥22% Brix had the highest STP, and lowest odds of FPT, of any suckling/Brix % combination. There was a trend for STP to be greater in calves that suckled in the paddock and fed <22% Brix compared with calves that did not suckle in the paddock and fed ≥22% Brix. However, the calves in the former group also tended to have a greater risk of FPT at d 3, and a greater STP variability. There were very large between-farm variabilities for rates of suckling, colostrum feeding, and FPT risk that urgently require further investigation for calves born at pasture.
Key words: suckling, failure of transfer of passive immunity, colostrum, quality, pasture-based

INTRODUCTION

In a recommended "best practice" traditional management system, calves are removed from their dam within 4 h, and fed 10 to 15% of their BW of high-quality colostrum (tested as having a high IgG concentration and low bacterial contamination or pasteurized; Godden, 2008; Beam et al., 2009). This system is designed to reduce the number of calves that do not get sufficient antibodies from colostrum to protect them against common calf diseases (failure of transfer of passive immunity; **FPT**). Failure of transfer of passive immunity results in increased morbidity and mortality (Tyler et al., 1998; Pardon et al., 2015; Cuttance et al., 2018b), and decreased growth rates (Furman-Fratczak et al., 2011; Pardon et al., 2015; Cuttance et al., 2019a). However, concern has been expressed as to whether this is indeed an ideal system (Beaver et al., 2019), with increased interest and concern from the general public in relation to cow-calf separation as a key area relating to the naturalness of dairy farming (Neave et al., 2022).

However, for dairy farms in New Zealand, where cows are predominantly kept at pasture all year round, the chief concern in relation to this "ideal" management system is that the rapid removal of calves from their dams within 4 h is not achievable from the majority of farmers' point of view. In New Zealand, dairy farms are generally large (440; DairyNZ, 2020) and have a very

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high ratio of cows to staff (current average 152 cows/full-time equivalent; DairyNZ, 2021). The seasonal calving system results in, on average, 64% of cows and 78% of first-calving heifers calving within 3 wk of the planned start of calving (DairyNZ, 2020). This compact calving pattern means that, despite many farms employing temporary labor during calving, staff resources are stretched during the calving season. Frequently picking up calves from the paddock requires significant staff resources that may not be available. Thus, despite over 20 years of industry recommendation of early cow-calf separation followed by colostrum feeding, very few New Zealand dairy farmers routinely pick up newly born calves and take them to the rearing shed more than once a day. Cuttance et al. (2018a) reported that only 4 of the 101 New Zealand dairy farmers they surveyed achieved more than 2 pick-ups per day with 66/101 picking up less than twice a day. Calves are picked up more frequently if farmers perceive this as a need (e.g., if the weather is poor; Cuttance et al., 2018a), so the failure to pick up calves more frequently on a routine basis suggests that lack of staff time and lack of a perceived benefit are the key drivers of the low percentage of farms picking up calves more than twice a day.

Thus, most farms in New Zealand are reliant, at least in part, on calves obtaining colostrum directly from their dam. Only a few studies have compared the prevalence of FPT in systems where dairy calves suckle their dams and where they are artificially fed colostrum. Selman et al. (1971), Stott et al. (1979b), Quigley et al. (1995), and Cuttance et al. (2017b) all presented data showing an improved transfer of immunoglobulins when calves suckled from the dam (Table 1); however, studies have also shown reduced transfer of immunoglobulins when suckling from the dam (Besser et al., 1991; Trotz-Williams et al., 2008; Beam et al., 2009). Yet, in all these studies, the volume and quality of the colostrum provided to each group of calves was not equivalent. In the studies which showed a benefit of suckling, the volume and quality of the colostrum provided to the calves that were not suckling from the dam were variable, and therefore the results in those calves were more likely to be associated with the colostrum management of the farmer, rather than the absence of the maternal contact and suckling. In contrast, in the studies that showed an apparently negative effect of suckling, comparison was between calves that received a known large quantity of high-quality measured colostrum and unmeasured, unmonitored suckling calves.

Nevertheless, it is clear that suckling behavior is variable and not all calves will suckle if left with their dams. Cuttance et al. (2022) summarized the previous studies in this topic. These studies observed between 20 and 161 cow and calf pairs and reported a range of suckling percentages from 50% calves suckling within 6 h (Selman et al., 1970c; 10 cows and 10 heifers observed) to 87.5% of calves suckling within 6 h in cows housed in stalls (Illmann and Špinka, 1993; 32 cattle observed). The failure of calves to suckle after birth may be one of the reasons why the prevalence of FPT in New Zealand, where calves are kept with their dams for longer periods, is higher than in the United States where early separation and the "ideal" approach is much more common [33 vs. 12%, respectively; Cuttance et al. (2017b) vs. Lombard et al. (2020)]. Another potential reason is the quality of colostrum fed to the calves once they reach the rearing shed. In New Zealand, only 10% of colostrum samples had sufficient immunoglobulins that met industry standards (Denholm et al., 2017), whereas in the United States, 70% had sufficient immunoglobulins (Morrill et al., 2012). The reasons for this difference include the time between calving and colostrum collection (delaying calf pick-up and, therefore, colostrum collection decreased colostrum Brix %; Denholm et al., 2017) and also the much greater use of pooled colostrum in New Zealand compared with the United States (USDA, 2014; Denholm et al., 2017). This poor colostrum quality reduces the chance that feeding after housing can make up for insufficient colostrum intake in the paddock.

Undoubtedly, a focus on better colostrum management of calves in the rearing shed could reduce the percentage of calves with FPT, especially in calves that have been collected soon after they have been born. However, if calves are kept at pasture with their dams for up to 24 h, management of calves in the rearing shed is likely to have only a limited effect on FPT. In such circumstances, there needs to be a greater understanding of how successful the transfer of antibodies from colostrum to calf is during the period that the cow and calf are kept together and the key risk factors which affect this transfer (including some that are specific to pasture-based animals, such as weather and area per cow in calving paddock). Understanding this will likely be a big part of reducing FPT in New Zealand dairy calves, and will also be of value for pasture-based farms switching to prolonged cow-calf contact, as they will be relying even more on direct intake of colostrum from the dam.

Therefore, the objectives of this study were to understand, under New Zealand conditions, the risk of FPT in calves that were left to suckle from the dam in the calving paddock, the possible risk factors that may contribute to FPT, and the success of colostrum feeding after calf collection on reducing FPT.

Table 1. Description of current available literature on the transfer of immunoglobulins in animals that have suckled from dams

Country	Breed	Number of animals	Number of farms	Definition of "left with the dam"	FPT[1]	Management	Reference
Scotland	Ayrshire	20	1	Animal monitored but left with the dam unassisted.	A total of 7/20 dairy calves (35%) had FPT. 5/7 calves with FPT had not suckled at all.	Housed	Selman et al. (1970a)
United States	Not reported	Not reported: 11 calves allowed to suckle dam	1	Allowed to suckle with the dam for 24 h, vs. calves removed from the dam and fed 0.5, 1, or 2 L of colostrum at birth and then again at 12 h postpartum.	The rate of absorption of IgG in suckled calves during the first 4 h was 7.30 mg/mL, vs. almost 3.77 mg/mL in calves receiving 2 L of colostrum by bottle at birth. Between 4–8 h and 8–12 h, the suckled calves absorbed almost double the rate of the best absorption in bottle-fed calves (bottle-fed colostrum quality not reported).	Housed	Stott et al. (1979a)
United States	Holstein and Guernsey	983	1	Collected once daily. Most left with dam for 12–26 h.	Analysis of blood for IgG and IgM at 24 h indicated that 42% of the calves had failed either to suckle or to absorb colostral immunoglobulins from suckling. Of the calves that had suckled, 35.7% did not obtain sufficient colostrum to provide any degree of passive immunity above that normally in calves at birth.	Housed	Brignole and Stott (1980)
Ireland	Predominantly Friesian	250	1	Left to suckle from the dam for 24 h.	140/250 calves had ZST[2] <20 units measured at 48 h old.	Not reported	Logan et al. (1981)
Scotland	Ayrshire, Friesian, or Ayrshire/Friesian cross	167 (15 animals in each group)	1 (research farm)	15 calves were left unassisted to feed from their dam for 48 h. Comparison groups were hand fed or assisted to suckle.	Calves assisted to suck immediately after birth ZST 281.3 mg/L. Calves allowed to suck themselves for 48 h ZST 222 mg/L. Calves removed from dam and given 1.7 L of colostrum at 8 h, ZST 150 mg/L (significantly different to animals assisted suckling).	Housed	Petrie (1984)
United States	Holstein Friesian	570	3	Allowed to nurse from the dam for 72 h.	61.5% of calves that were nursed by their dam had FPT (defined as IgG <10 mg/mL), vs. 19.3% of calves from a farm using nipple bottle feeding almost immediately after the calf had been born and 10.8% of calves from a dairy farm using tube feeding immediately after the calf was born.	Housed	Besser et al. (1985)

Continued

Table 1 (Continued). Description of current available literature on the transfer of immunoglobulins in animals that have suckled from dams

