Enhancing precision within winter feeding systems for dairy cows

End of Project Report for AgriSearch in Relation to
DAERA E&I 16/1/10

Research team

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August 2021

This research programme was funded by the Department of Agriculture, Environment and Rural Affairs for Northern Ireland and AgriSearch

STRUCTURE OF REPORT

This report begins with an Executive Summary which highlights the background to the overall project and provides a brief description of the work undertaken within the project.

The main body of the report provides a detailed description of a number of research areas, namely: two dairy cows feeding studies, the development of an individual cow intake prediction model, an examination of the potential of behavioural data to predict energy balance of individual cows, and an examination of the potential of MIR analysis of milk to predict individual cow energy balance.

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EXECUTIVE SUMMARY

- Dairying is a key component within the Northern Ireland agricultural sector. However the profitability of the dairy sector can vary greatly from year to year, with milk price and costs of inputs being two of the key factors influencing returns. Milk price is largely outside of the control of the dairy farmer, with local milk prices increasingly determined by world market forces. Similarly, while the costs of feed, fuel and fertiliser are largely determined by international factors outside of the control of local farmers, farmers can optimise the use of these resources on their own farms. This is particularly true for feeds, and especially concentrates, which currently represent approximately 60-70% of variable costs of production on Northern Ireland dairy farms.
- Concentrate feeding systems which involve a feed-to-yield approach are now common on many Northern Ireland dairy farms. This is due in part to the integration of computerized parlour systems and feeding systems, which enables farmers to offer concentrate supplements on an individual cow basis. This is often done on the basis of milk yield (i.e. feed-to-yield). These systems seek to improve precision of concentrate feeding by targeting concentrates to higher yielding cows, where an economic response is expected.
- In practice, most feed-to-yield systems involve a forage or forage-concentrate mix (basal ration), which is assumed to supply sufficient nutrients to meet the cow's maintenance energy requirements and to support the production of a given amount of milk (M+). Additional concentrates are then offered to individual cows on a feed-to-yield basis to support milk production above the yield that the forage/basal ration is assumed to support. A key component of this research project was to examine if the precision of concentrate feeding within these feed-to-yield systems could be improved.
- The project also recognised that new and emerging technologies may be able to make a contribution to improving the nutrition of individual cows.
- This report encompasses five separate sections: **Sections 1 and 2** describe two dairy cow feeding studies which seek to provide a better understanding off, and improve precision within feed-to-yield dairy systems, **Section 3** describes the development of an individual cow intake prediction model, **Section 4** examines the potential of behavioural data to predict dry matter intake and energy balance of individual cows, and **Section 5** provides a preliminary analysis of the potential of MIR analysis of milk to predict individual cow energy balance.

- Experiment 1 **(Section 1)** was designed to provide an improved understanding of the responses of individual cows when offered concentrates on a feed-to-yield basis, specifically when the approach is adopted with silages of differing feed values.
- Sixty Holstein-Friesian dairy cows were allocated to one of two diets: 'High' feed value silage mixed with concentrates in a basal ration or 'Medium' feed value silage mixed with concentrates in a basal ration. In both treatments the silage and concentrates were mixed in a 65 : 35 dry matter ratio in the basal diet. In both treatments extra concentrates were offered on a feed-to-yield basis through an out-of-parlour feeding system from 4 to 16 weeks post-calving.
- Cows offered the High feed value silage had a higher silage dry matter (DM) intake than cows offered the Medium feed value silage, and tended to have a higher total DM intake. However, concentrate intakes did not differ between the treatments. Silage feed value had no effect on milk yield, although the trend for a higher milk yield with the High feed value silage reflected the trend for a higher intake with this treatment.
- The higher milk protein content with the High feed value silage was likely a result of increased DM intake. There was no effect of treatment on milk fat content.
- Cows offered the High feed value silage had an improved energy balance, and this was reflected in these cows having a higher body condition score at the end of the experiment, suggesting that some of the extra energy consumed with this treatment was partitioned to body tissue.
- The quantity of concentrates required to support the production of each kg milk was higher with the Medium quality silage.
- The mean treatment outcomes were largely as expected when silages of two different qualities were offered; however, the primary objective of this study was to examine individual cow performance. As concentrate intakes increased, total DM intake also increased (a linear increase) with both silage types. In addition, silage DM intake also increased (or stayed relatively constant) as concentrate intakes increased. This is in contrast to non feed-to-yield systems where silage intakes would be expected to fall due to 'substitution'. That intakes do not fall off at higher concentrate levels reflects the fact that higher levels of concentrate are offered to higher yielding cows, and these cows have a greater intake capacity. This finding lends support to the practice of adopting a single M+ value for all cows in the group.
- As concentrate levels increased, milk yield also increased, with the response 'linear'. However, within feed-to-yield systems it is important to remember that concentrates

‘follow’ milk yields (i.e. 0.45 kg concentrate/kg milk), so the linear response is as expected. At any given concentrate level, milk yields of cows offered the High quality silage are generally higher than those of cows offered the Medium quality silage.

- Milk fat changed relatively little across the range of concentrate levels examined. However, there was a definite trend for milk protein to decrease, especially with the Medium quality silage. A wide variation in individual cow milk composition was observed, although feed-to-yield systems commonly assume a standard milk composition for all cows in a herd.
- The impact of concentrate level within a feed-to-yield system on margin-over-feed costs was examined at three different milk prices (18, 26 and 34 pence/kg). Feed costs were determined using actual feed intakes, with grass silage costed at £123/tonne DM and concentrates costed at £260/tonne fresh. The economic analysis also took into consideration the composition of milk produced.
- The marginal economic response decreased at higher concentrate levels. This was particularly evident at a low milk price (18 pence/kg), where an increase in milk yield beyond 40 kg/cow/day resulted in no real improvement in margin-over-feed costs. Even at a milk price of 26 pence per kg, the increase in margin-over-feed costs with many individual cows was small when milk yields were in excess of 40 kg/day. Part of this is due to the slight reduction in the value of milk produced due to the fall in milk quality at higher concentrate levels. However, the main driver of this decline in margin was the increasing cost of the diet with increasing concentrate inclusion level. For example, diet cost increased by an extra 2 - 3 pence per kg DM across the range of concentrate levels in this study. This was especially true for the cows offered the Medium quality silage, and this was reflected in generally lower margins at all milk yields with diets based on the Medium quality silage.
- The results of Experiment 1 confirm the benefits of higher quality silage in terms of improving intakes, milk protein content and economic performance. However, irrespective of silage quality, the economic benefits of offering additional concentrates was reduced at higher milk yields, even within a feed-to-yield system. When milk prices are poor, ‘pushing for extra litres’ will have little financial benefit.
- Experiment 2 **(Section 2)** examined if individual cow management could be improved within feed-to-yield systems by taking account of variation in milk composition and individual intakes. The study recognised that while a feed-to-yield approach brings some precision to concentrate feeding, many of the assumptions used are based on an ‘average cow’. For example, the approach assumes all cows produce milk with the same

fat and protein content, and that all cows consume the same quantity of basal ration. However, neither assumption is true, and this may lead to overfeeding or underfeeding of individual cows.

- This study was conducted over a 12 week period, and involved 69 mid-lactation Holstein dairy cows. All cows were offered the same basal ration which consisted of grass silage mixed with concentrate (at a rate of approximately 4.5 kg per cow per day), and offered via a mixer wagon. All cows were offered additional concentrates on a feed-to-yield basis via an out-of-parlour feeding system. Concentrate feed levels were adjusted weekly according to one of three approaches, as follows:

- *Conventional feed-to-yield*: this treatment followed a conventional feed-to-yield approach. The milk yield supported by the basal ration (M+) was determined based on the average intake of the group of cows on this treatment. Individual cows were then supplemented with concentrates at a rate of 0.43 kg concentrate per kg milk produced in excess of the M+ value. Over the course of the study the average M+ value was 14.4 kg/day for heifers and 20.8 kg/day for cows. Concentrate levels were adjusted each week based on milk yields during the previous week.

- *Precision 1 (feed-to-yield, with adjustment for milk composition):* this approach was similar to the ‘conventional’ treatment above, except with this treatment the concentrate feed level for each cow was adjusted taking account of each individual cow’s milk yield and milk composition. Thus, concentrate levels for cows producing milk with a high fat and protein content were increased to reflect the additional energy required to produce that milk, while concentrate levels for cows producing milk with a poorer composition were reduced. Concentrate levels were adjusted each week based on milk yields and milk composition during the previous week.

- *Precision 2 (feed-to-yield, with adjustment for milk composition and intakes):* as with the Precisions 1 above, this treatment also took account of differences in milk yield and milk composition of individual cows. However, this treatment was designed to be even more ‘precise’ in that it also took account of differences in intakes between individual cows. Thus, cows with higher intakes were assigned a higher M+ value while cows with lower intakes were assigned lower M+ value. Again, concentrate levels were adjusted each week based on milk yields, milk composition and intakes during the previous week.

- Cows managed using the Precision approaches consumed an additional 1 kg concentrate per day, compared to cows on the Conventional feed-to-yield treatment. However, silage DM intake and total DM intake was unaffected by treatment.

- Despite the higher concentrate intakes within the Precision treatments, milk yields with these treatments were not significantly higher than with the Conventional feed-to-yield treatment. However, milk protein content was higher with the two Precision treatments compared to the Conventional treatments, reflecting the higher concentrate levels. In addition, milk fat content tended to be lower in Precision 2 compared to the other two treatments, while cows on Precision 1 had a higher yield of fat plus protein yield (+0.13 kg/day) compared to the other two treatments.
- Despite these differences in intakes and milk composition, there was no evidence that any of the estimates of 'efficiency' were improved with the precision feeding approaches. For example, the amount of milk produced per kg of DM intake was almost identical across the three treatments (approximately 1.64 kg milk/kg DM intake).
- However, when 'concentrate use efficiency' was examined, more concentrate was offered per kg of milk (+0.04 kg) within the Precision treatments compared to the Conventional treatment. This indicates that the improved milk composition with the Precision treatments required extra concentrates.
- The results of Experiment 2 indicate that adoption of the precision approaches examined in this study cannot be recommended at this time. Rather, farmers should try to bring as much precision into their conventional feed-to-yield systems as possible by having good estimates of herd intakes, regular monitoring of forage composition, checking the current 'feed-rate' setting on the milking parlour software (and adjusting this according to herd milk composition if necessary), and ensuring that weigh cells in concentrate feeding systems are calibrated and accurate.
- Experiment 3 **(Section 3)** was designed to develop an individual cow DM intake prediction model for use within feed-to-yield systems, based on routine records available on farms.
- The rational for such a model was to improve precision within feed-to-yield systems. For example, a limitation of feed-to-yield systems is the assumption that the basal diet supports a single assumed M+ value for all cows. It was rationalised that if individual M+ values could be calculated for each individual cow, then concentrates could be offered with an increased level of precision.
- Data were obtained from five feed-to-yield studies conducted at the Agri-Food and Biosciences Institute, Hillsborough between 2013 and 2019. The following data was available from each study for each individual cow: lactation number, week in milk, and weekly data for total DM intake, milk production, milk composition, and live-weight.

Energy corrected milk yield (kg/day) and milk fat : protein ratio were subsequently determined for each week. In total, 3999 weekly records from four experiments, were used to develop the predictive models, and the 404 weekly records from the most recent experiment was used to estimate the accuracy of the estimation.

- Two linear regression models were constructed to predict daily DM intake. Model 1 included lactation number, energy corrected milk yield, fat : protein ratio and week-in-milk, while Model 2 also included live-weight.
- Both models were able to predict DM intake with good degree of accuracy. While Model 2 was the better Model, this relied on live-weight measurements which are not currently available on the majority of farms. There is substantial scope to develop these models further by incorporating some basic silage quality parameters, and this work will be taken forward in the future.
- This project also examined the potential of data obtained from some ‘wearable technologies’ to help predict DM intake and energy balance of individual cows (**Section 4**). Data was obtained from two studies. Study 1 involved 110 cows and was conducted from calving to 21 weeks of lactation. All of these cows were fitted with pedometers, while 45 of them were fitted with RumiWatch halters. Study 2 involved 69 mid lactation dairy cows fitted with pedometers over a 12 week period.
- Despite some significant correlations between behaviour parameters and production data, the fit of these relationships were too low to provide any useful value. Therefore, parameters derived from feeding behaviour halters and a pedometer systems were unable to make any practical contribution to predicting DM intake or energy balance in dairy cows.
- ‘MIR’, or mid-infrared spectroscopy, is the technique used by milk processors and milk recording organisation to predict the fat and protein content of bulk tank milk samples, and milk samples from individual cows. Over the last decade research has increasingly examined what MIR can tell us about the cow, including cows that are ‘metabolically at risk’, methane production, and nitrogen efficiency. This project looked at how MIR could predict the energy balance of individual cows (**Section 5**).
- Since 2017, all milk samples analysed at AFBI have been analysed using a MIR milk analyser. This instrument shines light within the MIR range at the sample, and measures the reflectance from the sample, with this captured in the form of a spectra. The spectra for each sample comprises 1060 data points.

- Within this project milk spectra data was sourced from 217 sampling occasions (spectra from am and pm samples weighted according to am and pm milk yields on each occasion), representing different stages of lactation. Daily energy balance values were determined using the equations outlined in Feed-into-Milk, the UK dairy cow rationing system. Basic chemometrics were then run using WinISI software (using first derivative equations) to identify relationships between production traits and the milk spectra.
- Good relationships were identified for ‘days in milk’ and ‘daily energy balance. While the former is not a trait that we would need to predict, the relationships shows that there is a strong relationship between MIR spectra and time of lactation, reflecting changes in milk composition that takes place over the lactation. With regards daily energy balance the MIR calibration had a standard error of calibration (SEC) of 23.88, a SECV or 28.013, and a variance ratio (1-VR) of 0.415. While this equation, developed with a limited data set is still not adequate for prediction purposes, it is strongly indicative that a relationship exists. Undoubtedly this equation can be further developed as more diverse datasets are incorporated into the dataset, and this work is part of an ongoing process.