Country	Breed	Number of animals	Number of farms	Definition of "left with the dam"	FPT[1]	Management	Reference
United States	Jersey	90		Allowed to nurse from the dam for 3 days, vs. being removed from the dam immediately and given 1 L of first milking colostrum at 0 h then again at 12 h (no testing of colostrum quality). Calves assisted with dam if they were not suckling within 4 h.	Serum IgG and IgM concentrations at 24 h were greater when calves were allowed to nurse the dam.	Housed	Quigley et al. (1995)
Canada (Ontario)	Not reported	423	119	Left with the dam for >3 h (typical collection 3–12 h).	Odds of FPT 2.05 (95% CI = 1.21–3.46) higher in calves from farms where 75% of calves were "left with the dam."	Housed	Trotz-Williams et al. (2008)
United States	Not reported	2,030	413	"Allowed to nurse" (unknown time from birth to first feeding of colostrum).	Odds of FPT 2.42 (95% CI = 1.48–3.96) higher in calves that were "allowed to nurse."	Housed	Beam et al. (2009)
New Zealand	Mixed	3,819	107	Once a day collection from the calving paddock, therefore left with the dam for 1–24 h.	Calves that were fed by a bottle, group feeder, or esophageal tube were 1.66 (95% CI 0.89–3.89), 1.69 (95% CI 0.93–3.02), and 1.82 (95% CI 0.98–3.4) times more likely to have FPT than calves left with the dam for 12–24 h, respectively.	Pasture	Cuttance et al. (2017b)
Norway and Sweden	Norwegian Red, Swedish Red and White, and Swedish Holstein	58	11	Unclear	Study did show whether offering nonroutine assistance for suckling calves (e.g., helping them suckle or providing a bottle with colostrum) improves or reduces suckling success.	Unknown	Johnsen et al. (2019)

[1]FPT = failure of transfer of passive immunity.

[2]ZST = zinc sulfate turbidity test. An indirect test to determine failure of transfer of passive immunity. Common cutoff is 200 m g/L (Cuttance et al., 2019b).

METHODS

All manipulation of animals was approved by the AgResearch (Ruakura) animal ethics committee application number 14794.

This study was a prospective observational study carried out on 8 farms in the Waikato (North Island; n = 4) and Canterbury (South Island; n = 4) regions of New Zealand. Half of the farms, evenly split over the regions, were observed in spring (August) 2019 and spring 2020. Eligible farms were convenience selected from the clients of a large veterinary business (VetEnt) by considering the location of the farm, location and accessibility of calving paddocks, calving management (timing and frequency of calf pick-up), length of the calving period and how closely together the calving dates were, and willingness to participate.

Farm Data Collection

Farms were enrolled to allow 12 full days of 24 h observation of cows and calves (6 d of consecutive observation, followed by a 1-d break, followed by another 6 consecutive days of observation) in 2019 and 8 full days of 24 h observation (two 4-d observation periods separated by a 3-d break) in 2020. The dates chosen for the observation period were to align with period of peak calving. The colostrum management on the 8 farms is described in Supplemental Table S1 (https://doi.org/10.17632/kdvcbwvrxm.1; Cuttance, 2022); the study did not attempt to control or alter any of the farm practices regarding colostrum management.

Full details of the method are presented in Cuttance et al. (2022). Briefly, observations were carried out by trained technicians (observers) working in pairs or triplets (depending on the farm), on 4- to 5-h shifts at a time over a 24-h period. Observers were positioned on a scissor lift that was in the middle or on the edge of the paddock/break that was being grazed by the calving cows. The farmers carried out their normal farm protocols for the duration of the trial and the observation team worked around these protocols.

One member of the pair or triplet of observers was responsible for recording information while the other member or members of the pair or triplet carried out observations. The observations collected are presented in Cuttance et al. (2022). Calves were excluded from any further observations if they were born dead or died before the farmer collected the calves, or if the cow or calf was removed from the paddock (out of the sight of the observation team) before general calf pick-up (e.g., to assist calving, seek treatment).

As calves were born, they were assigned unique identification alongside identification that the farmer provided (temporary necklaces or ear tags). Multiple identification methods, in combination with detailed calf descriptions, were designed to help with accuracy of recording (especially when multiple calves were all black without distinguishing features).

Any cows or calves deemed, by the observers, to be suffering or likely to be experiencing dystocia or milk fever were identified and reported to the farmer. They were removed from the study observations.

Data on potential risk factors contributing to feeding behaviors and colostrum quality were also collected daily. The initial grazing area as well as every new grazing area supplied to the calving cows was measured for area size, using a measuring wheel and pasture cover using a rising pasture meter (O'Donovan et al., 2002), before the cows grazed it. The pasture cover in the previous grazing area was then measured by plate meter to get an indication of feed consumed over the time period that the cows had been in that area. Temperature was measured every 30 min using an anemometer (HoldPeak, HP-866B). The number of cows in the observation area were recorded daily, and data on cow breed and age were downloaded from each farm's information management software. Observations ceased for a particular calf when it was removed from the grazing area by the farmer and taken to the rearing facility.

Once the calves were in the rearing facility, they were blood sampled from the jugular vein into plastic clot activator tubes (Vacutainer, BD) before receiving any colostrum from the farmer (d 1 samples) and then blood sampled again ~2 d later (d 3 samples). The samples were sent to the laboratory (SVS) on the same day or, if same day delivery was not possible, refrigerated for 1 to 2 nights and then sent. Samples were tested for serum total protein (**STP**) concentration using the Biuret method (Busher, 1990). Color intensity, which is directly proportional to the protein concentration, was determined photometrically using a Roche/Hitachi Modular analyzer (Roche Diagnostics; Bakker and Mücke, 2007). The limits of detection of the assay were 2.0 to 150 g/L.

The colostrum that was intended to be fed to the calves that had just arrived at the rearing facility was tested by the trial technician with an optical Brix refractometer (LH-T32, 0–32%, Shoof). If more than one batch of colostrum being fed and it was not being mixed (pooled) before feeding, each batch was tested separately and the calves associated with each batch given by the farmer were recorded.

Statistical Analysis

Median and interquartile range (**IQR**) were calculated for hours postbirth for when calves were blood sampled before being fed colostrum by the farmer (d 1 sample) and after the farmer had fed calves colostrum (d 3 sample). Histograms and descriptive statistics (median and IQR) were reported for STP for d 1 and d 3 blood samples, along with the proportion of samples that were >52 g/L for d 1 and ≤52 g/L for d 3. For d 3 samples, animals with STP ≤52 g/L were defined as having FPT (Cuttance et al., 2017a, 2018b). The Brix % of the colostrum fed to the calves was graphically described using a combination of a boxplot and a dot plot to assess the central tendencies and distribution of Brix % between farms. The median and IQR for the Brix % fed to the calves by the farmer and the number and proportion of colostrum samples that were <22% Brix was also reported (Denholm et al., 2017). All descriptive statistics were reported for each of the 8 farms, as well as an overall measure for calves on all 8 farms.

Due to the bimodal nature of STP at d 1, Spearman's rank correlation method was used to calculate the correlation between STP in d 1 and d 3. This was calculated for each farm and for all calves overall. Spearman's rank correlation coefficients were also reported for any combination of 2 continuous variables that visually had a linear relationship.

For each farm, the number and proportion of calves that suckled, and the number and proportion of calves that had STP >52 g/L at d 1 and ≤52 g/L at d 3, were tabulated. The effect of whether a calf suckled or not when at pasture had on the relative risk of STP >52 g/L at d 1 and STP ≤52 g/L at d 3 was reported. At the individual farm level, numbers in some categories were very low, so individual farm estimates of either relative risk or risk difference could not be reported. For d 1 samples only, the proportion of calves that had STP >52 g/L was calculated for calves that had suckled and remained at pasture for at least 6 h after birth and for the subset of those calves that had had at least 6 h between first suckling and blood sampling. This was done to assess how delaying sampling for at least 6 h after suckling (McGuirk and Collins, 2004) would affect STP.

The relationships between time from birth to removal from pasture, and time from birth to first suckle, with STP at d 1 and d 3 were first investigated using linear regression techniques. Separate linear regression models were carried out, with outcome variables STP at d 1 and d 3, respectively, and separate models for the continuous predictors, birth to removal from pasture and birth to first suckling event. For time to first suckling event, only the subset of calves that had a suckling event were included in the models, and for d 1 samples, calves that had suckled within 6 h of their d 1 blood sample were removed from this analysis. For all models, farm was included as a fixed effect to limit confounding and, if biologically plausible, an interaction term between farm and the continuous predictor was assessed. This interaction term remained in the model if the log-likelihood ratio test between 2 nested models, one with the interaction term and one without, had a $P < 0.05$. Linearity was assessed by plotting the residuals of the model against the continuous predictors and adding smoothed regression lines to the scatterplots. If the smoothed regression lines were straight, then the continuous predictor was assumed to have a linear relationship with STP. If they were not, then either polynomial terms were added for the predictor of interest, or generalized additive modeling (**GAM**) was conducted. The GAM allows the relationship between a continuous predictor (in this case, time to calf removal or first suckling event) and STP to follow a spline function, which allows the relationship to alter across the range of predictor values. This can identify possible biological relationships that do not follow a straight line, particularly when previous data on the relationship are scarce, as in this case. Heteroscedasticity was assessed by plotting the residuals of each model against the linear predictor.