SECTION 1

Understanding the production and economic responses of individual dairy cows when offered either a high or medium feed value silage and concentrates within a feed-to-yield system

Introduction

Much of our understanding of the response of cows to concentrate feeding is derived from studies where the experimental design required the cows to be divided into balanced groups (for example, balanced for pre-experimental milk yield), and with groups then randomly allocated to a number of predetermined concentrate feed levels or concentrate proportions in the diet (e.g. Gordon, 1984; Ferris et al., 1999; Ferris et al. 2001). In these studies a decreasing marginal milk yield response has been observed as concentrate intakes increase. Reasons for this include the decrease in the marginal increase in total energy intake as concentrate intakes increase, due to substitution of forage for concentrates (Sloan et al., 1988), and a greater likelihood that dietary energy will be partitioned away from milk production and towards body-tissue reserves with increased concentrate feeding (Yan et al., 2006). This is due in part to the experimental design, with both higher and lower yielding cows allocated across each concentrate level examined.

However, offering concentrates to individual cows based on their actual milk yields (i.e. a 'feed-to-yield' (FTY) approach), has become commonplace on many farms. While the technology is not new, the use of automated concentrate feeding systems, which are linked directly to milking-parlour software, have increased uptake in the last couple of decades. A FTY approach often involves offering a basal diet (normally a mixed ration comprising forage(s) and concentrate), which is designed to supply the cows maintenance energy requirements plus a given milk yield, with additional concentrates then offered at a given feed rate (often 0.45 kg concentrate/kg (or litre) of milk) to supply the energy required to sustain milk yields in excess of those supported by the basal diet. The 0.45 kg feed rate highlighted above is based on the assumption that one kg of concentrate contains approximately 11.5 MJ of ME, and that the production of one kg (or litre) of milk requires approximately 5.2 MJ of ME (5.2/11.5 = 0.45).

Despite the wide uptake within Northern Ireland, there is also little published information on the responses of individual cows offered concentrates according to FTY principles. For example, when concentrates are offered FTY, only the 'highest' and 'lowest' yielding cows will be offered the 'highest' and 'lowest' concentrate levels, respectively. The impact of this individualised feeding on forage intakes, substitution rates, milk composition, energy balance (EB) and metabolic profiles of individual cows is much less understood compared to traditional flat-rate feeding. The impact of adopting a FTY system does not appear to have been examined with silages of different feed values. Therefore, the objectives of this study were to examine the production and economic response of high yielding dairy cows (both as a group, and as individuals) offered concentrates using a FTY approach, alongside grass silages of two different feed values.

Methodology

This experiment was conducted at the Agri-Food and Biosciences Institute (AFBI) at Hillsborough, Northern Ireland. All experimental procedures in this study were conducted under an experimental licence granted by the Department of Health, Social Services & Public Safety for Northern Ireland in accordance with the Animals (Scientific Procedures) Act 1986.

Animals, pre-calving management and housing: The study involved 60 Holstein-Friesian dairy cows (40 multiparous and 20 primiparous: mean parity, 2.7). Cows were housed in a free stall house during the three week period prior to calving and offered ad-libitum access to grass silage mixed with pre-calving minerals and calcined magnesite (the latter mixed in the silage to achieve target intakes of 100 and 50 g/cow per day, respectively). Cows calved in a straw-bedded maternity pen (mean calving date, 8 November (s.d., 26.8 days)), and were transferred to a free stall cubicle house within 24 h of calving. Cubicles were fitted with rubber mats and bedded with sawdust three times weekly. Concrete floors were scraped every three hours by an automated system.

Diet management and implementation of treatments: Following calving cows were allocated to one of two treatments, based on either a 'High' or 'Medium' feed value silage. Treatment groups were balanced for lactation number (primiparous and multiparous cows balanced separately), calving date, Predicted Transmitting Ability (PTA) kg milk, milk fat and milk protein, mean liveweight (LW) and body condition score (BCS) during the three week period prior to drying off (multiparous cows) and during the six week period pre-calving (primiparous cows), and previous 305 day milk yield, milk fat content and milk protein content (multiparous cows only).

Cows on each treatment were offered a basal mixed ration comprising either the High or Medium feed value grass silage mixed with a concentrate blend (in a 65 : 35 dry matter (DM) ratio), with a different concentrate blend being offered with each silage type. Grass silages were initially mixed for approximately 4 – 5 minutes using a complete-diet mixer wagon (Redrock, Armagh, Northern Ireland). The appropriate concentrate blend was then added to the mixer wagon at a rate necessary to achieve the appropriate forage to concentrate DM ratio, and mixing continued for another 5 – 6 minutes. Following mixing the basal rations were then transferred directly from the mixer wagon to a series of feed-boxes mounted on weigh platforms. Access to feed in these boxes was controlled by a Calan-gate feeding system (American Calan; NH, USA) linked to an automatic cow-identification system (Griffith Elder; Bury St Edmunds, UK), which recorded intakes of cow each day. Uneaten food remaining in the feed-boxes (refusals) was removed daily at approximately 08.30 h, while the basal ration was prepared and offered between 10.00 and 11.00 h each day. The ingredient composition of the concentrates included in the basal ration is presented in Table 1, while the chemical composition of silages and concentrates offered is presented in Table 2.

Additional concentrates (a common concentrate for both silage types) were offered through an in-parlour concentrate feeding system (fixed at 1.0 kg/day, 0.5 kg at each milking, for the duration of the study) and through an out-of-parlour concentrate feeding system. Concentrate levels with the latter were built up over the first 21 days post calving (commencing at 1.0 kg/cow per day for both primiparous and multiparous cows on the day of calving) and increasing in daily increments (0.15 and 0.25 kg/day for primiparous and multiparous cows, respectively) to an intake of 4.0 and 6.0 kg/cow day (primiparous and multiparous cows, respectively).

After the build-up phase, cows moved to a FTY concentrate allocation system. To facilitate this, the basal ration involving the High feed value silage was initially calculated to meet the maintenance energy requirements of the cows plus the energy required to sustain the production of either 19 (primiparous) or 25 (multiparous) kg of milk/cow per day, while respective values for the Medium feed value silage were 14 and 18 kg of milk/cow per day. These values were based on predicted intakes of the ration, and energy requirements for milk production and maintenance derived from equations documented in Feed-Into-Milk, the current UK feed rationing systems for dairy cows (Agnew et al., 2004). Additional concentrates were then offered to individual cows on a FTY basis at a feed rate of 0.45 kg concentrate/kg milk produced above that supported by the basal ration. Concentrate feed levels were adjusted weekly based on milk yields during the previous 7 days. Milk yields supported by the basal ration were be reviewed every 2 weeks throughout the study, based on actual group intakes. Maximum concentrate feed level through the out-of-parlour feeding system was set at 16 kg/cow per day. The FTY approach to concentrate feeding was adopted from day 21 and the experiment continued until day 112 of lactation.

Animal measurements: Cows were milked twice daily (between 06.00 and 08.00 h and between 15.00 and 17.00 h) throughout the experiment using a 50-point rotary milking parlour, with milk yields recorded automatically at each milking, and the total milk yield for each cow for each 24 h period calculated. Milk samples were taken during two consecutive milkings each week and analysed for fat, protein, and lactose concentrations using an infrared milk analyser

(Milkoscan Model 605; Foss Electric, Hillerod, Denmark), and a weighted composition (based on morning and afternoon milk yields) for each 24 h sampling period calculated.

Individual cow LW were recorded twice daily (immediately after each milking) using an automated weighbridge, and a mean weekly LW for each cow determined. The BCS of each cow was assessed fortnightly according to Edmondson et al. (1989) by a trained technician. Blood samples were collected from the coccygeal vein of each cow prior to feeding on weeks 4, 8, 12 and 16 (± 3 days) post-partum, after which samples were centrifuged (1690 g for 15 minutes) to isolate the serum or plasma.

The mean daily ME requirements (MreqFiM) and ME balances (EB) for each cow were calculated using the equations of Thomas (2004), where daily EB (MJ/cow per day) was determined using the equation:

$$EB \;=\; \left([M_{ml} \times LW^{0.75}] + \left[\frac{[0.0013 \times LW]}{K_m}\right] - 10\right) - \; MEi$$

where M_{ml} is the ME required for maintenance and milk production (MJ/cow per day), $LW^{0.75}$ is metabolic LW, K_m is the efficiency of utilisation of ME for maintenance (calculated as 0.35 × ME/gross energy + 0.503), and MEi is the ME intake (MJ/cow per day).

Feed analyses: Grass silages offered were sampled daily throughout the experiment, dried at 85°C for 18 hours to determine oven DM content, and milled through a sieve with 0.8 mm apertures. Sub-samples of the dried milled silages were taken weekly and bulked for every 28 days, and analysed for neutral detergent fibre (NDF), acid detergent fibre (ADF), and ash concentrations. In addition, the maize silage was sampled every 14 days, dried at 60°C for 48 hours, milled through a 0.5 mm sieve, and analysed for starch concentration. Fresh samples of the grass silage were taken weekly and analysed for concentrations of N, ammonia-nitrogen, fermentation acids (lactic, acetic, propionic, n-butyric, and iso-valeric acids), ethanol, propanol, gross energy (GE), and for pH. Silage digestible organic matter in the dry matter (D value) was predicted using near-infrared spectroscopy (NIRS), as described by Park et al. (1997), with silage ME concentration estimated by multiplying the D value (%) by 0.16. The concentrate feeds (pellets and meal) were sampled every 14 days, dried at 100°C for 24 h, milled (0.8 mm sieve), bulked for every 28 days, and analysed for crude protein (CP; N × 6.25), NDF, ADF, ash, and GE concentrations. An additional concentrate sample was taken at the same frequency, dried at 60°C for 48 h and milled (0.5 mm sieve) prior to analysis for starch concentration.

Statistical analysis: Mean animal performance data from week 4 to week 16 was analysed using ANOVA. Within this study, individual cows were used as the experimental units. Data for mean intakes, milk yield, milk composition, milk composition yields, LW, BCS, EB and blood metabolites were analysed by ANOVA. Within these analyses, cow lactation number was used as a covariate. The mean of blood variables over weeks 4, 8, 12 and 16 were analysed using ANOVA. All analyses were carried out using the statistical software package GenStat 20th edition (VSN International Limited, Oxford, UK).

Results and discussion

The concentrate offered as a supplement to the High feed value silage (in the basal diet) had a CP and starch content of 170 g/kg DM and 390 g/kg DM, respectively (Table 1), while the respective values for the concentrate offered as a supplement to the Medium feed value silage was 291 g/kg DM and 230 g/kg DM. The High feed value grass silage offered had a DM, CP and ME content of 327 g/kg, 167 g/kg DM, and 12.0 MJ/kg DM, while the respective values for the Medium feed value silage were 227 g/kg, 126 g/kg DM and 10.9 MJ/kg DM (Table 2).

Impact of silage feed value on cow intake and performance: The term 'High feed value silage' in this paper encompasses both the intake potential of the silage and its nutritive value. As expected, cows offered the High feed value silage had a significantly higher silage dry matter intake (DMI) compared to cows offered the Medium feed value silage (2.1 kg/d; $P < 0.001$). It has been demonstrated that for each 10 g/kg increase in silage D-value, DMI can increase by 0.27 kg/d (Huhtanen et al., 2013). Therefore, given the 1.1 MJ/kg DM difference in ME between the High and Medium feed value silages (equating to a difference of 69 g/kg D-Value), the observed increase in silage DMI was similar to what would have been predicted, namely 1.9 kg/d. Increasing silage digestibility can also lead to 'concentrate sparing' (Huhtanen 2018); however, despite the numerically lower concentrate DMI in this study this difference was not significant and is likely to reflect the fact that concentrates were offered FTY. Total DMI tended to be 1.6 kg/d greater in cows offered the High feed value silage compared to cows offered the Medium feed value silage ($P = 0.078$).

Despite the increase in total DMI, silage feed value did not have a significant impact on milk yield, milk fat yield, milk fat content milk lactose content, or fat plus protein yield. However, cows offered the High feed value silage did have an improved milk protein content (1.5 g/kg; P = 0.010) and milk protein yield (0.14 kg/d; P = 0.014). As milk protein content is generally influenced by energy intake (Osorio et al., 2016), the improved silage energy content and tendency towards a higher DMI would likely explain the increase in milk protein.

Silage feed value did not have a significant effect on cow BW. While mean BCS was not affected by treatment, final BCS was lower for cows offered the Medium feed value silage (0.1; P = 0.015) indicating an increased level of tissue mobilisation with this treatment. Indeed, cows offered the Medium feed value silage had reduced EB (P < 0.001) compared to the cows offered the High feed value silage, with this reflected in higher concentrations of betahydroxybutyrate (P = 0.085), an indicator of adipose tissue break down (Macrae et al., 2012). Silage treatment had no effect on non-esterified fatty acid or glucose content of the blood. Cows offered the Medium feed value silage tended to have higher blood urea (P < 0.001) levels compared to cows offered High feed value silage, likely an impact of the lower quality silage and high concentrate crude protein levels with this treatment, and the associated balance between degradable protein and fermentable energy in the rumen.

Impact of concentrate feeding level on individual cow performance: As cows were managed on a FTY system, within each silage type there were a range of concentrate intakes. These mean concentrate intake values mask the effect of concentrate intake on silage and total DMI at an individual cow level. Figure 1 shows the effect of increasing concentrate level on silage DMI and total DMI. As concentrate intakes increased, total DMI increased in a linear fashion within both silage types. These results demonstrate a key difference between traditional studies examining performance responses to concentrate feeding, and studies examining a FTY approach. As concentrate feed level increases, total DMI normally shows a curvilinear increase (Huhtanen et al., 2008) which is a consequence of the inability of cows with a lower yield potential to fully respond to higher concentrate levels (Ferris et al., 1999). In contrast, within a FTY approach higher levels of concentrates are offered only to higher-yielding cows, which also have greater intake potential/drive; therefore, the absence of a curvilinear intake response is observed. The results from the current study support the findings of Purcell et al. (2016) and Little et al. (2016) who noted that the increase in DMI with increasing milk yield was greater for cows offered concentrates on a FTY basis compared to 'flat rate' feeding strategies.

Similarly, forage DMI normally shows a curvilinear decrease (Huhtanen et al., 2008) with increasing concentrate levels. However, within the current study the decrease was marginal, indicating a low substitution rate. Purcell et al. (2016) concluded that substitution rates within FTY systems are low due to the overall higher intake potential of cows offered the higher concentrate levels within a FTY system. The low substitution rates within these FTY studies lends support to the assumption commonly used when rationing cows on a FTY basis, namely that the basal diet is likely to sustain a relatively constant level of performance for cows across a range of milk yield potentials. Figure 1 also highlights that at any given concentrate intake, intakes of the cows offered the High feed value silage were greater than intakes of those offered the Medium feed value silage.