For d 3 samples only, the associations between FPT status and time to first suckling event, and time to removal from pasture, respectively, were assessed. This binary outcome variable (FPT or not) was assessed using logistic regression, with separate models for birth to removal from pasture and birth to first suckling event, as described above under STP. To assess the linearity of the relationships, the continuous predictors were plotted against the logit of FPT status across the range of the predictors, using locally weighted smoothed regression. If the resultant plot resembled a straight line, then the continuous predictor could be concluded to be linearly associated with the log odds of FPT. The GAM models were also carried out as a secondary measure to assess linearity, as discussed above under time from birth to removal from pasture.

The total number of suckling events for each calf was tabulated, and this variable was collapsed into 0, 1, 2, 3–5, or >5 suckles when at pasture. The hypothesis that the number of suckling events at pasture was associated with FPT at d 3 was assessed using logistic regression. For this, all calves without a suckling event were removed from the analysis. The Brix % of the colostrum fed by the farmer was included in the model

as a potential confounder; if this altered coefficients or standard error by >20%, then it was included as a confounder and remained in the model. The presence of an interaction between Brix % and number of feeds was also assessed, and this interaction term remained in the model if the log-likelihood ratio test between 2 nested models had a $P < 0.05$.

The relationship between Brix % of colostrum fed by the farmer at the first fed after removal from pasture and the odds of FPT was investigated using logistic regression. It was of interest to assess first if any relationship existed between Brix % and FPT, and then if that relationship was linear. To assess this, the data were subsetted to include only those calves that did not suckle at pasture from the dam. The outcome variable was FPT status at d 3, and the only predictor of interest was Brix %. Farm was controlled by including it as a fixed effect in the model. Linearity was assessed, as described above, under FPT at d 3 samples.

A key outcome was to define the combined effects of suckling at pasture and the quality of the colostrum fed by the farmer at the first feed after removal from pasture. To assess this, calves were categorized into 1 of 4 categories: did not suckle at pasture and fed colostrum with Brix <22%, suckled at pasture and fed colostrum with Brix <22%, did not suckle at pasture and fed colostrum with Brix ≥22%, and suckled at pasture and fed colostrum with Brix ≥22%. The relationship between these 4 categories and STP at d 3 was modeled using an unconditional linear model. Farm was not included, as all 4 categories were not present on all farms. Heteroscedasticity was assessed by plotting the standardized residuals in boxplots for each of the 4 categories. If variances differed between suckling and Brix % groups, variance weighting was incorporated into the model, allowing different variance inflations for each group. The association between the 4 categories and the odds of FPT were also assessed. Logistic regression was used, with FPT status as the outcome, and suckling and Brix % category as the predictor variable.

Finally, accessory individual (age of dam, breed of dam, and BCS of dam pre-calving) and farm level (minimum ambient temperature within 6 h of birth) risk factors were assessed for their relationship to the odds of FPT at d 3. For age of dam, all calves from farm 8 were excluded, as all calves from first-calving heifers were culled at 4 d of age. Although this practice also occurred on the other farms, on farm 8 colostrum management depended on whether calves would be kept as replacement heifers or not. Thus, this would bias the association between age and odds of FPT. These variables and categorization of them are defined in Cuttance et al. (2022). Again, logistic regression models were used to assess each of the risk factors, separately. Farm was included in all models.

For all models, model assumptions and diagnostics were carried out, and any outliers or influential observations were investigated. All analyses were conducted using R Version 4.1.0 (R Foundation for Statistical Computing).

RESULTS

A total of 697 calves across 8 farms had data on time from birth to removal from pasture. Descriptions of the farm and their neonatal calf management are presented in Supplemental Table S1 and Table 2.

Descriptive Data

A total of 689 blood samples were collected from calves at d 1 at a median of 11.5 (IQR 5.6 to 19.2) h postbirth. The distribution of the d 1 STP samples was bimodal with a mode for the 2 distributions at 40 and 62 g/L, respectively (Figure 1a). Of those that had a d 1 blood sample collected, a total of 442/689 (64.1%; 95% CI = 60.5 to 67.6) calves suckled at pasture, and 44 (10.9%) of those samples were collected within 6 h of the first suckling event. Of those that did not suckle at pasture, the median d 1 STP was 41.0 (IQR 39.0 to 44.0 g/L), and for those that did suckle at pasture, the median d 1 STP was 59.0 (IQR 42.2 to 70.0 g/L). Across the 8 farms, the proportion of calves observed suckling at pasture ranged from 40.0% (60/100 in farm 8) to 90.2% (55/61 in farm 7; Table 2). Two hundred eighty-three of the 689 calves (40.1%; 95% CI 37.4 to 44.9) had STP >52 g/L at the d 1 sample, with a range between farms of 10% (18/143 in farm 5) to 78% (65/83 in farm 4). The proportion of those calves that suckled and had been left with their dam for at least 6 h that had STP >52 g/L was 58.8 (95% CI = 54.2 to 63.3). When the 296 calves that had suckled had at least 6 h with their dam, and had at least 6 h from first suckling event to blood testing, they were analyzed and 76.5% (95% CI = 71.2 to 80.8) had STP >52 g/L.

A total of 680 calves had a d 3 blood sample collected at a median of 65.5 (IQR 58.0 to 73.3) h postbirth. The distribution of STP from the d 3 blood samples was normally distributed (Figure 1b), with a median of 65.5 (IQR 58.0 to 73.3) g/L. Of those calves that had blood samples collected at d 3, a total of 439/680 (64.6%; 95% CI = 60.9 to 68.1) suckled at pasture. A total of 109 (16.0; 95% CI 13.5 to 19.0) calves were diagnosed

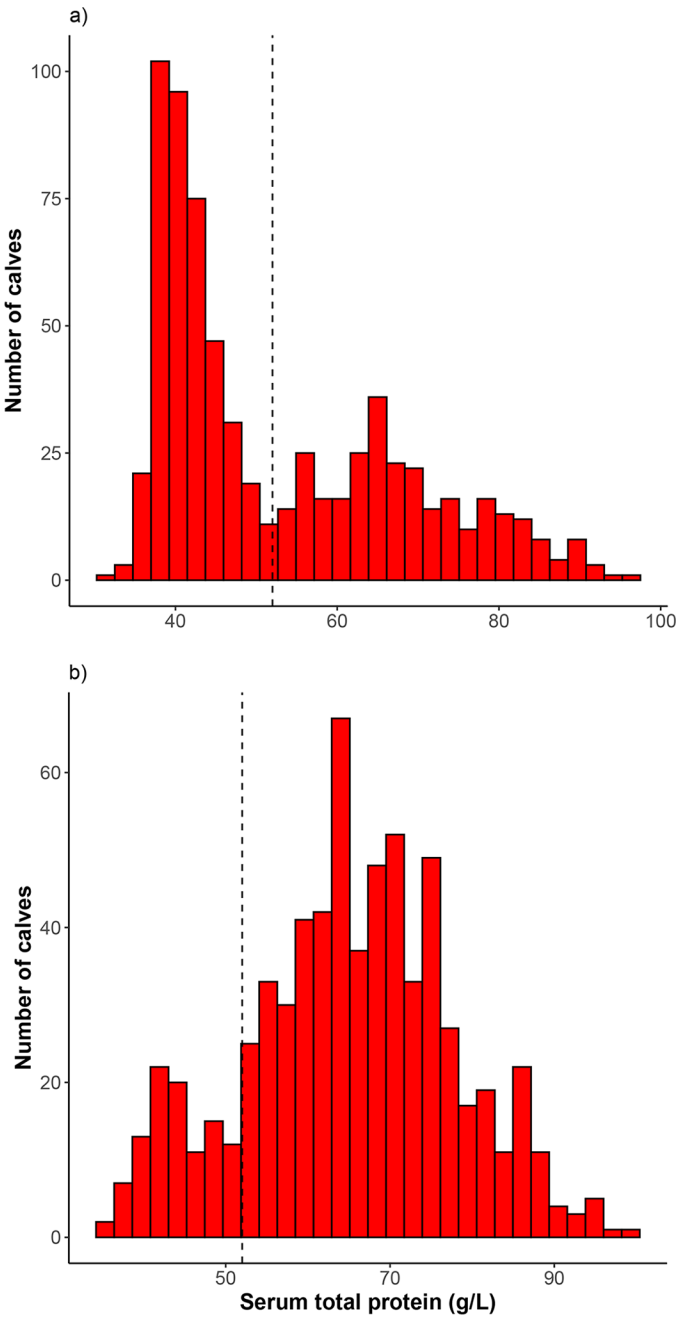

Figure 1. Histograms of the concentrations of serum total protein (STP; g/L) from (a) 689 dairy calves blood sampled after removal at pasture but before farming feeding colostrum (d 1: median 11.5 h postbirth) and (b) 680 dairy calves blood sampled at a median of 65.5 h postbirth (d 3). The vertical dashed line represents STP cutoff of >52 g/L, determining adequate colostral transfer (Cuttance et al., 2017a).

with FPT (STP ≤52 g/L) at the d 3 blood sample. This ranged between farms from 2.5% (2/80 calves from farm 1) to 31.6% (31/98 calves from farm 8), with a median farm FPT prevalence of 18.6% (Table 2).