As concentrate levels increased, milk yield also increased (Figure 2) in a linear fashion. A linear response is expected within FTY systems as concentrates 'follow' milk yields (i.e. 0.45 kg concentrate/kg milk). However, at any given concentrate level, milk yields of cows offered the High quality silage are generally higher than those of cows offered the Medium quality silage highlighting that improved quality silage can sustain greater milk yields. Therefore, improving the nutritive value of the silage can reduce the amount of concentrates required to sustain a given milk yield.

An important outcome highlighted by Figure 3 and 4 is the wide variation in individual cow milk composition, and yet most FTY systems assume a standard milk composition for all cows in a herd. Increasing concentrate levels has previously been associated with a reduction in milk fat content due to the increasing starch content of the diet (Keady et al., 1998; 1999). Rapid rumen fermentation of the starch in some concentrate diets results in a fall in rumen pH (Agle et al., 2010), which inhibits milk fat synthesis in the mammary gland, resulting in milk fat depression. Therefore, as found in previous studies (Ferris et al., 1999 and 2001; Purcell et al., 2015), milk fat was expected to drop at higher concentrate feeding levels. Conversely, in this study milk fat changed relatively little across the range of concentrate levels examined (Figure 3). However, a significant reduction in milk fat content was not observed until the concentrate proportion of the diet reached 0.70 (Ferris et al., 2001), and in this study the highest concentrate proportion was 0.68. While Purcell et al. (2015) found a reduction in milk fat at a concentrate proportion of 0.56 this is likely to do with the range of feed rates used within that study.

There was an obvious decrease in milk protein at higher concentrate levels, especially with the medium quality silage (Figure 4). This is perhaps a surprising result as energy is a driver of milk protein. Therefore, an increase in concentrate intake would be expected to increase milk protein. Indeed, most studies have recorded increased milk protein content with increasing concentrate level (Keady et al., 1998; Beever et al., 2001). The likely explanation for the decrease in milk protein is the dilution effect as milk yield increased (Garcia and Holmes, 2001).

Impact of concentrate feeding level on margin-over-feed costs: The impact of concentrate level within a FTY system on margin-over-feed costs is shown in Figure 2.4 at three different milk prices. Costs for grass silage, maize silage and whole crop silage were assumed as £123, £189, £225/t DM, respectively, based on a recent update of forage costs in Northern Ireland (Craig et al., 2021), while the cost of concentrates was assumed to be £260/t fresh. Margins were modelled at three different milk prices, namely 18, 26 or 34 pence per kg (p/kg). The economic analysis also took into consideration the composition of milk produced using a bonus/deduction of 0.022 pence for every 0.1 g/kg above/below a base level of 38.5 g/kg fat, and a bonus/deduction 0.036 pence for every 0.1 g/kg above/below a base level of 31.8 g/kg protein (based on Dale Farm milk pricing structure, 2020). The results of the economic exercise indicate that the marginal economic response decreases at higher concentrate levels. This is particularly evident at a low milk price (18 pence/kg), where an increase in milk yield beyond 40 kg/cow/day resulted in no real improvement in margin-over-feed costs. Even at a milk price of 26 pence per kg, the increase in margin-over-feed costs was small with milk yields in excess of 40 kg/day with many individual cows. This decreasing marginal response at higher concentrate levels is due to two effects, namely the increasing cost of each unit of food consumed, and the decreasing value of each litre of milk produced due to declining milk quality observed on most farms. The impact of these latter effects are particularly important at lower milk prices, where there may be little overall benefit in continuing to feed additional concentrates. However, in this study the main driver of this decline in margin was the increasing cost of the diet with increasing concentrate inclusion level. For example, diet cost increased by an extra 2 - 3 pence per kg DM across the range of concentrate levels in this study. This was especially true for the cows offered the medium quality silage, and this was reflected in generally lower margins at all milk yields with diets based on the medium quality silage.

Table 1. Ingredient composition of the concentrate feedstuffs offered as part of the basal diet and through the out-of-parlour feeding systems (kg/t inclusion rates).

	Concentrate offered in blend		Concentrate offered via in-parlour and out-of-parlour feeders
	High feed value silage	Medium feed value silage	
Maize (milled)	420	250	193
Soya hulls (toasted)	200	120	158
Wheat (milled)	200	100	158
Soya bean meal (Hi-Pro)	100	300	75
Rapeseed meal	50	200	75
Molaferm	-	-	40
Pure palm oil	-	-	8
Acid Buff	10	10	-
Limeflour	9	9	5
Salt	5.5	5.6	4.2
Magnesite	4.9	3.6	3.9
Dairy cow minerals	4.0	4	4

Table 2. Chemical composition of the grass silages (g/kg volatile-corrected dry matter (DM), unless otherwise stated, except for pH), and of the concentrates (g/kg) offered during the experiment.

	Grass silages				Concentrates					
	High feed value		Medium feed value		In basal diet (High feed value silage)		In basal diet (Medium feed value silage		Offered via out-of-parlour feeders	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Oven DM (g/kg)	327	68.2	227	34.3	897	5.3	900	3.7	898	4.1
Volatile-corrected DM (g/kg)	342	67.4	243	31.5	-	-	-	-	-	-
Neutral detergent fiber	479	66.5	525	28.9	260	39.6	226	18.9	296	19.8
Acid detergent fiber	280	34.8	325	15.5	143	20.8	124	12.1	165	6.4
Crude protein	167	25.6	126	6.5	170	10.7	291	8.6	174	1.5
Starch	-	-	-	-	390	23.6	230	13.5	265	7.2
Ash	86	9.7	88	6.5	64	4.2	79	8.3	67	2.0
Gross energy (MJ/kg DM)	18.9	0.72	18.8	1.26	17.9	0.08	18.2	0.09	18.1	0.04
Silage fermentation variables										
Lactic acid	122	51.9	149	32.8	-	-	-	-	-	-
Acetic acid	14.6	4.68	22.6	8.22	-	-	-	-	-	-
Propionic acid	0.03	0.11	1.4	2.00	-	-	-	-	-	-
Ethanol	7.8	2.85	14.2	11.51	-	-	-	-	-	-
Propanol	0.1	0.20	2.6	3.13	-	-	-	-	-	-
pH	3.99	0.21	3.7	0.16	-	-	-	-	-	-
Ammonia-nitrogen (g/kg total N)	71	10.5	89	21.0	-	-	-	-	-	-
Metabolisable energy (MJ/kg DM)[1]	12.0	0.41	10.9	0.38	-	-	-	-	-	-

[1] *Determined using near-infrared reflectance spectroscopy (NIRS)*

Table 3. Effects of silage quality on mean dry matter intakes (DMI), milk production, body tissue reserves and blood metabolites during weeks 3 to 16 post-partum.

	Silage feed value			
	High	Medium	SED	P-value
DMI (kg/cow per day)				
Concentrate	12.5	13.0	0.66	0.430
Silage	11.3	9.2	0.37	<0.001
Total	23.8	22.2	0.91	0.078
Yield (kg/cow per day)				
Milk	39.0	36.6	1.79	0.187
Milk fat	1.54	1.50	0.072	0.626
Milk protein	1.29	1.15	0.054	0.014
Milk fat plus protein	2.83	2.66	0.121	0.161
Milk composition (g/kg)				
Fat	40.3	41.2	1.15	0.477
Protein	33.3	31.8	0.56	0.010
Lactose	47.9	48.0	0.24	0.806
Mean LW (kg)	628	618	12.1	0.422
Final LW (kg)	643	625	12.8	0.152
Mean BCS	2.5	2.5	0.06	0.217
Final BCS	2.5	2.4	0.07	0.015
Mean ME balance (MJ/cow per day)	22.7	6.7	3.96	<0.001
Betahydroxybutyrate (m*M*)	0.38	0.43	0.023	0.085
Non-esterified fatty acids (mEq/L)	160.7	168.7	16.91	0.640
Glucose (m*M*)	3.48	3.52	0.059	0.558
Urea (m*M*)	3.37	4.56	0.208	<0.001

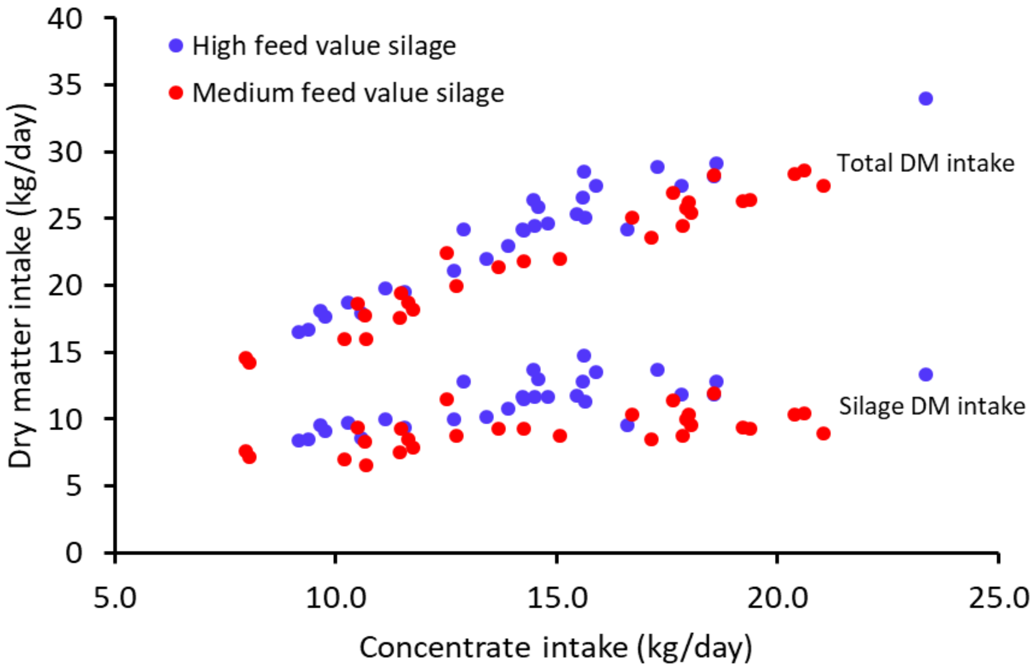

Figure 1. Effect of offering increasing levels of concentrates on a feed-to-yield basis on silage DM intake and total DM intake of individual cows (with a High and Medium feed value silage)

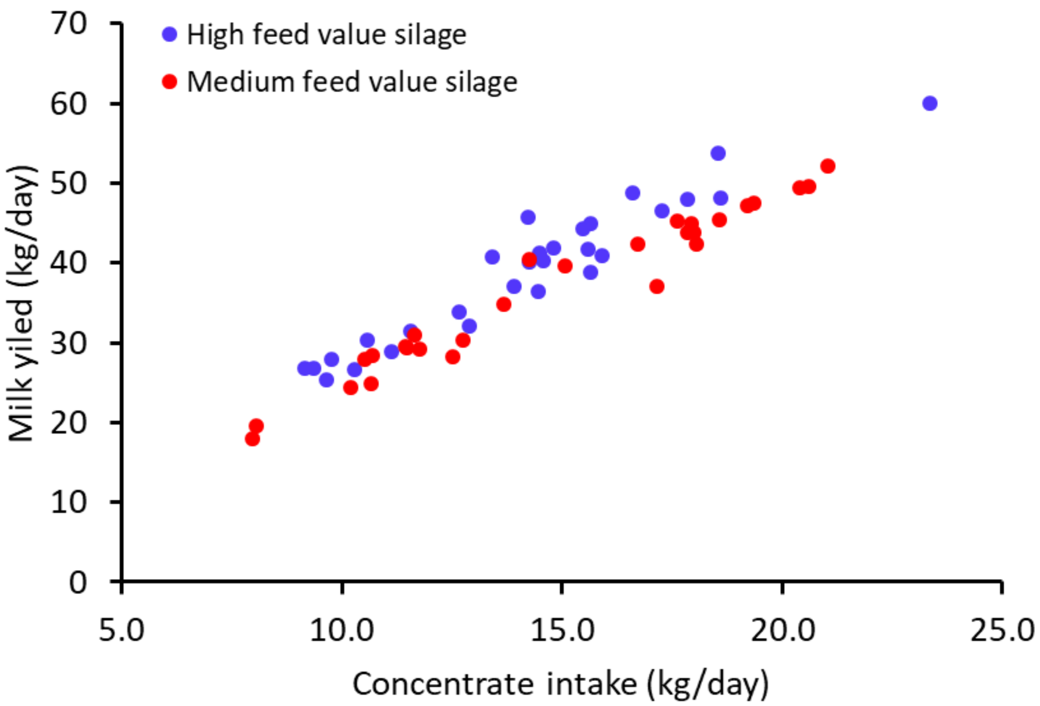

Figure 2. Effect of offering increasing levels of concentrates on a feed-to-yield basis on milk yield of individual cows (with a High and Medium feed value silage).

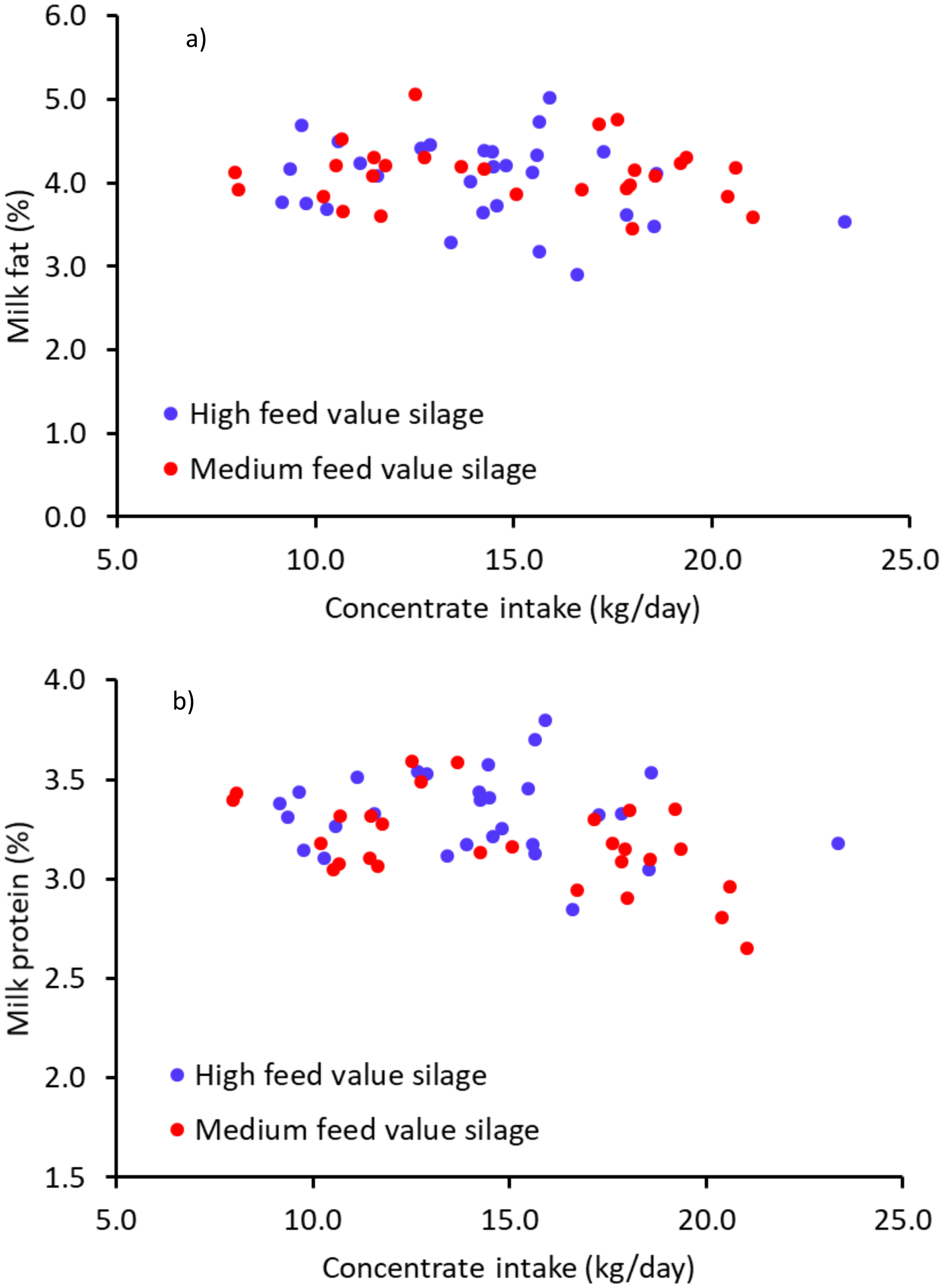

Figure 3. Effect of offering increasing levels of concentrates on a feed-to-yield basis on milk (a) fat % and (b) milk protein % of individual cows (with a High and Medium feed value silage)

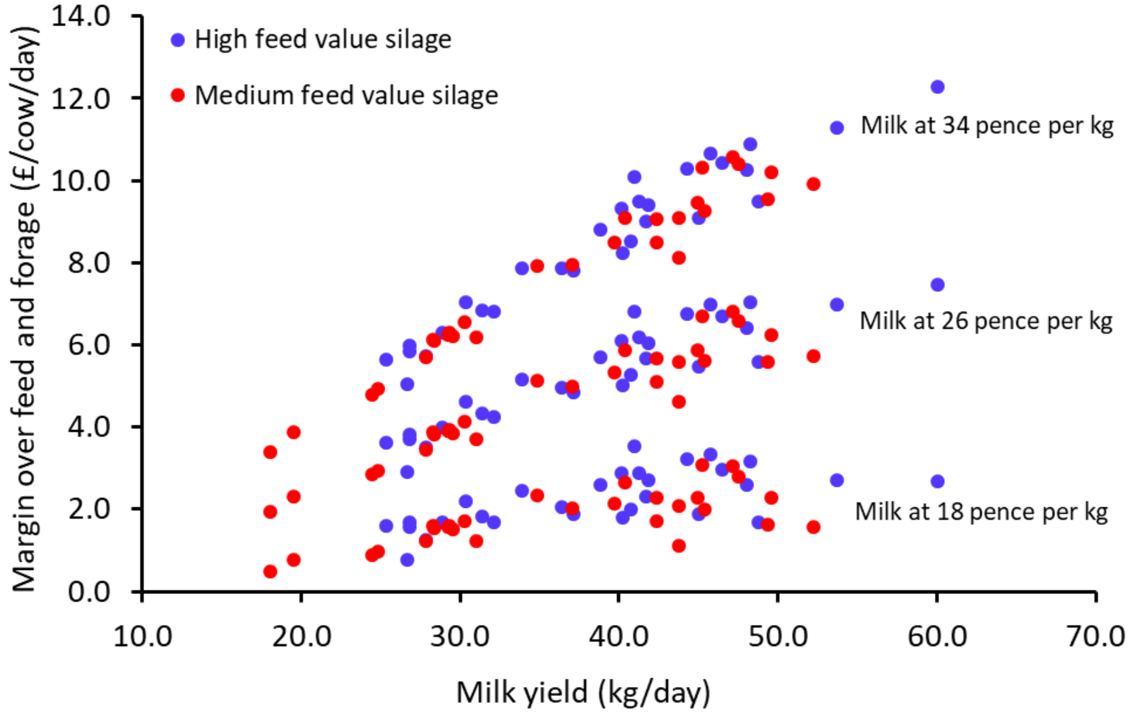

Figure 4. Effect of increasing milk yield on margin-over-feed costs at milk prices of 18, 26 and 34 pence per kg (with a High and Medium feed value silage)

Conclusion

The results of this study confirm the benefits of higher quality silage in terms of improving intakes, milk protein content and economic performance within feed-to-yield systems. However, irrespective of silage quality, the economic benefits of offering additional concentrates was reduced at higher milk yields, even within a feed-to-yield system. When milk prices are poor, 'pushing for extra litres' will have little financial benefit.

SECTION 2

Accounting for milk composition and energy intake of individual cows to improve precision when allocating concentrates to dairy cows within a feed to yield system

Introduction

The quantity of concentrates offered to dairy cows has increased in many countries. For example, in Northern Ireland (NI) concentrate levels increased from 1.8 to 2.6 t/cow/yr between 2004 and 2019, with an associated increase in milk production from 5,894 to 7,252 kg (DAERA statistics 2004-2019). As concentrates are considerably more expensive than conserved forages (Finneran et al., 2012), it is critical that they are used efficiently if overall farm profitability is to be increased.

Concentrates are offered to dairy cows using a wide variety of feeding systems, including as part of mixed rations, and/or via in-parlour and out-of-parlour feeding (OPF) systems. While some approaches involve offering all cows in the herd/production group a common diet, others allow concentrate levels for individual cows to be adjusted according to milk yield. Given that within any herd there is variation in milk yield as a result of cow genotype (Veerkamp et al., 1994), parity (Horan et al., 2005) and stage of lactation (Garcıá and Holmes, 2001), allocating concentrates to cows individually is expected to bring benefits from increased 'precision'. Indeed, precision feeding seeks to exploit the normal within-herd variation by increasing concentrates offered to cows with potential to produce higher milk yields, and which exhibit a greater response to concentrate feeding (Veerkamp et al., 2003), and reducing concentrate offered to cows that are likely to show a lesser milk yield response and are more likely to partition excess energy into body tissue reserves (Ferris et al., 1999). It has been suggested that managing cows according to their nutritional requirements, based on production potential, may improve productivity, efficiency, and increase feed cost savings (Wu et al., 2019).

Within the UK and Ireland many farms have adopted a feed-to-yield (FTY) approach to increase precision of concentrate allocation. In practice, a forage or forage-concentrate mix (basal ration) is offered and is assumed to supply sufficient nutrients to meet the cow's maintenance energy requirements and to support the production of a given amount of milk. Additional concentrates are then offered to individual cows on a FTY basis to support milk production above the yield that the forage/basal ration is assumed to support. However, despite the widespread use of FTY systems within NI, the literature provides little evidence of a significant improvement in production when FTY systems are compared to 'flat-rate' feeding systems (Lawrence et al., 2015, 2016; Little et al., 2016; Purcell et al., 2016). However, within these studies equal concentrate inputs were planned for each treatment, and therefore, they were unable to demonstrate if an improvement in concentrate use efficiency could have been achieved had alternative assumptions been adopted.

While FTY systems are designed to increase precision in concentrate allocation, the approaches adopted on farm involve multiple assumptions based on a hypothetical 'average cow', despite the recognition that there is no such thing as an 'average cow' (Ben Meir et al., 2018, 2019). For example, energy requirement calculations are normally based on the average milk composition of the herd and do not take account of the wide range of milk compositions that exist in practice. This could be a particular issue given that milk fat content may be reduced in cows offered higher concentrate levels, as are frequently found in FTY systems (Purcell et al., 2015). Furthermore, FTY systems require assumptions to be made on the level of milk production that can be sustained by the forage/basal ration offered. If rations are offered using a mixer wagon fitted with weigh-cells, then farmers can obtain a reasonable estimate of average intakes of the forage/basal ration for the herd. Nevertheless, intakes of individual cows will vary greatly.

A number of studies have investigated the use of parameters other than milk production as a basis for concentrate allocation. These measures have included daily body weight (BW) measurements as an indicator of dry matter intake (DMI) (Maltz et al., 1992; 1997, Bossen and Weisbjerg, 2009) or individual cow energy balance (EB) which accounts for BW, DMI and milk energy output (Maltz et al., 2013). Other authors have adopted a modelling approach to demonstrate that accounting for milk composition (Berger and Hovav, 2013), energy intake (Huhtanen et al., 2012) and body condition (Bercovich et al., 2013) may also improve efficiency of concentrate supplementation.

The current study was designed to examine if increased precision could be achieved by taking account of individual cow milk composition and DMI when allocating concentrates on a FTY basis. Preliminary results from this study have been published previously in the form of a conference abstract (Craig et al., 2021).

Methodology

This study was conducted at the Agri-Food and Biosciences Institute (AFBI), Hillsborough, NI. All experimental procedures were conducted under an experimental licence granted by the Department of Health, Social Services & Public Safety for Northern Ireland in accordance with the Animals (Scientific Procedures) Act 1986.

Animals and Housing: This 12 week study involved 69 mid-lactation (mean of 120 days calved, s.d. 13.9) Holstein dairy cows, 45 multiparous and 24 primiparous (mean lactation number 2.4, s.d. 1.24). Cows had a mean pre-experimental milk yield of 33.6 (s.d. 7.36) kg per day. For three weeks prior to the study commencing, cows were offered a partial mixed ration (grass silage and concentrates mixed in a 70:30 ratio on a dry matter (DM) basis), which was calculated to support milk yields of 13.5 and 19.6 kg, for primiparous and multiparous cows, respectively. Additional concentrates were offered through an OPF system according to individual cow milk yields (0.43 kg additional concentrate for each kg of milk in excess of yields assumed to be supported by the basal ration).

Cows were housed in a free-stall house with concrete flooring, and had access to individual cubicles which were fitted with rubber mats and bedded with sawdust. The cubical-to-cow ratio was > 1:1 at all times, meeting the recommendations of FAWC (1997). The floor area was scraped every 3 h using an automated system.

Treatments: Three treatments were examined in the experiment, with cows on each treatment balanced for lactation number and days in milk, and for mean milk yield, milk composition, DMI, and BW during the two week period prior to the start of the experiment.

Throughout the experiment all cows were offered a basal mixed ration consisting of a common grass silage produced from a perennial ryegrass (Lolium Perenne) based sward: DM, 292 g/kg; crude protein (CP), 130 g/kg DM; metabolisable energy (ME), 11.1 MJ/kg DM (Table 1), mixed with a common concentrate in the form of a meal (ingredient composition, Table 2). Rations were prepared using a mixer wagon (Vari-Cut 12, Redrock, Armagh, NI). Concentrates were included in the mix at a rate of 4.3 and 5.3 kg/d on a fresh weight basis for primiparous and multiparous cows, respectively, to achieve a nominal target concentrate intake of 4.0 and 5.0 kg/d for primiparous and multiparous, respectively.

The total silage required for all three treatments (based on diets being offered at 107% of the previous day's intake) was initially mixed for approximately five minutes and then deposited on a clean silo floor. The quantity of silage required for each individual treatment was then removed from this 'pile' in turn, placed back in the mixer wagon, and the appropriate quantity of concentrate added to the mix, and mixing continued for another five minutes. The rations were then transferred from the mixer wagon to a series of feed boxes mounted on weigh scales, with cows accessing food in these boxes via an electronic identification system, thus enabling individual cow intakes to be recorded daily (Controlling and Recording Feed Intake, Bio-Control, Rakkestad, Norway). The rations were prepared daily and offered between 09.00 and 10.00 h, while uneaten food was removed the following day at approximately 08.00 h. Cows had access to fresh water at all times.

Cows were offered additional concentrates on a FTY basis, with 1.0 kg/d of this offered via an in-parlour feeding system (fixed throughout the duration of the study; 0.5 kg at each milking) and the remainder offered via an OPF system. Concentrate levels were reviewed and adjusted weekly according to treatment as follows:

1) ***Control***: this treatment involved a 'conventional' FTY approach, with concentrate feed levels adjusted according to individual cow milk yields each week. The first step in determining concentrate allocation involved calculating the milk yield that the basal ration could sustain. This was determined weekly based on the average daily DMI of the silage and concentrate component of the basal diet over the previous week for multiparous cows (heifer intake was set at 77% that of multiparous cows: Edward Cabezas-Garcia, unpublished data), multiplied by the ME content of the silage (based on weekly analysis) and the estimated ME content of the concentrate (13 MJ/kg DM, FeedByte, SRUC). This level of ME intake was assumed to support maintenance energy requirement, plus the production of a certain amount of milk. Maintenance energy requirements were calculated to be 73 and 84 MJ ME/d for primiparous and multiparous animals, respectively (based on mean pre-experimental BW), and using equations detailed by Agnew et al. (2004) in 'Feed into Milk').

In the second step, the ME required for maintenance was deducted from the ME intake from the basal ration, and the difference divided by 5.11 to determine the kg milk supported by the basal ration. The ME required for milk production (5.11 MJ/kg), was calculated using the average pre-experimental gross energy content of milk (3.17 MJ/kg, based on a fat, protein and lactose content of 41.5, 32.5 and 48.4 g/kg, respectively: Tyrrell and Reid (1965), equation below) and an assumed lactation efficiency (k_l) of 0.62 (McDonald et al, 2002).

$$GE, MJ/kg = [0.0384\ x\ fat] + [0.0223\ x\ protein] + [0.0199\ x\ lactose] - 0.108$$

On average, the basal ration was calculated to provide sufficient ME to meet maintenance energy requirements plus an average of 20.8 and 14.4 kg milk/d for cows and heifers, respectively, throughout the study (commonly referred to as the M+ value).

Finally, the milk yield not supported by the basal ration was determined as the difference between average milk yield for each individual cow over the previous week, and the weekly group M+ value. Cows were supplemented for milk produced in excess of that supported by the basal ration at a rate of 0.43 kg concentrate/kg milk (based on the assumed ME requirement for milk production of 5.11 MJ/kg, divided by the ME content of the concentrate offered, on a fresh basis (MJ/kg)).