There was moderate correlation between STP at the d 1 sample and STP at the d 3 sample (ρ = 0.63; 95%

Table 2. Serum total protein (STP) before and after the farmer-fed colostrum, number and percentage of calves that suckled at pasture, and the Brix % of the colostrum fed to calves in a study investigating the success of calves feeding from their dam at pasture from 8 farms in the North and South Island of New Zealand

Item	Farm							
	1	2	3	4	5	6	7	8
Time at pasture [median (IQR)][1]	7.7 (2.4–12.4)	15.3 (8.4–18.6)	12.6 (8.8–17.5)	14.3 (9.8–19.1)	3.8 (2.2–6.6)	13.9 (7.6–18.6)	11.8 (7.6–17.9)	5.7 (2.9–10.7)
STP [median (IQR)] g/L								
d 1[2]	42 (39–46.8)	52 (40–65.8)	62 (50–72)	68 (56–79)	42 (40–46)	61 (42–70)	62 (47–72)	42 (39–45)
d 3[3]	70 (62–78)	66 (54.5–72.5)	65.5 (52–72.2)	70 (60–80)	64 (59–70)	66.5 (56.2–72)	64 (45–73)	64.5 (45–72)
d 1 STP >52 g/L [N (%)]	12/82 (21)	53/110 (48)	25/37 (68)	65/83 (78)	15/143 (10)	47/74 (64)	43/61 (70)	18/99 (18%)
d 3 STP ≤52 g/L [N (%)]	2/80 (3)	21/107 (20)	9/36 (25)	10/81 (12)	4/143 (3)	13/74 (18)	19/61 (31)	31/98 (32%)
Suckled at pasture [N (%)]	42/83 (51)	41/110 (37)	7/39 (18)	11/85 (13)	66/145 (45)	20/74 (27)	6/61 (10)	60/100 (60%)
Brix % [mean (IQR)]	25.3 (24.0–26.0)	18.6 (16.6–20.6)	15.1 (14.5–15.5)	19.1 (16.1–20.6)	22.5 (21.3–23.6)	20.8 (18.6–22.0)	15.2 (14.0–16.5)	20.9 (14.3–26.0)
Brix % ≥ 22% [N (%)]	81/83 (98)	1/110 (1)	0/39 (0)	6/85 (7)	102/145 (70)	23/74 (31)	0/61 (0)	54/100 (54%)

[1]IQR = interquartile range.
[2]d 1 defined as samples taken before the farmer-fed colostrum to the calf in the rearing shed.
[3]d 3 defined as sample taken at least 48 h after the farmer started feeding colostrum to the calf in the rearing shed.

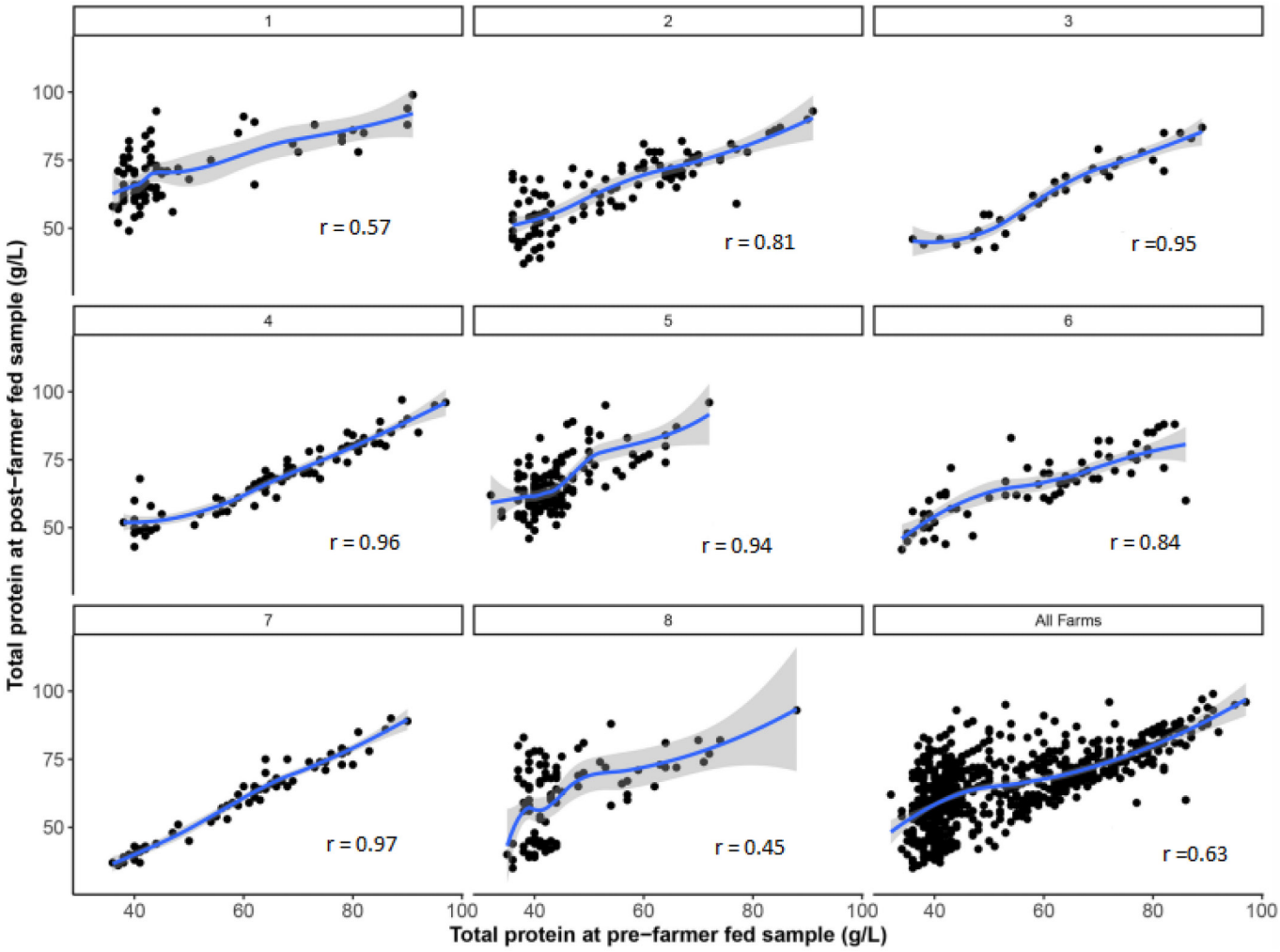

Figure 2. Scatterplot of calf serum total protein concentrations of the blood samples collected before farmer feeding colostrum (d 1, x-axis, median 11.5 h postbirth) and after farmer feeding colostrum (d 3, y-axis, median 65.5 h postbirth) for each of the 8 farms, and all calves combined. A locally weighted regression line is represented by a solid blue line, and the extent of the gray shaded area surrounding the regression line is the 95% confidence limits of the regression line. Spearman's rank correlation coefficient is included for each farm, and overall.

CI 0.58 to 0.67). Within farms, this correlation ranged from 0.45 (farm 8) to 0.97 (farm 7; Figure 2).

The Brix % of the colostrum fed to the calves once removed from pasture by the farmer varied considerably between farms (Figure 3). On farms 2, 3, and 7, none of the colostrum that was fed to calves as their first feed after being removed from pasture had a Brix ≥22%. In farm 7 in particular, the greatest Brix % that was fed over the study period was 16.5%. In contrast, calves in farm 1 were fed colostrum with a Brix ≥22% at every first feeding event after removal from pasture. A large variation existed within some farms; for example, on farm 4, one colostrum sample had a Brix % of 26.6, but the next greatest Brix % was 21.0%, and on farm 8, Brix was either >24% or <18%.

Association Between Feeding and Removal from Pasture and STP Before Any Farmer-Fed Colostrum (d 1 Blood Sample)

Of those calves that suckled at pasture, 260/442 (58.8%) had STP >52 g/L at d 1, compared with 23/247 (9.3%) of the calves that had not been recorded as suckling at pasture; however, this varied between farms (Supplemental Table S2; https://doi.org/10.17632/kdvcbwvrxm.1; Cuttance, 2022). Across all calves, the risk ratio of having STP >52 g/L in calves that suckled in the paddock was 2.20 (95% CI 1.96 to 2.48) times that of calves that did not suckle in the paddock. Time from birth to removal from pasture had a linear association with STP concentration at the d 1

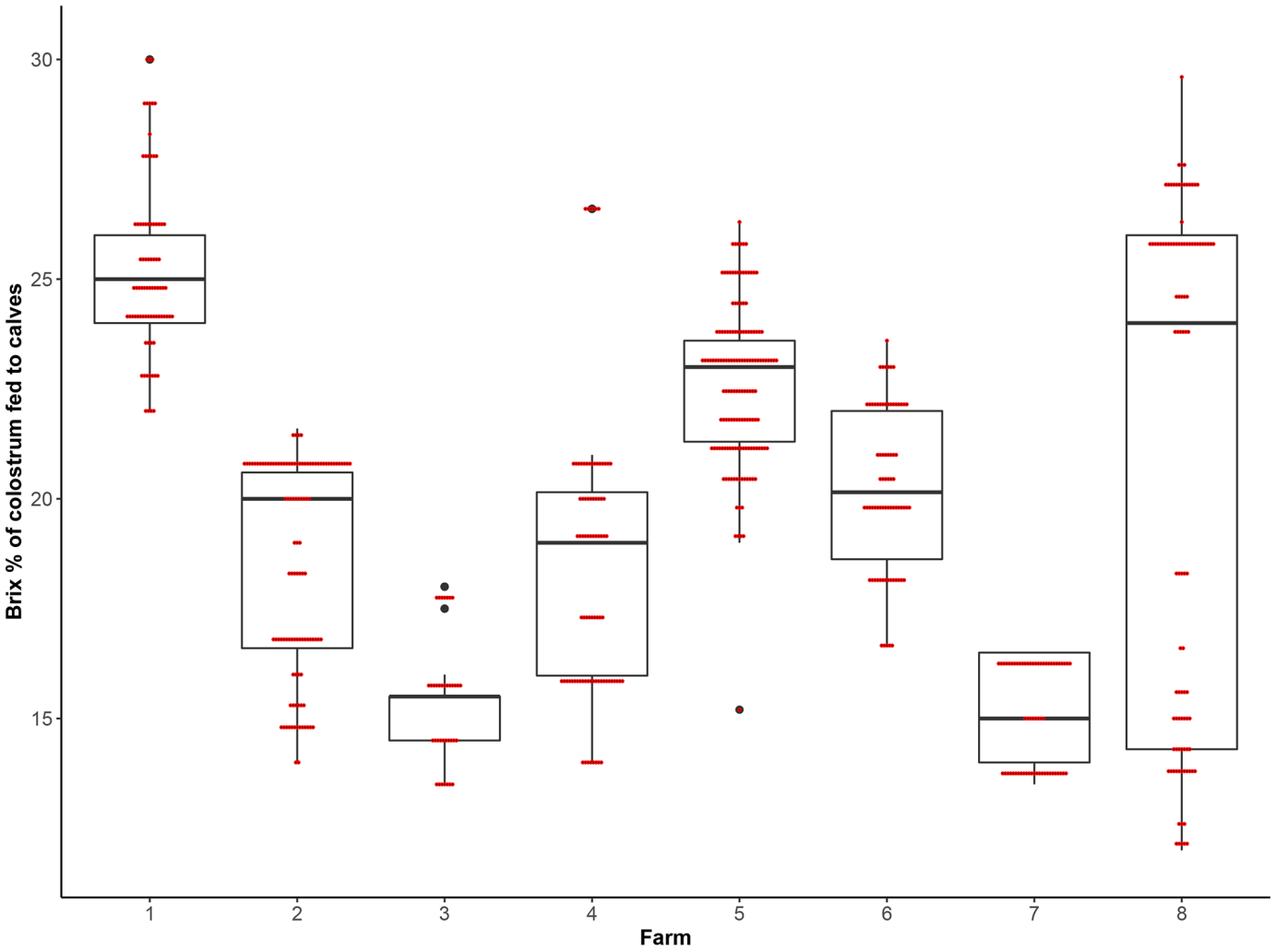

Figure 3. Boxplots and jittered dot-plots of the colostrum Brix % that was fed to the calves by the farmer at their first feed after removal from pasture shown for each of the 8 farms. Red dots show the raw data of every measured Brix data point for the farm. The box shows the interquartile range of Brix %, with the black line inside the box representing the median value. The whiskers indicate the upper and lower quartile of Brix % values, and the black dots are measurement outliers (more than 1.5× interquartile range.

sample. After accounting for farm, every hour longer that a calf remained at pasture postbirth was associated with a 1.30 (95% CI 1.16 to 1.44) g/L greater STP. No interaction was found for farm and time from birth to removal from pasture ($P = 0.95$; Supplemental Figure S1; https://doi.org/10.17632/kdvcbwvrxm.1; Cuttance, 2022).

After removal of those calves that had their first suckle within 6 h of the time of the d 1 sample (n = 63), calves that suckled at pasture had a curvilinear relationship between time to first suckle at pasture and STP at d 1 (Supplemental Figure S2; https://doi.org/10.17632/kdvcbwvrxm.1; Cuttance, 2022). After accounting for the differences between farms, calves that suckled at 2 h postbirth had a predicted marginal mean STP of 61.1 (95% CI 59.5 to 62.6) g/L; calves that suckled at 6, 9, and 12 h had a predicted marginal mean STP of 51.6 (95% CI 48.6 to 54.6) g/L, 49.1 (95% CI 45.4 to 52.8) g/L, and 50.5 (95% CI 44.8 to 56.3) g/L, respectively.

In this model, 2 calves had large Cook's distance values. Both were from farm 4, and one had a standardized residual of 2.5 and the other of −2.4. No reasons were found to exclude these 2 values, and they did not have undue influence on the model output.

Association Between Feeding and Removal from Pasture and STP or FPT at the d 3 Sample

Of those calves that suckled at pasture and had a d 3 blood sample, 42/439 (9.6%) were diagnosed with FPT, compared with 67/241 (27.9%) of the calves that were not recorded as suckling at pasture; however, this

Table 3. Numbers of calves and percentages that were classified as having failure of passive transfer of immunity (FPT; defined as serum total protein ≤52 g/L) in each of the 8 farms enrolled in a study investigating the feeding of calves from their dam from calves tested approximately 48 h or more after the farmer fed the first colostrum when the calves arrived at the rearing shed

	Did suckle			Did not suckle		
Farm	FPT positive	FPT negative	% FPT	FPT positive	FPT negative	% FPT
1	0	39	0	2	39	5
2	7	62	10	14	24	37
3	6	25	19	3	2	60
4	6	66	8	4	5	44
5	0	79	0	4	60	6
6	8	46	15	5	15	25
7	14	41	25	5	1	83
8	1	39	3	30	28	52

varied between farms (Table 3). The FPT risk at d 3 in calves that did not suckle in the paddock was 2.91 (95% CI 2.04 to 4.13) times the risk of those calves that did suckle in the paddock. And again, although a range existed, all 8 farms had a greater proportion of calves with FPT in those that did not suckle at pasture compared with those did suckle.

After accounting for farm, a moderate positive linear association existed between time at pasture and STP at d 3; every hour extra calves were left at pasture was associated with a 0.48 g/L (95% CI 0.31 to 0.65) increase in STP by d 3. No interaction between farm and length of time at pasture was identified ($P = 0.56$). Furthermore, despite calves remaining at pasture for differing lengths between farms, the point estimate for the Spearman's rank correlation coefficient for all 8 farms were all positive, with an overall ρ of 0.17 (95% CI 0.10 to 0.25). The relationship between the odds of FPT and time at pasture was not linear. From the output from a generalized additive model, no association was identified between the odds of FPT and a nonlinear smoothed term for time at pasture.

From the subset of calves that did suckle at pasture, a curvilinear relationship was noted between time to first suckle at pasture and STP at d 3 (Supplemental Figure S3; https://doi.org/10.17632/kdvcbwvrxm.1; Cuttance, 2022). After accounting for the differences between farms, calves that suckled at 2 h postbirth had a predicted marginal mean STP of 68.8 (95% CI 67.6 to 69.9) g/L; calves that suckled at 6, 9, and 12 h had a predicted marginal mean STP of 63.1 (95% CI 60.7 to 65.6) g/L, 62.0 (95% CI 58.8 to 64.9) g/L, and 63.1 (95% CI 58.3 to 67.9) g/L, respectively.

When assessing the relationship between FPT at d 3 and time to first suckle, however, a linear relationship was identified between the log odds of FPT at time to first suckle. After accounting for differences between farms, every hour longer postbirth that it took for a calf to have its first suckling event was associated with a 1.21 (95% CI 1.08 to 1.36) times the odds of FPT at d 3. One calf had a Cook's distance of 0.076, 4 times greater than the next highest Cook's distance. This calf had a STP of 52 g/L (so was on the cutoff value of FPT) and suckled in the paddock at 2.2 h. However, this calf did not have a large influence on the model output, and remained in the model.

The number of suckling events was associated with the odds of FPT at d 3. Compared with one suckling event, calves had 0.42 (95% CI 0.15 to 0.99), 0.35 (95% CI 0.15 to 0.76), and 0.10 (95% CI 0.005 to 0.47) times the odds of FPT if they had 2, 3–5, or >5 suckling events, respectively. The colostrum Brix % fed by the farmer did not confound the relationship between number of suckling events and FPT, nor was there an interaction between Brix % and number of feeds and the odds of FPT.