2) ***Precision 1***. The calculation of concentrate levels in this treatment took account of the energy content of the milk produced by each cow. First, total ME intake from the basal ration, and the mean ME required for maintenance was calculated as per the Control treatment. The ME required for milk production was calculated using each individual cow's average milk yield over the previous week and each individual cow's average milk composition over the previous two weeks. The GE content of milk produced for each cow was calculated according to Tyrrell and Reid (1965) and ME required for milk production calculated assuming a k_l of 0.62, as for Control.

Finally, the mean ME provided by the basal ration was subtracted from the total ME required for maintenance (set as per control) and milk production for each individual cow (as calculated above). The difference between the ME supplied by the basal ration and the ME requirements for each cow was divided by the ME content of the concentrate offered through the OPF (MJ/kg), to determine the quantity of concentrates required to meet individual cow ME requirements.

3) ***Precision 2***. This treatment took account of individual cow milk yield, milk composition and ME intake from the basal ration. First, total ME intake from the basal ration was calculated as per the other two treatments, but on an individual cow basis instead of a group basis. Next, the ME required for maintenance and milk was calculated as per Precision 1. Finally, the difference between the ME provided to each individual cow by the basal ration and the ME requirements for each cow was divided by the ME content of the concentrate offered through the OPF (MJ/kg), to determine the quantity of concentrates required to meet individual cow ME requirements.

Across all treatments a maximum concentrate level offered through the OPF was set at 16 kg/d, while the maximum increase in concentrate intakes between successive weeks was restricted to 4 kg/week for cows or 3 kg/week for heifers. All cows were offered a minimum of 0.5 kg/d through the OPF for the duration of the study.

Cow measurements: All cows were milked twice daily (between 06.00 and 08.00 h and between 15.00 and 17.00 h) throughout the experiment using a 50-point rotary milking parlour (Boumatic, Madison, USA). Milk yields were automatically recorded at each milking, and a total daily milk yield for each cow for each 24 h period calculated. Milk samples were taken during two consecutive milkings each week, treated with a preservative tablet (lactab Mark III, Thompson and Cooper Ltd., Runcorn, UK), and stored at 4°C until analysed (normally within 48 h). Milk samples were analysed for fat, protein and lactose concentrations using an infrared milk analyser (Milkoscan CombifossTM7; Foss Electric, Hillerød, Denmark), and a weighted concentration of each constituent determined for the 24 h sampling period.

The daily EB of each individual cow was calculated using equations contained within 'Feed into Milk', the current UK dairy cow rationing system, as the difference between the cow's total ME requirements (maintenance, milk production, and activity) and total ME intake (Agnew et al., 2004). Energy corrected milk (ECM) yield (kg/d) was calculated as described by Muñoz et al. (2015):

$$ECM, kg/d = \frac{milk\ yield\ (kg/d)\ x\ GE\ (MJ/kg)}{3.1}$$

Body weight was recorded twice daily (immediately after each milking) using an automated weighbridge, and a mean weekly BW for each cow was determined. The body condition score (BCS) of each cow was estimated by a trained technician at the beginning, mid and end of the experiment, according to Edmonson et al. (1989) on a 5 point (including quarter points) scale.

Feed analysis: A sample of the grass silage offered was taken daily throughout the experiment and dried at 60°C for 48h to determine oven DM content. Twice weekly a sample of the dry silage was collected, bulked for each 14 d period, with the bulked sample milled through a sieve with 0.85 mm aperture and analysed for neutral detergent fibre (NDF), acid detergent fibre (ADF) and ash concentrations. Each week a fresh silage sample was analysed for GE, N, pH, ammonia-N and volatile components, and the ME concentration of the sample predicted using near infrared reflectance spectroscopy (NIRS) according to Park et al. (1998). A sample of each concentrate offered was taken weekly, dried at 60°C for 48 h to determine ODM, and a dried sample from one day each week retained, bulked over each 14 d period, milled through a 0.85 mm sieve, and subsequently analysed for N, NDF, ADF, ash and starch concentrations. All chemical analysis of the feedstuffs offered were undertaken as described by Purcell et al. (2016).

Statistical analysis: One cow was removed from treatment Precision 2 due to mastitis. Data for milk yield, milk composition, BW, intake and efficiency parameters were analysed using REML repeated measure analysis, with week (or time period in the case of BCS) as the time point and an autoregressive model of order 1 was set as the correlation structure. Pre-experimental variables (milk yield, milk fat content, milk protein content and total DMI) were included as covariates when analysing corresponding dependent variables. For variables where significant treatment effects were identified ($P < 0.05$), differences were tested using Fisher's protected-adjusted multiple comparisons. All data were analysed using GenStat (18.1; VSN International Limited, Oxford, UK).

Results

Silage DMI did not differ between treatments ($P > 0.05$). Control cows had significantly lower concentrate DMI ($P = 0.040$; Table 3; Figure 1) compared to cows in Precision 1 and 2; however, total DMI was unaffected by treatment. Intakes of all diet components decreased over the course of the study ($P < 0.001$) and there were significant interactions between treatment and week for silage DMI, concentrate DMI and total DMI ($P < 0.001$).

There were no significant differences between treatments for milk yield or ECM yield ($P > 0.05$; Table 3). There was a tendency for milk fat content ($P = 0.055$) and milk fat yield ($P = 0.064$) to be lower in Precision 2 compared to the other two treatments. Cows on Control had a lower milk protein content ($P = 0.003$) and milk protein yield ($P = 0.001$) than those on Precision 1 and Precision 2. Fat plus protein yield was significantly greater in Precision 1 compared to the other two treatments ($P = 0.017$; Table 3; Figure 2). Milk yield, ECM, fat yield, protein yield and fat plus protein yield all changed over time ($P < 0.001$), declining over the course of the study. There was a significant week × treatment interaction for milk yield ($P = 0.002$), but no interaction for the other milk production parameters.

While ECM/DMI and ECM/ME intake were unaffected by treatment, these two parameters decreased as the study progressed ($P < 0.001$). Both concentrate DMI/milk yield and concentrate DMI/ECM yield were lower with Control than with either of the other two treatments ($P < 0.001$). The concentrate efficiency parameters changed over time following a similar pattern to milk yield, and there were significant week × treatment interactions.

Energy balance, BW and BCS were not affected by treatment, but changed over time ($P < 0.001$; Table 3), increasing as the study progressed. There was a week × treatment interaction for EB, but not for BW or BCS.

Table 1. Chemical composition of silage offered to cows in all treatments as part of the basal ration.

	Mean	SD
Oven dry matter (g/kg)	292	29.2
VCODM (g/kg)	303	28.7
Crude protein (g/kg DM)	130	8.4
Ash (g/kg DM)	95	3.4
Acid detergent fibre (g/kg DM)	286	4.5
Neutral detergent fibre (g/kg DM)	482	9.0
Gross energy (MJ/kg DM)	18.5	1.57
Metabolisable energy (MJ/kg DM)	11.1	0.26
pH	4.01	0.103
Lactic acid (g/kg DM)	97	23.0
Acetic acid (g/kg DM)	19.2	4.15
Ethanol (g/kg DM)	13.1	3.37
Ammonia (g/kg total N)	75	0.81

VCODM., volatile corrected oven dry matter

Table 2. Ingredient list (g/100 g fresh) and chemical composition (SD in parenthesis) of the concentrates offered to all cows through the out-of-parlour feeding system (OPF), and of concentrates mixed with silage as part of the basal ration.

	OPF Concentrate	Blend Concentrate
Ingredients		
Wheat	17.4	
Maize meal	17.5	28.0
Extruded rapeseed meal		19.0
Distillers dried grains	8.5	
Maize gluten	11.0	
Sugar beet pulp	6.1	
Soyabean meal (high protein)	8.6	19.1
Soya hulls	17.5	25.4
Molaferm	8.0	2.5
Palm fatty acid distillate	1.0	
Protected fat (Megalac)[1]	1.5	3.0
Limestone (CaCO3)	0.9	0.6
Calcined magnesite	0.2	0.2
Salt	0.6	0.9
RumiTech[2]	0.7	0.7
Mineral/vitamin mix	0.7	0.7
Chemical Composition		
Oven dry matter (g/kg)	888 (4.6)	894 (4.5)
Starch (g/kg DM)	262 (8.0)	193 (34.0)
Crude protein (g/kg DM)	169 (2.5)	239 (16.8)
ADF (g/kg DM)	152 (5.8)	191 (47.7)
NDF (g/kg DM)	295 (24.0)	342 (80.0)
Ash (g/kg DM)	77 (2.0)	79 (8.0)
Metabolisable energy (MJ/kg DM)[3]	13.5	13.3

[1]Volac Wilmar Feed Ingredients Ltd, Hertfordshire, UK
[2]Harbo, Aberdeenshire, UK
[3] using ME values in Ultramix (AGM systems Ltd.)
ADF, acid detergent fibre; NDF, neutral detergent fibre.

Table 3. Effect of a three feed-to-yield concentrate allocation strategies, each differing in 'precision', on feed intake, milk production, body tissue reserves and efficiency measures.

	Treatment				P Values		
	Control[1]	Precision 1[2]	Precision 2[3]	SED	Treatment	Week	Week × Treatment
Silage DMI (kg/d)	12.4	11.6	11.5	0.36	0.242	<0.001	<0.001
Concentrate DMI (kg/d)	9.4[a]	10.5[b]	10.3[b]	0.43	0.044	<0.001	<0.001
Total DMI (kg/d)	21.2	21.8	21.5	0.24	0.113	<0.001	<0.001
Milk yield (kg/d)	32.9	34.5	34.3	0.68	0.181	<0.001	0.002
Fat (g/kg)	45.1	44.9	43.1	0.81	0.055	<0.001	0.767
Protein (g/kg)	32.7[a]	33.5[b]	33.1[b]	0.24	0.003	0.059	0.910
Lactose (g/kg)	48.0	48.1	48.1	0.20	0.940	0.192	0.972
Fat yield (kg/d)	1.47	1.54	1.46	0.035	0.064	<0.001	0.726
Protein yield (kg/d)	1.07[a]	1.15[b]	1.13[b]	0.022	0.001	<0.001	0.461
Fat plus protein yield (kg/d)	2.54[a]	2.69[b]	2.58[a]	0.052	0.017	<0.001	0.607
Energy corrected milk (kg/d)	34.6	37.0	36.3	1.93	0.563	<0.001	0.578
ECM/DMI (kg/kg)	1.63	1.65	1.64	0.031	0.783	<0.001	0.092
ECM/ME intake (kg/MJ)	0.14	0.14	0.13	0.002	0.984	<0.001	0.187
Concentrate DMI/milk yield (kg/kg)	0.27[a]	0.31[b]	0.30[b]	0.007	<0.001	<0.001	<0.001
Concentrate DMI/ECM (kg/kg)	0.25[a]	0.29[b]	0.29[b]	0.007	<0.001	<0.001	<0.001
Energy balance (MJ/d)	8.7	10.9	11.1	2.51	0.592	<0.001	0.021
Body weight (kg)	626	644	645	19.8	0.416	<0.001	0.181
Body condition score	2.1	2.3	2.4	0.20	0.694	<0.001	0.798
Locomotion score	2.3	2.4	2.5	0.07	0.958	<0.001	0.397

[1] *CON; concentrates offered on a FTY basis, adjusted on the basis of individual cow milk yields,*

[2] *Precision 1; concentrates offered on a FTY basis, adjusted on the basis of individual cow milk yields and milk composition*

[3] *Precision 2; concentrates offered on a FTY basis, adjusted on the basis of individual cow milk yields, milk composition, and DMI*

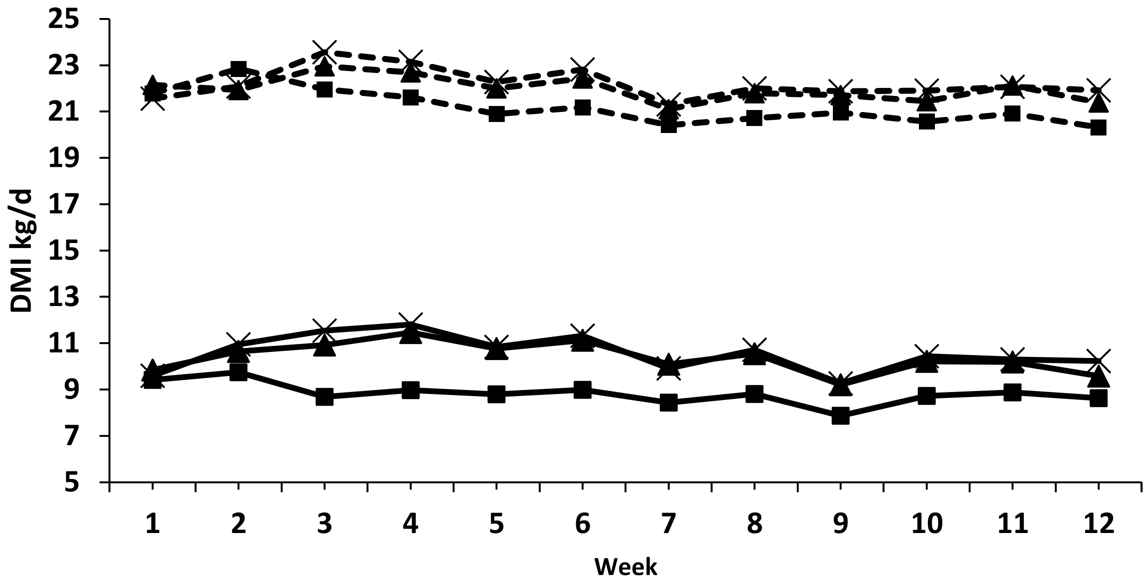

Figure 1. Concentrate DMI (solid line) and total DMI (broken line) of cows offered concentrates according to a conventional FTY system (Control; ▪), or corrected for milk composition (Precision 1; ×), or corrected for milk composition and individual intake (Precision 2; ▲) over a 12 week period.