A total of 240 calves did not suckle at pasture had a blood sample collected at d 3 and had an associated Brix % of the colostrum that was fed by the farmer recorded. All 8 farms were represented with a range of 5 to 64 calves per farm (median 29 calves). After accounting for the effect of farm ($P < 0.001$), every 1 percentage unit increase in Brix % was associated with a 0.33 (95% CI 0.24 to 0.42) reduced odds of FPT. This relationship was linear on the log odds of FPT scale, with the predicted probability of FPT across the range of Brix % for this subset of calves presented in Figure 4. For calves that did not suckle at pasture, those that were fed colostrum with Brix % of 22 had a risk of FPT of 0.13 (95% CI 0.07 to 0.22), compared with 0.25 (95% CI 0.17 to 0.36) and 0.43 (95% CI 0.31 to 0.55) for those calves fed colostrum with Brix % of 20 and 18, respectively.

When assessing the joint effect of suckling and Brix %, calves that did not suckle at pasture and were fed colostrum with Brix <22% had a lower STP concen-

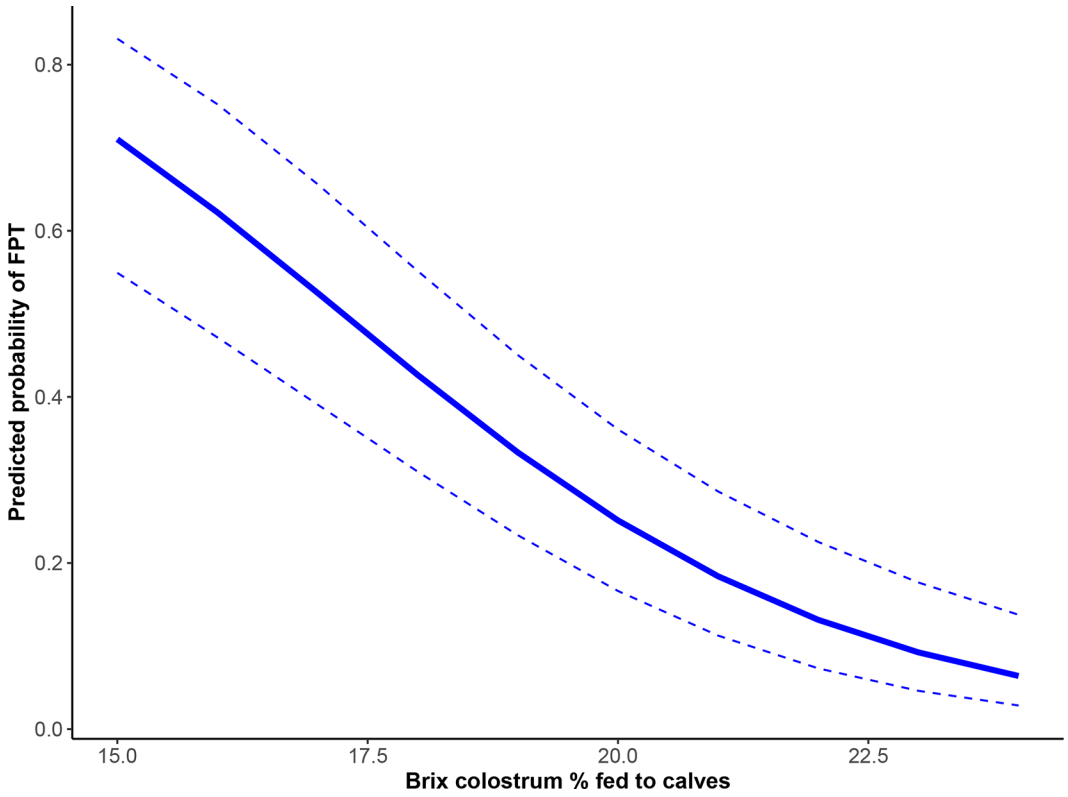

Figure 4. Predicted probabilities of failure of passive transfer (FPT; serum total protein ≤52 g/L) for calves that did not suckle at pasture over the range of Brix % of first colostrum fed to calves by the farmer. Outputs are estimated marginal means (solid line) and 95% confidence intervals (dashed lines) from a linear model, after accounting for farm (n = 240 calves from 8 farms).

tration compared with the other 3 groups (Table 4; Figure 5), ranging from 11.4 (95% CI 9.1 to 13.8) g/L lower STP compared with calves that suckled at pasture, and had a Brix <22%, to 18.6 (95% CI 16.0 to 21.1) g/L lower STP compared with calves that both suckled and were fed colostrum, with Brix ≥22%. Furthermore, calves that both suckled and were fed colostrum with Brix ≥22% had a 4.8 g/L (95% CI 2.6 to 7.0) and 7.2 g/L (95% CI 4.9 to 9.4) greater STP, when compared with calves that suckled at pasture and had a Brix <22% and calves that did not suckle and were fed colostrum with Brix ≥22%, respectively. The data were consistent with no difference in STP between calves that suckled at pasture and had a Brix <22% and calves that did not suckle and were fed colostrum with Brix ≥22% (STP 2.4 g/L, 95% CI −0.3 to 5.0 greater). The variance was greatest in the calves that suckled and were fed colostrum with Brix <22% and lowest for those that did not suckle yet fed Brix ≥22%; therefore, weighted variance inflation factors were added to the model to account for this (Table 4). The odds of FPT were 42.5 (95% CI 15.0 to 178.7) times lower for calves that suckled and were fed colostrum with Brix ≥22% compared with calves that did not suckle at pasture and were fed colostrum with Brix <22% (Table 4). After adjusting for multiple comparisons, the data were also consistent with no difference in FPT between calves that suckled at pasture and had a Brix <22% compared with calves that did not suckle and were fed colostrum with Brix ≥22% (OR 0.48, 95% CI 0.14 to 1.28).

Risk Factors for FPT at d 3

After removal of all calves from farm 8, age of the dam had an association with FPT status of the calf at d 3 (n = 597 from 7 farms). After accounting for farm, compared with calves that were born from dams >7 yr of age (n = 78), the odds of FPT was 0.33 (95% CI 0.14 to 0.72) and 0.52 (95% CI 0.28 to 0.98) times for calves born from dams 2 to 3 yr of age (n = 155), and 4 to 7 yr of age (n = 364), respectively. Additionally, this association was present in both calves that suckled at pasture and those that did not suckle at pasture; therefore, no interaction was identified between age and whether a calf has suckled as pasture or not ($P = 0.51$).

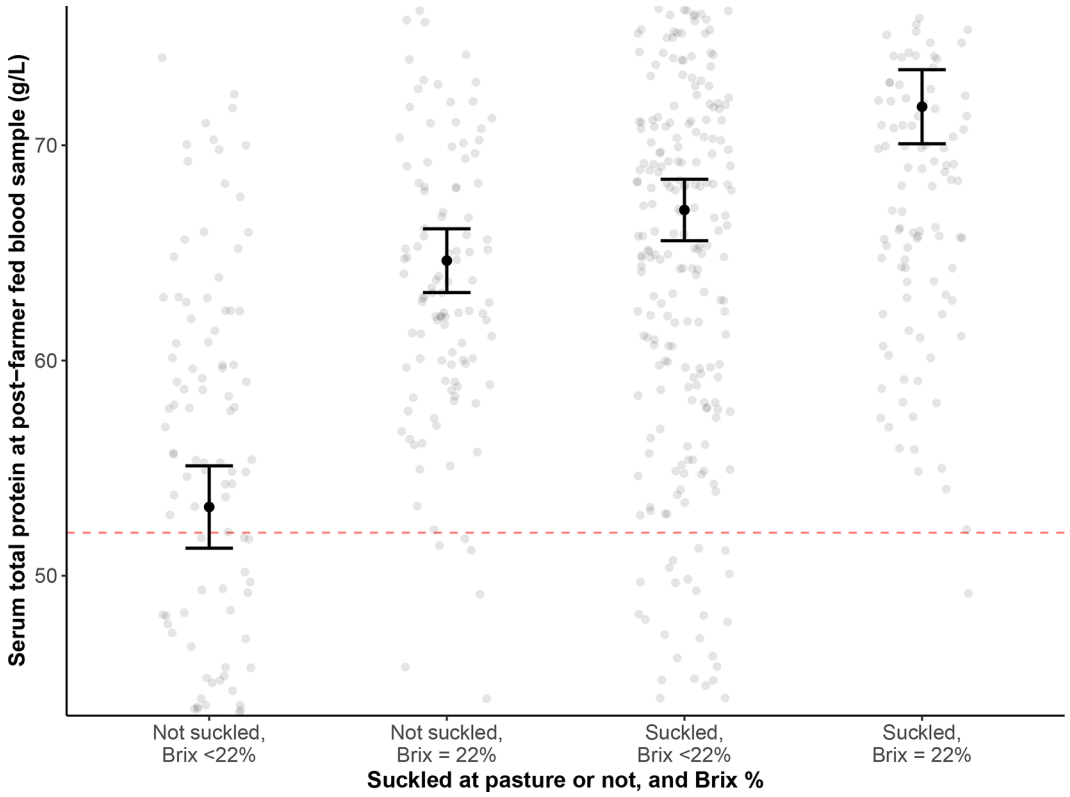

Figure 5. Error plot for the estimated marginal means of serum total protein at the post-farmer-fed blood sample for suckling status and Brix % of colostrum of first fed after removal from pasture. Outputs from a linear model (n = 678 calves from 8 farms). The gray points are the raw data for calves from each group, with some data points extending beyond the y-axis margin. The horizontal dashed red line represents serum total protein cutoff of >52 g/L, determining adequate colostral transfer (Cuttance et al., 2017a). Error bars represent SEM.