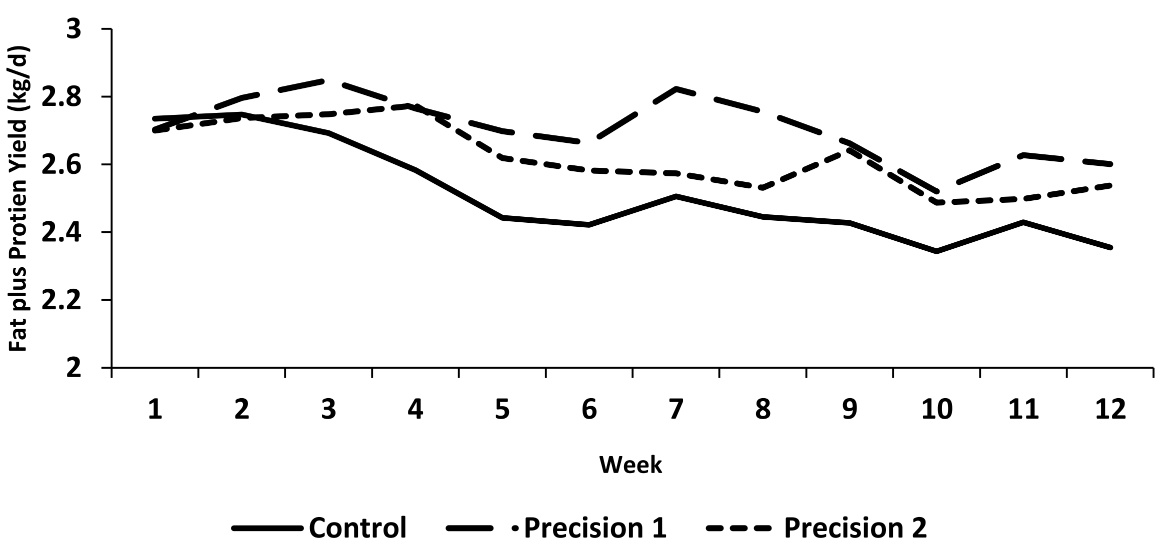

Figure 2. Mean fat plus protein yield (kg/d) for cows offered concentrates according to a conventional FTY system (Control), or corrected for milk composition (Precision 1), or corrected for milk composition and individual intake (Precision 2) over a 12 week period.

Discussion

A successful precision concentrate feeding strategy should offer opportunities to improve overall feed use efficiency. The first attempts to match individual cow concentrate inputs with energy needs used milk production as the sole variable as this was the only performance measurement readily available on farm at that time, and on the majority of farms this is still the case (Maltz et al., 2020). However, three decades ago Maltz et al. (1991) suggested that individual feeding strategies need to consider more than simply milk yield in order to be successful. Within the current study, the Precision feeding treatments were designed to investigate the impact of allocating concentrates according to either milk energy output, or milk energy output in combination with actual energy intakes.

***Cow intake and performance**:* Traditional studies examining the milk yield response of dairy cows to concentrate feeding generally offer concentrates at a fixed, predetermined level, thus making interpretation of outcome relatively straight forward. Similarly, a number of earlier studies comparing concentrate allocation strategies were designed to ensure total concentrate inputs over the feeding period were similar with both treatments (Purcell et al., 2016; Little et al., 2016; Lawrence et al., 2016). In contrast, within the current study it was not the intention to equalise concentrate inputs across the three treatments. Rather concentrate inputs were adjusted on a weekly basis throughout the study, according to the specific components of each treatment (milk yield, milk composition, forage/total intakes), and in reality 'responded' to the changes in these parameters, perhaps sometimes creating a repeated feedback loop. As a result, concentrate levels deviated between treatments with cows in the Precision treatments consuming significantly more concentrates (1.0 kg/d) than those on the Control treatment, perhaps as a result of adjusting for actual milk composition. This difference, while making interpretation of outcomes more difficult, is an almost inevitable outcome of the treatment regimens imposed. Nevertheless, despite the higher concentrate intake with the Precision treatments, treatment had no significant impact on milk yield. When Maltz et al. (2013) adopted a precision feeding strategy to achieve a target EB, concentrate intakes were increased over the course of the 16 week study by an average of 0.9 kg/d within the precision approach compared to the control group. The increase in concentrate intakes led to an accompanying 3 kg/day increase in milk yield. However, as the latter study included the early lactation period, most of the difference in concentrate intakes (up to 2.4 kg/d) was found in the first 13 weeks post-partum when milk yields are more responsive to concentrate levels, and this may have set the precision fed cows on a higher milk yield trajectory. In contrast, the current study focused on mid-lactation cows to avoid the effects of early lactation and the period of major tissue change, so it is possible that different results may have been found in a longer study encompassing early lactation and peak yield.

Within the Control treatment, mean milk composition at the start of the experiment was used in the calculation of concentrate feed rates throughout the study, as is standard practice on dairy farms. However, incorporating milk composition more frequently into concentrate allocation calculations has been shown to improve both the fat and protein content of milk (Maltz et al., 2009). The increase in milk protein found in the Precision treatments in the current study (+0.6 g/kg) is likely due in part to the increased concentrate intake within these treatments (Keady et al., 1998; Beever et al., 2001; Huhtanen et al., 2012), as milk protein content is generally influenced by energy intake, particularly the breakdown of starch to glucose (Osorio et al., 2016).

In contrast to the improvement in milk protein content, both milk fat content (-1.9 g/kg) and subsequently milk fat yield (-0.08 kg/d) tended to be reduced in Precision 2 compared to Control, which was unexpected and difficult to explain. Milk fat content has been shown to be reduced in cows fed high levels of concentrates or as a response to the subsequent depression in forage intake (Alatas et al., 2015; Purcell et al., 2015; Dewanckele et al., 2020). However, within this study similar levels and ranges of concentrate levels were offered to the two Precision treatments. Furthermore, concentrate intake had no effect on silage intakes, giving no obvious reason why accounting for individual cow intake resulted in a reduction in milk fat content.

While there was no obvious reason why Precision 2 treatment resulted in a reduction in milk fat content, it is known that cows offered the same ration can respond differently (Broster and Broster, 1998), and a cow’s response to ration intake is dependent on how energy is partitioned between milk yield, body tissue and reproductive performance, which may be driven by genetics (Friggens and Newbold, 2007). Due to the reduction in fat content, Precision 2 did not have a higher fat plus protein yield compared to the Control. However, Precision 1 had a significantly greater fat plus protein yield (+0.13 kg/d) compared to the other two treatments.

The adoption of a FTY approach has been shown to reduce the range of EB values experienced by individual cows within a group, compared to a group feeding approach, while having no effect on mean EB (Purcell et al., 2016). However, the latter study was designed to have similar concentrate inputs with all treatments. In the current study the precision feeding approaches had no significant impact on cow EB, which was positive for all treatments (average, 10.2 MJ/d) reflecting the mid-lactation status of the cows. There was also no difference in BW or BCS between treatments, supporting the absence of an effect on EB. By taking account of differences in milk composition and energy intakes between cows, it might have been expected that cows on these precision treatments would have moved closer to zero EB; however, this was not the case. Maltz et al. (2013) found no difference in EB, BW or BCS when feeding cows on the basis of EB, suggesting similar levels of body tissue mobilization or deposition across the treatments. In the current study it is possible that mean EB values may have been closer to zero if the calculations had taken account of changes in body tissue mobilisation/deposition, and differences in individual cow BW (with correspondingly higher or lower maintenance energy requirements compared to the set BW used within this study). A cow's BW can be used as a variable which either characterizes her intake potential or, when combined with milk yield and composition data, can indicate the energetic and physiological status of the cow (Maltz et al., 2009). When daily BW changes were incorporated into the feeding calculations in full lactation studies, there was some improvement to production and concentrate use efficiency (Maltz et al., 1992; Bossen and Weisbjerg, 2009; Gaillard et al., 2016). However, despite the availability of walk-through weighing systems, these are not widely installed on dairy farms for individual daily weighing.

Feed use efficiency: Within both Precision treatments cows were offered concentrates on the basis of individual milk energy (i.e. individual milk composition and milk yield). Therefore, it was hypothesised that the nutrient requirements of cows within the Precision treatments would be met more accurately with a subsequent improvement in efficiency. However, feed use efficiency, when expressed as either ECM/DMI or ECM/ME intake, did not differ between treatments, with an average value of 1.64 for the former, and 0.14 for the latter. Similarly, Bossen and Weisbjerg (2009) found no improvement in energy efficiency (ECM : MJ NE) when feeding cows according to BW changes. Maltz et al. (2013) observed an increase in efficiency of conversion of DMI into ECM during early lactation in precision fed cows; however, it is likely that the increase in efficiency in this study was due to the increase in energy density of the precision ration as the proportion of calories consumed that the cow partitioned into milk synthesis was similar between precision and control groups.

Concentrate DMI/milk yield is a 'crude' efficiency factor often used by farmers and nutritionists to provide an indication of efficiency of concentrate use on farms. Wilkinson (2011) estimated a mean efficiency of 0.31 (converted to a DM basis) for the UK dairy sector, meaning the Control cows used less concentrates per kg milk than the UK average. Within this study, more concentrate was offered per kg of milk (+0.04 kg) or per kg of ECM (+0.04 kg) within the Precision treatments compared to the Control treatment. This reflects the fact that the proportional reduction in concentrate intake with the Control treatment was greater than the proportional reduction in milk yield, resulting in an apparent improvement in concentrate use efficiency in the Control group.

Practical implications: On the majority of farms individual cow rationing systems (i.e. FTY) continue to use milk yield alone as the basis on which to adjust concentrate feed levels. Nevertheless, on many farms information already exists that would allow more precision to be adopted in terms of concentrate allocation strategies, and given the speed of agri-tech development, additional information will become increasingly available in the future. For example, while many farms now have access to individual cow test-day milk composition data on a monthly basis, robotic milking systems and developments within in-line sensors means that milk composition data will increasingly be available in real time on a day-to-day basis. Furthermore, while group intakes can be measured with a reasonable degree of accuracy by recording feed offered using a diet feeder, a number of systems are being developed that would allow individual cow intakes to be either predicted or 'measured'. For example, equations exist which allow intake to be predicted using readily available farm data such as lactation number, ECM, fat : protein ratio and week of lactation (Shriali et al., 2020). Furthermore, there is increasing interest in the development of camera and positioning systems that could allow individual cow intakes to be predicted (Bloch et al., 2019). In addition, automatic body condition scoring systems, and systems which record BW at each milking have already been commercialised, and these can provide information on the 'energy status' of individual cows. Additional information on the energy status of individual cows is also increasingly available through the use of MIR analysis of milk (Grelet et al., 2018).

Nevertheless, despite the potential to greatly improve the precision with which concentrates are allocated to individual cows, there is still limited evidence that the adoption of improved precision at an individual cow level will improve production efficiency. While it was hypothesised that a precision FTY allocation strategy would improve cow efficiency due to the energy requirements of all cows being met more accurately, no such benefit was observed in the current study. Rather, the results of this study demonstrate that improving the 'precision' of concentrate allocation to cows, did not improve performance or efficiency measures in agreement with previous studies (Bossen and Weisbjerg, 2009; Gaillard et al., 2016; Fischer et al., 2020). While Maltz et al. (2013) found an improvement when feeding concentrates on the basis of EB, these calculations may not be practical in an on-farm setting. Therefore, further research is required to determine what readily available measurements could be utilized to improve the methods used to allocate concentrates as it is vital that the dairy industry utilises concentrates as effectively as possible to improve sustainability and profitability.

Conclusion

Adjusting concentrate levels to account for milk composition increased concentrate intakes and improved milk protein composition and milk protein yield compared to only adjusting concentrates on the basis of milk yield. However, accounting for milk composition and individual DMI did not improve milk yield, ECM yield, EB or efficiency parameters. Therefore, this study found no benefit in adjusting concentrate allocation on the basis of milk composition or individual DMI compared to a standard milk yield based FTY.

SECTION 3

Using routine commercial records to predict dry matter intake within feed-to-yield concentrate allocation strategies

Introduction

There is considerable interest in the adoption of 'precision feeding' approaches within dairy systems, with the allocation of concentrates on a feed-to-yield (FTY) basis being one approach to 'precision feeding'. This approach normally involves offering a 'basal diet' (often a mixture of forage and concentrate ingredients, in the form of a mixed ration) which is designed to supply the maintenance energy requirements, plus the production of a certain volume of milk, based on the average cow in the herd. This is often known as the 'Maintenance plus' or M+ value. Additional supplements are then offered to each individual cow, normally through an in-parlour or out-of-parlour feeding system, at a level designed to support milk yields in excess of those assumed to be supported by the basal diet. However, a potential limitation of this approach is the assumption that the basal diet supports a single assumed M+ value for all cows. It is postulated that if individual M+ values could be calculated for each individual cow, then concentrates could be offered with an increased level of precision. The first step in achieving this, and the objective of the current study, is to use readily available farm data to develop dry matter intake (DMI) prediction equations for individual cows. If a robust model could be developed, then intake of the basal diet for each cow could be determined by deducting the known quantity of concentrate (DM basis) offered on a FTY basis from the total predicted DMI. The M+ supported by the basal diet could then be determined for individual cows based on the ingredient composition of the basal diet.

This study was designed to develop a robust total DMI prediction model for use within FTY systems, which would utilise routine records available on farms. The aim was to develop a model which could help dairy farmers and nutritionists better manage concentrate allocations to optimise performance and profitability.

Methodology

Data were obtained from five studies conducted at the Agri-Food and Biosciences Institute, Hillsborough between 2013 and 2019. All of these studies involved a FTY approach to concentrate allocation. Weekly records from the five studies (AFBI project IDs: D107, D113, D130, D138 and D143) were used. In all the experiments a basal diet, comprising a mixture of grass silage and concentrates, was offered, with additional concentrates then offered to each individual cow through an out-of-parlour feeding system. All studies commenced at calving, and normally involved a 3 - 4 week concentrate build-up strategy, before cows moved onto the FTY approach. Studies were conducted over the first 140 – 180 days of lactation. Studies differed in a number of ways, including, concentrate feed rate through the out-of-parlour feeders, silage types offered, and assumptions used to determine concentrate allocations.

The following data was available from each study for each individual cow: current lactation number (1, 2, 3 and $\geq$4), week in milk, and weekly data for total dry matter intake (DMI), milk production, milk composition, and live-weight. Energy corrected milk (ECM) yield (kg/day) and milk fat : protein ratio (Fat : Protein) were subsequently determined for each week. In total, 3999 weekly records from four experiments (D107, D113, D130, and D138), were used to develop the predictive models, and the 404 weekly records from the most recent experiment (D143) were used to estimate the accuracy of the estimation.

A detailed description of the phenotypic data used in this analysis (from each of the 5 studies) are presented in Figure 1: These comprised the distribution of daily milk yield (A), fat (B), protein(C), lactose (D), ECM (E), Fat : Protein (F), and BCS (G), live-weight (H), lactation number (I), and DMI (J).

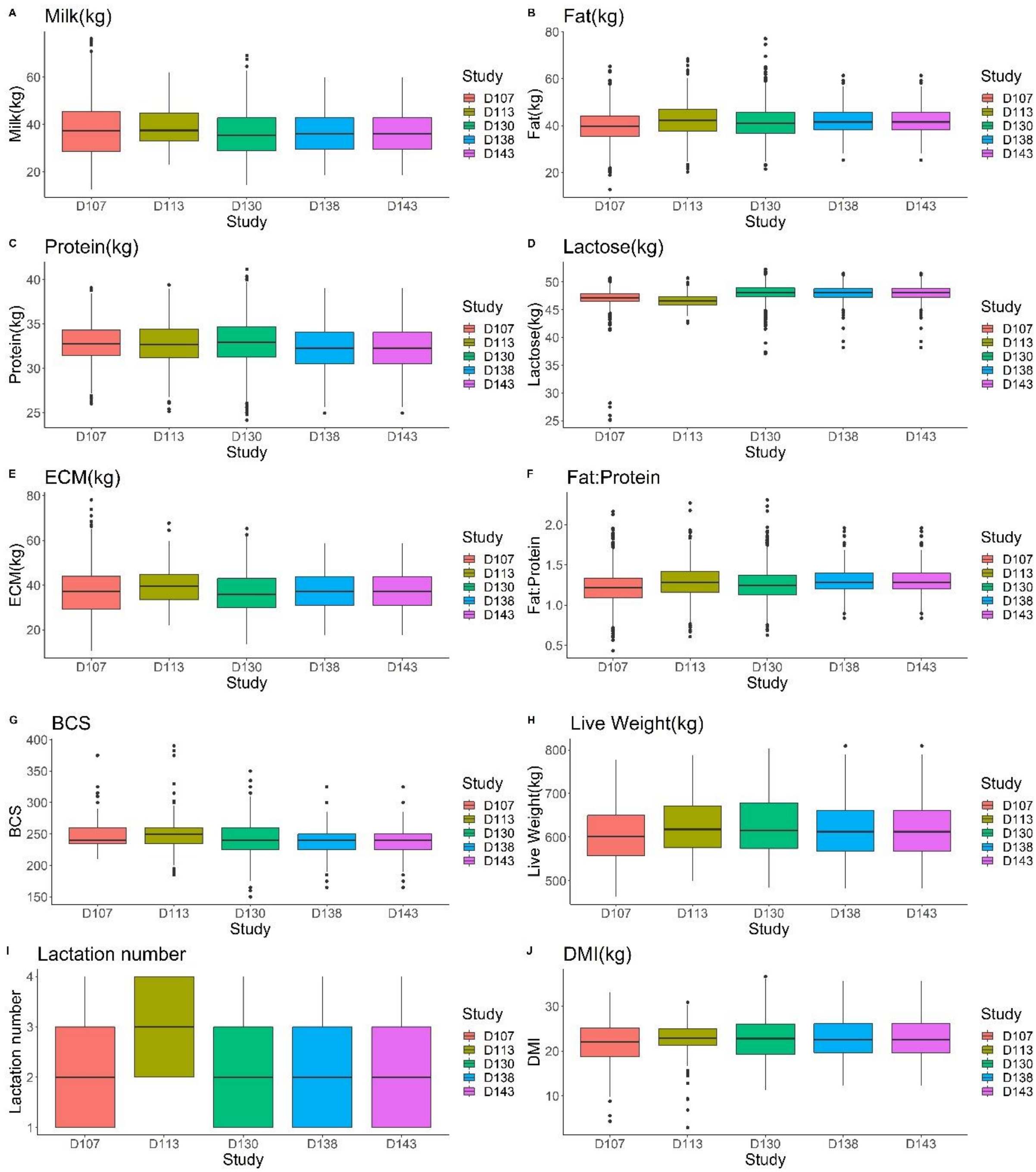

Figure 1. Mean values, and distribution of phenotypic data used in the modelling exercise from each of the 5 studies: milk yield (A), fat (B), protein(C), lactose (D), ECM (E), Fat : Protein (F), and BCS (G), live-weight (H), lactation number (I), and DMI (J).

A wide range of data science approaches (including machine learning approaches) were used for data modelling in order to provide the most reliable predictive models. Eight different approaches, encompassing three broad data modelling methods, were used. These are summarised below:

1. *Linear methods*:
    a. Linear Model (LM): a linear approach to modelling the relationship between a dependent and independent variables.
    b. Generalized Linear Model with Step wises selection based on AIC (GLM_StepAIC)
2. *Non-Linear methods*:
    a. Support Vector Machine (SVM): a supervised machine learning model with associated learning algorithms that analyse data for classification and regression analysis.
    b. k-Nearest Neighbours algorithm (k-NN): a non-parametric, simple, supervised machine learning algorithm that can be used to solve both classification and regression problems. This approach is easy to implement and understand, but has a major drawback of becoming significantly slower as the size of the data increases.
3. *Trees and Ensemble decision making learning methods*
    a. Classification and Regression Tree (CART): a predictive model, which explains how an outcome variable's values can be predicted based on other values. A CART output is a decision tree where each fork is a split in a predictor variable and each end node contains a prediction for the outcome variable.
    b. Bagged classification and regression trees (Bagged CART): creates several subsets of data from training samples chosen randomly with replacement. Then, each collection of subset data is used to train their decision trees. As a result, it ends up with an ensemble of different models. Average of all the predictions from different trees are used which is more robust than a single decision tree.
    c. Random Forest: an ensemble learning method for classification, regression and other tasks that operates by constructing a multitude of decision trees at training time and outputting the class that is the mode of the classes (classification) or mean/average prediction (regression) of the individual trees. Random decision forests correct for decision trees' habit of overfitting to their training set.

d. Stochastic Gradient Boosting (SGB): a machine learning technique for regression and classification problems, which produces a prediction model in the form of an ensemble of weak prediction models, typically decision trees. When a decision tree is the weak learner, the resulting algorithm is called gradient boosted trees, which usually outperforms random forest. It builds the model in a stage-wise fashion like other boosting methods do, and it generalizes them by allowing optimization of an arbitrary differentiable loss function.

In order to compare the accuracy of proposed models with each of the above methods, we used three common statistical measures (mean absolute error (MAE), Root Mean Square Error (RMSE) and R-squared). The three measures are explained in details as follow:

Mean Absolute Error (MAE) measures the average magnitude of the errors in a set of predictions, without considering their direction. It's the average over the test sample of the absolute differences between prediction and actual observation where all individual differences have equal weight. Thus higher MAE translates to lower accuracy of prediction.

Root-Mean-Square Error (RMSE) is a frequently used measure of the differences between values (sample or population values) predicted by a model or an estimator and the values observed. RMSE is the standard deviation of the residuals (prediction errors). Residuals are a measure of how far from the regression line data points are; RMSE is a measure of how spread out these residuals are. In other words, it tells you how concentrated the data is around the line of best fit. Thus higher RMSE translates to lower accuracy of prediction.

R-squared (R2) is a statistical measure that represents the proportion of the variance for a dependent variable that's explained by an independent variable or variables in a regression model. R-squared represents how close the data are to the fitted regression line. It is also known as the coefficient of determination, or the coefficient of multiple determination for multiple regression. The definition of R-squared is fairly straight-forward; it is the percentage of the response variable variation that is explained by a linear model. R-squared is always between 0 and 100%. 0% indicates that the model explains none of the variability of the response data around its mean and 100% indicates that the model explains all the variability of the response data around its mean.

Results and discussion

A comparison of the accuracy (mean absolute error (MAE), Root Mean Square Error (RMSE) and R-squared) between the 8 different methods examined is presented in Table 1. Although the three machine learning methods (SVM, Random Forest and SGB) have in general a higher accuracy than other methods, due to the small sample size used in this study, these machine learning based methods did not provide any significant accuracy over the standard linear methods. Consequently, standard linear models were used for developing and optimizing predictive models. Two linear regression models were constructed to predict daily DMI, using weekly data from experiments 1 – 4.

Model 1 included lactation number, ECM, Fat : Protein ratio and week-in-milk, while Model 2 also included liveweight. These models were developed based on backward selection, and all the variables retained in the equations had a P value lower than 0.05. For diagnosing collinearity in the regression model, Variance Inflation Factor (VIF) values were estimated. Data from the fifth experiment were then used to validate the two equations. The Pearson's product-moment correlation, R-squared and root mean square error (RMSE) between predicted DMI and actual DMI were obtained. All analysis was undertaken using R v3.5.3.

The two DMI prediction models are presented in Table 2. Model 1 uses data that is readily available for individual cows on many farms, while Model 2 includes live weight, which will becoming more available. The collinearity tests demonstrated that VIFs were less than 4, meaning that collinearity between predictors was not observed. These models can be used to predict DMI within dairy systems where a feed-to-yield concentrate allocation approach has been adopted with a reasonable degree of accuracy.

Figure 2 shows the plot of estimated DMI by the models (A, model 1 and B, model 2) and the actual measured DMI in experiment D143. Furthermore, Figure 3 shows the plot of actual DMI and estimated DMI by the models (model 1 and model 2) for weeks in milk in experiment D143.

Table 1. The accuracy comparison between the 8 methods used for developing predictive models using three parameters, mean absolute error (MAE), Root Mean Square Error (RMSE) and R-squared.

MAE							
	Min.	1st_Qu.	Median	Mean	3rd_Qu.	Max.	NA's
LM	1.53	1.62	1.67	1.67	1.71	1.83	0
GLM_StepAIC	1.53	1.62	1.67	1.67	1.71	1.83	0
SVM	1.51	1.62	1.67	1.66	1.71	1.81	0
k-NN	1.61	1.69	1.72	1.73	1.78	1.97	0
CART	1.91	2.08	2.14	2.14	2.23	2.29	0
Bagged CART	1.60	1.74	1.79	1.79	1.84	1.95	0
Random Forest	1.44	1.54	1.62	1.60	1.65	1.77	0
SGB	1.47	1.58	1.65	1.63	1.68	1.73	0
RMSE							
	Min.	1st_Qu.	Median	Mean	3rd_Qu.	Max.	NA's
LM	1.93	2.17	2.23	2.21	2.28	2.48	0
GLM_StepAIC	1.93	2.17	2.23	2.21	2.28	2.48	0
SVM	1.93	2.16	2.22	2.20	2.25	2.45	0
k-NN	2.06	2.23	2.27	2.27	2.33	2.64	0
CART	2.42	2.63	2.75	2.74	2.88	2.96	0
Bagged CART	2.04	2.27	2.36	2.35	2.41	2.62	0
Random Forest	1.85	2.06	2.14	2.13	2.21	2.38	0
SGB	1.88	2.11	2.18	2.16	2.22	2.38	0
R-squared							
	Min.	1st_Qu.	Median	Mean	3rd_Qu.	Max.	NA's
LM	0.68	0.71	0.72	0.73	0.74	0.76	0
GLM_StepAIC	0.68	0.71	0.72	0.73	0.74	0.76	0
SVM	0.68	0.71	0.73	0.73	0.74	0.78	0
k-NN	0.63	0.70	0.71	0.71	0.72	0.76	0
CART	0.51	0.55	0.57	0.58	0.61	0.66	0
Bagged CART	0.64	0.67	0.69	0.69	0.72	0.75	0
Random Forest	0.70	0.73	0.74	0.75	0.77	0.79	0
SGB	0.70	0.72	0.74	0.74	0.76	0.78	0

Min.: minimum; 1st_Qu.; first quartile; 3rd_Qu.; third quartile; NA's: number of not available data.

Table 2. Prediction equations for dry matter intake (DMI) within feed-to-yield dairy systems

Model	**Equation**	**Correlation[1]**	**Adjusted R-squared**	**RMSE**
Model 1	$DMI = 11.032 + (0.554 \times Lactation\ number) + (0.343 \times ECM) + (-3.194 \times Fat{:}Protein) + (0.107 \times week\ in\ milk)$	0.84*	0.71	2.03
Model 2	$DMI = 3.745 + (0.015 \times Live\ weight) + (0.155 \times Lactation\ number) + (0.311 \times ECM) + (-2.829 \times Fat{:}Protein) + (0.068 \times week\ in\ milk)$	0.86*	0.73	2.04

*[1] Pearson's product moment correlation between predicted and actual DMI; * P <0.05*

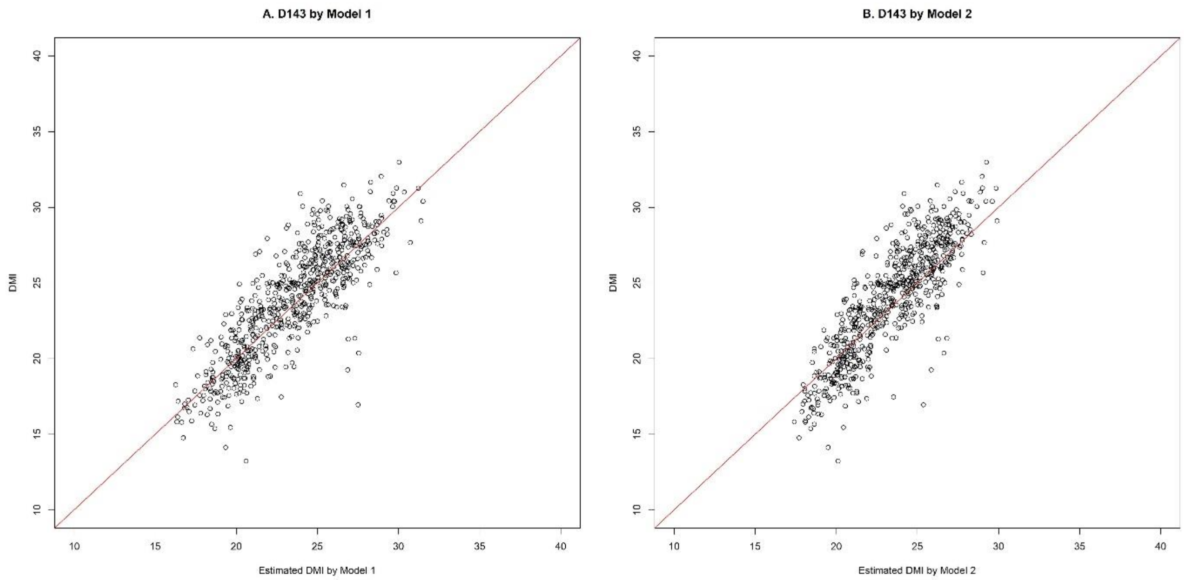

Figure 2. Plot of the estimated DMI and the actual measured DMI in the experiment D143: Model 1 (A) and Model 2(B).