Suckling status also did not confound the relationship between age and FPT status.

No associations were identified between breed of the dam and FPT status ($P = 0.32$) and pre-calving BCS of the dam and FPT status ($P = 0.96$).

Six hundred seventy-seven calves had a blood sample collected at d 3 and had a corresponding minimum ambient temperature around the time of birth. After accounting for the differences between farms, the odds of FPT if minimum temperature was < 10°C was 0.71 (95% CI 0.38 to 1.28), compared with if minimum temperature was ≥10°C.

DISCUSSION

As far as we are aware, this study is the largest study investigating the suckling of calves from their dam, and the only one that has followed calves at pasture, collected and transferred to a rearing shed, until they are approximately 4 d old, therefore, allowing both the success of suckling before housing, and the success of colostrum feeding upon housing in transferring passive immunity, to de determined.

The first measurement of STP (d 1 measurement) was made after transfer from pasture to housing but before

Table 4. The number of calves that had suckled or not and the colostrum quality they received from the farmer and the associated serum total protein (STP), number with failure of passive transfer (FPT; defined as STP ≤52 g/L), and odds of FPT in a study investigating the feeding behavior of calves from 8 farms in New Zealand[1]

Suckling at pasture	Colostrum Brix %	Number calves	Variance weighting (95% CI)	STP (95% CI)	Number with FPT	Odds ratio (95% CI)
Not suckled	Brix <22	129	0.86 (0.74–0.99)	Referent	60 (47)	Referent
	Brix ≥22	118	0.64 (0.55–0.75)	11.4 (9.1–13.8)	7 (6)	0.068 (0.027–0.150)
Suckled	Brix <22	302	1.00 (referent)	13.8 (11.4–16.2)	39 (13)	0.16 (0.10–0.26)
	Brix ≥22	141	0.82 (0.71–0.94)	18.6 (16.0–21.1)	3 (2)	0.024 (0.006–0.067)

[1]Heteroskedasticity was present between the 4 groups, and different variance weightings were applied to each group.

calves being fed colostrum by farm staff. This measurement provided an indication of whether suckling events had resulted in a successful feed (i.e., STP >52 g/L). Sampling at this point is generally not recommended, as it will underestimate the adequacy of passive transfer. For example, Trotz-Williams et al. (2008) reported that the mean STP concentrations of calves <1 d of age was markedly less than that of calves between 1 and 8 d of age (54 vs. 63 g/L, respectively). Therefore, it is important to emphasize that our d 1 measurements will underestimate the success of suckling in producing adequate transfer of passive immunity. Although d 1 STP results >52 g/L do indicate that a calf (if healthy and not dehydrated) has suckled and successfully fed, STP results ≤52 g/L, may indicate several possibilities. It may indicate that (1) a calf has not taken in sufficient IgG from the dam (because of a failure to suckle at all, or because the colostrum that was suckled was poor quality or of insufficient quantity) or (2) there was not enough time between suckling (including all suckling events) and blood sampling for the IgG to be absorbed. Hence, this test needs to be interpreted with caution if it is used to assess whether feeding has failed, and any such interpretation needs to be coupled with a good understanding of the farm management; however, it is useful to confirm if the suckling events before any farmer intervention have been successful, in terms of ingestion of enough IgG.

If we just looked at the total number of animals that had >52 g/L from the total number of calves (41.1%; 95% CI = 37.4 to 44.9), we would assume that allowing calves to feed with the dam in the paddock was unsuccessful. However, the 41.1% figure included calves that were kept with their dams for as little as 0 min right up to 25.3 h and included animals that were tested within 6 h of suckling. This figure, then, does not provide a true assessment of the potential success of suckling. Our analysis showed that every hour longer that a calf remained at pasture postbirth was associated with a 1.30 (95% CI 1.16 to 1.44) g/L increase in STP. This is consistent with the data of suckling behavior reported in Cuttance et al. (2022), which showed that the longer calves are able to stay with the dam, the more likely they are to suckle their dam and the more likely they are to have multiple suckling events. This is also likely a function of IgG absorption increasing over time (Hancock, 1985; Burton et al., 1989). Thus, if we look at the calves that suckled, had at least 6 h with their dam, and had at least 6 h from first suckling to blood testing (n = 296), the equivalent figure was 76.5% (95% CI = 71.2 to 80.8). This figure is more favorable to the success of suckling, but it does not reflect the large farm variability. The proportion of calves with STP >52 g/L on d 1 varied from 10% (farm 5) to 78% (farm 4) and was likely contributed by the proportion of time left with the dam and when calves were blood sampled. However, even for farms that picked up once a day, considerable variability was still observed. Although differences were present in STP concentration at d 1 in animals that were sampled >6 h and <6 h from the first suckling event, the time period from ingestion of colostrum and absorption, and subsequent increase in STP concentrations, is still not known. Further work on this is required to be able to produce practical guidelines for farmers and advisors to assess the success of colostral transfer from the dam.

In contrast to the d 1 measurement, the d 3 measurement of STP is a true reflection of the concentration of immunoglobulins absorbed. The FPT prevalence across all calves was 16.0% (95% CI 13.5 to 19.0) with a range between farms of 2.5–31.6%. This is quite a lot lower than had been previously reported in New Zealand (24.8 and 33%; (Lawrence et al., 2016; Cuttance et al., 2017b) and does suggest that the farms enrolled may not necessarily be typical of New Zealand dairy farms (at least in regard to colostrum management). Overall, it is very difficult to compare our study to other studies that look at calves feeding from the dam, as the definition of "being left with the dam" varies so much between publications (Table 1).

Day 3 STP is dependent on the combined success of suckling at pasture and farmer feeding of colostrum once the calves reach the rearing facility. The success of the suckling component of this measurement at the d 3 sample was affected by how long it took for calves to have their first feed, length of time spent with the dam, and the number of feeds the calf had. This relationship was present across all farms, regardless of colostrum feeding practices after calves were housed. Time to first feed and number of feeds had the greatest effect on the risk of FPT. For every hour longer postbirth that it took for a calf to have its first suckling event, the odds of FPT at d 3 increased by 1.21 (95% CI 1.08 to 1.36) times; whereas, compared with calves that only suckled once, calves had 0.42 (95% CI 0.15 to 0.99), 0.35 (95% CI 0.15 to 0.76), and 0.10 (95% CI 0.005 to 0.47) times the odds of FPT if they had 2, 3–5, or >5 suckling events, respectively. These 2 measures are likely to be linked, as the sooner a calf has their first feed, the more feeds they will likely fit in before they are separated from the dam (Selman et al., 1970a). Anecdotally, the observation teams working on the study felt that more than one feed was important, as the second feed generally appeared to be more successful than the first. At the first feed, the calf often spent time figuring out where the teats were while the

dam was getting used to the calf suckling (Selman et al., 1970b,c). The result of this was that during their first feeds, calves tended to come on and off the teat a lot, whereas, second feeds tended to be longer and more controlled (once they started). This would logically increase the volume of colostrum ingested by the calf and, therefore, naturally increase the STP and reduce the FPT.

The second key component contributing to the d 3 STP and FPT results was colostrum quality. Colostrum quality varied considerably between farms; on farm 3 the greatest Brix % of colostrum fed over the study period was 15.5% and, in contrast, on farm 1 81/83 calves were fed ≥22% Brix colostrum at their first feeding event after removal from pasture. These results have similarities with the results from Denholm et al. (2017), who reported a range of colostrum quality from 6.1 to 28.5 Brix % from 298 colostrum samples from 105 farms across New Zealand. Colostrum quality made a difference to the overall FPT outcome, regardless of whether calves had suckled. In the calves that suckled and were given high-quality colostrum, STP was higher and fewer calves had FPT than if they suckled and were fed colostrum of lower quality (<22% Brix), when compared with the other 3 groups. This is an important finding because it suggests that both suckling at pasture and farmer management of colostrum feeding can work synergistically to improve passive transfer of immunity in calves, even when colostrum feeding is delayed. Even if calves have suckled, feeding high-quality colostrum on housing allows those calves that may not have ingested enough colostrum (quantity, volume, or both) to "catch up." In addition, even in the calves that have already ingested sufficient IgG from the dam, it allows them to ingest even more. This is becoming increasingly recognized as important, with higher cutoffs of STP/IgG being suggested as cutoff points for FPT (Lombard et al., 2020), as well as a linear relationship between increasing STP and decreasing mortality risk (Cuttance et al., 2018b).

One of the most interesting findings was that calves that suckled but were given poor-quality colostrum revealed a trend of greater STP compared with calves that did not suckle but were given high-quality colostrum. Yet, the direction of association for the odds of FPT was the opposite; the odds of FPT was greater in the suckled or poor colostrum group than the not-suckled or good colostrum group. This is because the variance of STP in calves given poor-quality colostrum was greater than that of calves given good-quality colostrum (Table 4).

High-quality colostrum reduces variability in STP (compare groups 1 vs. 2 and 3 vs. 4 in Table 4). This is because when calves are housed and get between 1 and 4L of high-quality colostrum (depending on the farm), they are more likely to take in sufficient IgG to prevent FTP, irrespective of previous suckling history. This reduced variability has been reported before in Cuttance et al. (2018a), where the natural log of the standard deviation of concentrations of TP in serum decreased with an increasing Brix percentage. In contrast, when poor-quality colostrum is fed, calves are more dependent on what they have suckled before housing. Thus, in calves that have suckled but are fed poor-quality colostrum, the combination mean STP increases but the large variation originally present from suckling remains unaffected. Calves that have not suckled start with little STP but also little variance. Adding quality colostrum means that the variance does not change very much but mean STP goes up. Calves that have not successfully suckled, and are not fed high-quality colostrum, represent a very high risk group because they are not able to rely on any method to gain IgG. This is shown by calves that did not suckle and were given <22% colostrum having a 42.5 (95% CI 15.0 to 178.7) times greater odds of FPT than calves that suckled and were given high-quality colostrum. Large variability still exists in this particular group, though, with 53% of calves in this group still ending up with >52 g/L STP. Some of these calves may actually have fed but not have been recorded as doing so (9.3% of calves that had not suckled had STP on d 1 >52 g). However, the most likely reason that these calves did not have FPT was that, despite being fed less than optimal colostrum, they were still able to intake sufficient antibodies (Quigley et al., 2013; Bartier et al., 2015). For example, on some farms, if calves were collected only hours after birth, they could have received 3 feeds of 2 to 3 L of colostrum within the first 24 h. Even if Brix % was <22, ingesting this volume of could have resulted in sufficient IgG absorption. This is especially likely to be the case if Brix % was close to 22% (e.g., 20 or 21%).

One of the most practical findings of this study was that the effect of the quality of colostrum on the odds of FPT was not just reserved for high-quality colostrum with a Brix percentage over 22%. The effect of colostrum quality was linear and, for every 1% increase in the Brix % of colostrum, the odds of FPT decreased by 33% (95% CI 24 to 42). In the New Zealand system, this finding is very important because one of the challenges with getting farmers on board with measuring colostrum quality is that the high frequency of colostrum tests that are <22% means that farmers frequently get disappointed with measurement, especially if they are not able to identify any colostrum

that measures >22% Brix. This is particularly likely when calves are left with their dam for up to 24 h, as colostrum quality will decrease over this period, even if the calf has not fed (Kruse, 1970). Thus, this analysis suggests that feeding the highest quality colostrum available will still have some value, even if it is not at the targeted 22% (i.e., 20% is still better than 18%, which is better than 16%). Even if the Brix % is not ideal, a higher quantity of IgG will still be beneficial, and advice for trying to increase the volume or number of feeds in this scenario will be beneficial. Using all of this information from this research together, the ultimate goal for the future is to have the ability to tailor the optimal colostrum management for each farm, depending on the interacting aspects of timing of consumption, colostrum IgG concentration, and volume, with each aspect potentially being used to make up for inadequacies in the others.

The final section of this study investigated risk factors for FPT and they were similar to the risk factors for suckling (Cuttance et al., 2022), with calves born to older dams (>7 yr) having a 3 and 2 times higher odds of FPT when compared with 2- to 3-yr-old dams and 4- to 6-yr-old dams, respectively. As suggested in Cuttance et al. (2022), age is likely to affect udder conformation which, in turn, can affect calves' ability to find the udder and teats and successfully suckle (Selman et al., 1970c; Ventorp and Michanek, 1992); however, this relationship was also present in animals that did not suckle. We are unsure of how this relationship could occur, especially given that calves are not fed their own dam's colostrum but are fed pooled colostrum from the group of recently calved dams. Nonetheless, practically, this relationship suggests that farmers may need to pay extra attention to calves born to older dams and adjust their management accordingly.

Despite the fact that the associations and relationships presented from our study account for the farm in the analysis and are consistent across all the farms (e.g., the time to first suckling and FPT), this does not mean that there is not considerable between-farm variability. Therefore, applying these results as generalized advice to individual farms is risky for several reasons. First, simply leaving the calves with the dam longer to help reduce FPT is not necessarily the answer for all farms. Although the pattern is similar across the farms, there were still farms where the calves suckled considerably slower than other farms and, overall, fewer calves suckled at all (Cuttance et al., 2022). So, on these farms, even if leaving calves with the dam may help increase STP, this may not actually be better than removing them and focusing on giving them high-quality colostrum (the farms with the lowest FPT in this study were farms that picked up calves quickly and fed them high-quality colostrum). Conversely, on other farms, calf FPT status may not be improved by removing them from the dam more regularly, as they are not able to achieve the management steps required to give high-quality colostrum quickly (e.g., farm 3, 4, and 7). Practically, this study has demonstrated that providing animals with colostrum as soon as possible after birth and leaving animals to suckle can both be successful strategies (i.e., minimize FPT). Whether one is more successful than the other will often depend on how well both practices are carried out. In New Zealand, we know already that the provision of measured, high-quality, hygienic colostrum is poor (Denholm et al., 2017) and so providing animals with colostrum as soon as possible after birth will not necessarily be effective, let alone practically achievable. Still, leaving calves to suckle will not be effective if the calves are not monitored to ensure they are indeed feeding and intervention used if necessary (e.g., inclement weather, dystocia, calves with poor vigor).

The issue for farmers who leave animals to suckle is that very little research exists on how to improve the success of natural suckling in dairy cattle. As far as we are aware, there have been no peer-reviewed studies in this area. For example, all of the studies cited in Table 1 include a suckling group, but only one study (Petrie, 1984) has more than one such group. In that study, calves kept with their mothers were allowed to either suckle naturally or assisted to suckle immediately after birth (an intervention that is even more unfeasible under New Zealand conditions than collecting calves more frequently than twice a day). Johnsen et al. (2019) only had one suckling group but had a within-group comparison, which allowed the immunoglobulin uptake of calves that were visually assessed after birth and thought not to need assistance to suckle with calves that were thought to need assistance. Unfortunately, such data does not identify whether that approach improved the success of suckling. Most published research has focused on headline figures from studies such as Brignole and Stott (1980) who reported that 42% of calves fail to either suckle or to absorb colostral immunoglobulins from suckling, and responded by recommending artificial feeding rather than investigating why the success rate of natural suckling was so low.

The 42% reported by Brignole and Stott (1980) was, comparable to our d 1 result, based on sampling after separation but before farmer feeding, so, is subject to the same caveats as our d 1 result. In particular, it is an overestimate of the failure of suckling and that figure includes calves that were born relatively close to pick, which would have had less chance of suckling

and less chance of multiple suckling events, and calves which have fed recently but not yet absorbed the colostrum antibodies. Interestingly, despite differences in the methods of assessment of antibody uptake, their figure of 42% is similar to the 36% of calves on farms with once a day pick-up that had STP ≤52 g/L on d 1 (farms 2, 3, 4, 6, and 7; Table 2).

Nevertheless, this average figure hides a very large variation, even within these farms that picked up calves at very similar rates. These large between-farm differences highlight the potential for better management to improve the transfer of passive immunity from dam to calf at pasture, but it also highlights that if the dairy industry is indeed planning to consider a future where calves are allowed to stay with their dam for longer periods of time, further research is urgently needed to understand the reasons for such pronounced variability and whether farmers have any control over such variability.

This study was an observational study conducted on a convenience sample of 8 farms. Potential measurement bias existed with multiple observations being collected at any time point. Occasions were present where, due to the sheer number of cows and calves being observed at one time point, observations (e.g., standing, first feed) could have been missed. However,, if this bias does exist, then it would likely tend toward the null (i.e., any associations between suckling and FPT success presented are likely to be conservative). Furthermore, despite the farm variability, on all farms, calves that suckled at pasture had lower d 3 FPT prevalence than those that did not suckle, and on all farms that had colostrum samples with >18% Brix, a positive association existed between Brix % of colostrum and FPT prevalence. That is, on these farms both allowing calves to suckle and feeding them good-quality colostrum on housing increased the transfer of passive immunity. Despite the enrolled farms potentially not being representative of all New Zealand dairy farms with respect to colostrum management, these consistent findings within and between farms give us confidence that they can be applied to the greater New Zealand dairy farming population.

CONCLUSIONS

This study has demonstrated that providing animals with high-quality colostrum after birth and leaving animals to suckle can both be successful strategies to minimize FPT. How successful they are depend a lot on the individual farm. There is no value in collecting calves frequently and feeding colostrum, if farmers are not able to ensure that the colostrum is high-quality and hygienic, since colostrum quality had a linear effect on FPT, then, the lower the colostrum quality, the higher the FPT odds. In a similar argument, although on all farms, time in the paddock with the dam and number of feeds that calves managed to have reduced FPT risk, this was in calves that were actually suckling. Therefore, if they suckle, this strategy is great but, if they do not suckle or take longer to suckle, this strategy is equally risky and we do not yet have robust strategies to improve this (other than regular checking). Therefore, the large herd variation needs to be urgently investigated further to help improve passive immunity in calves born at pasture.

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