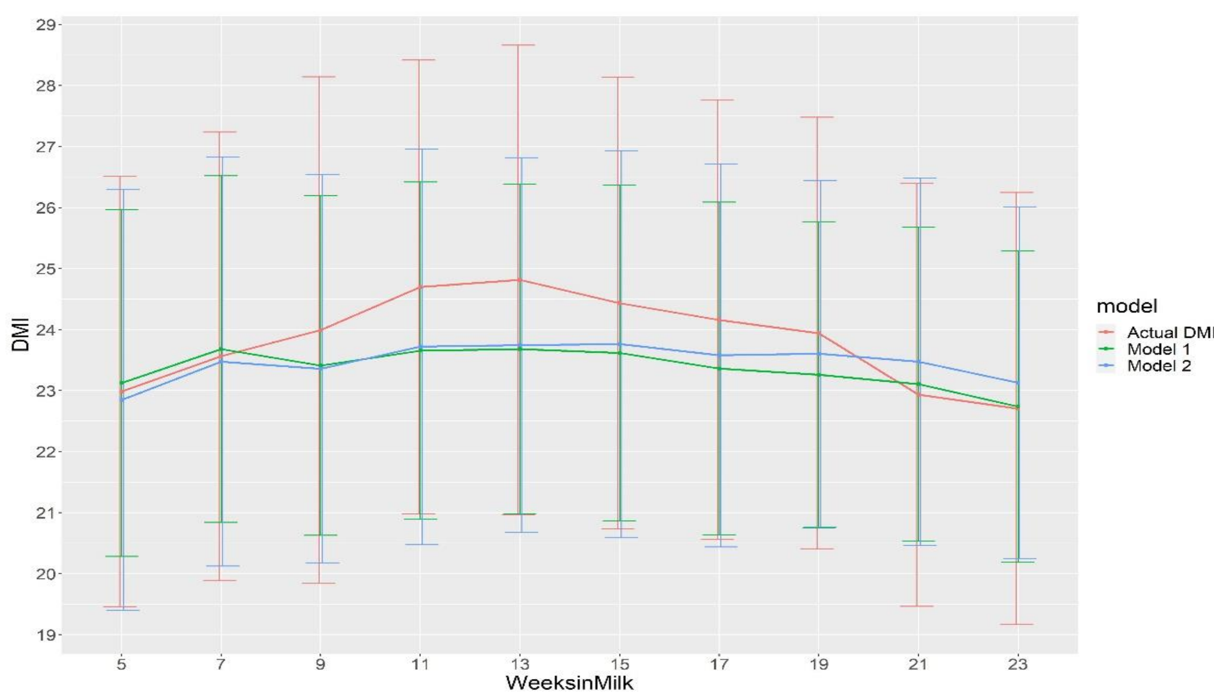

Figure 3. Plot of the estimated DMI and the actual measured DMI for weeks in milk in the experiment D143.

Conclusion

The ability to predict intakes of individual dairy cows creates opportunities to increase the precision with which concentrates are allocated to individual cows within feed-to-yield systems. Two robust models were developed based on the limited datasets available, and while Model 2 is a slightly better model, this model requires live-weight data which is not currently available on the majority of farms. Undoubtedly, both models could be refined further with larger data sets, especially data containing some indication of silage quality. Furthermore, this analysis has clearly demonstrated that applying data science and machine learning approaches has the potential to increase the accuracy of predictive models. AFBI are currently finalising a data set from 40 dairy cow feeding experiments, which includes details of diet composition, including silage quality, and moving forward, this will be an active research area. AFBI are currently trying to recruit a PhD student to take this work forward on this much larger data set.

SECTION 4

The potential of using feeding behaviour halters and pedometers to predict dry matter intake and energy balance of dairy cows

Introduction

Over the past few decades there has been substantial progress in the development of electronic devices with which to monitor dairy cow behaviour (Benaissa et al., 2016a, 2016b; Braun et al., 2015; Chapinal et al., 2011; Dutta et al., 2015; Maselyne et al., 2017; Piccione et al., 2011; Van Nuffel et al., 2015). For example, it is well established that identifying changes in behaviour can assist farmers in predicting time of calving (Kok et al., 2017; Pahl et al., 2014; Schirmann et al., 2013), oestrus (Pahl et al., 2015; Reith et al., 2014), and lameness (Whay and Shearer, 2017). In addition, behaviour monitoring systems can also provide important information about the welfare of dairy cows. For instance, fluctuations in the time a cow spends feeding and ruminating could be due to a change in cow comfort (Ledgerwood et al., 2010; Tucker and Weary, 2004; Urton et al., 2005).

Wearable pedometers and noseband halters have been widely tested and validated as means of examining cow behaviours (Martiskainen et al., 2009; Müller and Schrader, 2003; Robert et al., 2009; Vázquez Diosdado et al., 2015). For example, the RumiWatch noseband sensor was developed and validated as a monitoring device for ruminating and eating activities in indoor dairy cows (Braun et al., 2013; Zehner et al., 2012, 2017; Benaissa et al., 2019). Chewing is an essential physiological process in cattle, and long and intensive chewing periods promote saliva secretion and reduction of feed particle size, thus stimulating nutrient degradation while maintaining rumen health (Zebeli et al., 2012). Chewing consists of eating and rumination activity and both are strongly dependent on the diet (Zebeli et al., 2012). Indeed, the length of the chewing periods reflects secretion of alkaline saliva and rumen buffering, and this can provide a good indicator of rumen health status (Allen, 1997). In addition, while pedometers have been adopted by many dairy farms around the world to assist with oestrus detection (Matlz et al., 2020), information provided by pedometers may have value in helping to assess other useful traits, including nutritional status. Dry matter intake (DMI) and energy status of individual cows are two key traits in rationing dairy cows. Having improved information on these would greatly improve the accuracy with which we can ration cows, and potentially reduce feed costs and improve health and fertility. Consequently the current study was designed to examine if parameters obtained from RumiWatch halters or pedometers could aid farmers in predicting traits such as DMI and energy balance.

Methodology

Two experiments were conducted to examine if pedometers or RumiWatch halters could help predict DMI and EB. These experiments were conducted over two consecutive periods during 2017/18 and 2019 at the Agri-Food and Biosciences Institute (AFBI), Hillsborough. Experimental procedures in both studies were conducted under an experimental license granted by the Department of Health, Social Services and Public Safety for Northern Ireland in accordance with the Animals Scientific Procedures Act 1986.

Animals and housing: Study 1 involved 80 Holstein cows and 30 heifers which calved between 1st October and 31st December 2017. Cows remained on the study for 150 days (21 weeks) post-calving. Study 2 was a 12 week study involving 69 mid-lactation Holstein dairy cows, 45 multiparous and 24 primiparous. In both studies cows were housed in a free-stall house with concrete flooring, and had access to individual cubicles, fitted with rubber mats and bedded with sawdust. The cubical-to-cow ratio was > 1:1 at all times, meeting the recommendations of FAWC (1997). The floor area was scraped every 3 h using an automated system.

Diets: In study 1 all cows were offered a basal mixed ration consisting of a common grass silage produced from a perennial ryegrass (*Lolium Perenne*) based sward: dry matter (DM), 330 g/kg; crude protein (CP), 151 g/kg DM; metabolisable energy (ME), 11.6 MJ/kg DM (Table 1), mixed with a common concentrate in the form of a meal (ingredient list and chemical composition, Table 2). Concentrates were included in the mix at a rate of 4.0 and 5.4 kg/d on a fresh weight basis for primiparous and multiparous cows, respectively, to achieve a target concentrate intake of 3.75 and 5.0 kg/d for primiparous and multiparous, respectively. Additional concentrates were offered on a feed-to-yield basis, as outlined later.

In study 2 all cows were offered a basal mixed ration consisting of a common grass silage produced from a perennial ryegrass (*Lolium Perenne*) based sward: dry matter (DM), 292 g/kg; crude protein (CP), 130 g/kg DM; metabolisable energy (ME), 11.1 MJ/kg DM (Table 1), mixed with a common concentrate (in the form of a meal; ingredient composition, Table 2). Concentrates were included in the mix at a rate of 4.3 and 5.3 kg/d on a fresh weight basis for primiparous and multiparous cows, respectively, to achieve a target concentrate intake of 4.0 and 5.0 kg/d for primiparous and multiparous, respectively.

In both studies, rations were prepared using a mixer wagon (Vari-Cut 12, Redrock, Armagh, Northern Ireland). The rations were then transferred from the mixer wagon to a series of feed boxes mounted on weigh scales, with cows accessing food in these boxes via an electronic identification system, thus enabling individual cow intakes to be recorded daily (Controlling and Recording Feed Intake, Bio-Control, Rakkestad, Norway). The rations were prepared daily and offered between 09.00 and 10.00 h, while uneaten food was removed the following day at approximately 08.00 h. Cows had access to fresh water at all times.

In both studies cows were offered additional concentrates on a FTY basis (ingredient list and chemical composition, Table 2), with 1.0 kg/day of this offered via an in-parlour feeding system (fixed throughout the duration of the study; 0.5 kg at each milking) and the remainder offered via OPF. Within both studies a number of different FTY strategies where adopted, but analysis of behavioural data was run across all treatments.

Cow measurements: All cows were milked twice daily (between 06.00 and 08.00 h and between 15.00 and 17.00 h) throughout both studies using a 50-point rotary milking parlour (Boumatic, Madison, USA). Milk yields were automatically recorded at each milking, and a total daily milk yield for each cow for each 24 h period calculated. Milk samples were taken during 2 consecutive milkings each week, treated with a preservative tablet (lactab Mark III, Thompson and Cooper Ltd., Runcorn, UK), and stored at 4°C until analysed (normally within 48 h). Milk samples were analysed for fat, protein and lactose concentrations using an infrared milk analyser (Milkoscan CombifossTM7; Foss Electric, Hillerød, Denmark), and a weighted concentration of each constituent determined for the 24 h sampling period.

Body weight (BW) was recorded twice daily (immediately after each milking) using an automated weighbridge, and a mean weekly BW for each cow was determined. The body condition score (BCS) of each cow was estimated fortnightly by a trained technician according to Edmonson et al. (1989) on a 5 point (including quarter points) scale. The locomotion score (LS) of each cow was also estimated fortnightly by a trained technician according to Manson and Leaver (1988) on a 5 point (including half points) scale.

In Study 1 blood samples were also collected from the tail of each cow prior to feeding at 4, 8, 12, 16 and 20 week of lactation, and centrifuged (3000 rpm for 15 minutes) to isolate either the serum (tubes with a clot activator) or the plasma (fluoride oxalate tubes). Serum βHB, non-esterified fatty acids (NEFA) and urea concentrations, and plasma glucose concentrations were determined using a dry chemistry analyser system (Sapphire 800, Glenbio, UK), using Olympus kits (Olympus Life Science Research Europa, Munich, Germany).

All cows on Study 1 and 2 were fitted with pedometers (IceRobotics, Edinburgh, UK) at 28 days post-calving and these remained on the cows for the duration of the study. The pedometers recorded the number of steps, lying time, lying bouts, standing time, standing bouts, and 'motion index' each day. In study 1 pedometer data was averaged for each week and mean values for four periods (7-10, 11–14, 15–18 and 19–22 weeks post-calving) calculated. In study 2 the pedometer data was averaged over the entire study (12 weeks).

In Study 1 RumiWatch halters (ITIN + HOCH, Switzerland) were used to assess a range of feeding/rumination parameters ('other activity time', 'ruminate time', 'eat time', 'drink time', 'other chew', 'ruminate chew', 'total eat chew', 'drink gulp', 'bolus/hr', 'chews/min', 'chews/bolus', 'activity', 'head up time', 'head downtime' and 'temperature') on a subset of 45 multiparous cows from weeks 10–21 of lactation. The equipment consisted of a halter equipped with an oil-filled tube with a built-in pressure sensor, a 3-axis accelerometer, data logger and two 3.6 V batteries. The oil-filled tube was placed over the bridge of the animal's nose with pressure in the oil-filled tube altering with jaw movements. These pressure signatures and acceleration patterns were collected at a frequency of 10 Hz resolution. Raw data was stored on 4GB SD memory card and downloaded regularly during the recording period. As detailed and validated by Werner (2018) specialist software (RumiWatch Converter version V0.7.4.5) was used to classify pressure and acceleration data into a range of grazing and ruminating variables. Halters were reviewed twice daily to ensure animals did not have any abrasions. Mean data was collected at hourly time points, and daily data averaged over two periods (10-15 and 16–21 weeks post calving).

Feed analysis*:* A sample of the grass silage offered was taken daily throughout the experiment and dried at 60°C for 48h to determine oven DM content. Twice weekly a sample of the dry silage was collected, bulked for each 14 d period, with the bulked sample milled through a sieve with 0.85 mm aperture and analysed for neutral detergent fibre (NDF), acid detergent fibre (ADF) and ash concentrations. Each week a fresh silage sample was analysed for GE, N, pH, ammonia-N and volatile components, and the ME concentration of the sample predicted using near infrared reflectance spectroscopy (NIRS) according to Park et al. (1998). A sample of each concentrate offered was taken weekly, dried at 60°C for 48 h to determine ODM, and a dried sample from one day each week retained, bulked over each 14 d period, milled through a 0.85 mm sieve, and subsequently analysed for N, NDF, ADF, ash and starch concentrations. All chemical analysis of the feed stuffs offered were undertaken as described by Purcell et al. (2016).

Statistical analysis: The statistical analysis was designed to examine if relationships could be identified between behaviour data and production data. For each of the periods outlined above (Study 1: pedometer 7-10, 11–14, 15–18 and 19–22 weeks post-calving; RumiWatch 10-15 and 16–21 weeks post calving; Study 2: pedometer weeks 1-12 of study) a univariate analysis of the cow production data to each variable recorded by the pedometers and rumination halters was undertaken to examine relationships.

A multivariate analysis was also conducted to identify if any variables, or selection of variables, could predict total DMI or EB. Using data from study 1 a stepwise regression analysis was conducted for all pedometer data against all production data, while a stepwise regression analysis was conducted on RumiWatch data against milk yield, total DMI and EB. The stepwise regression analysis was carried out using forward selection, with backward elimination according to a criterion based on variance ratios. For each response variable in question all explanatory variables were selected and then models were refitted using linear mixed model methodology (REML estimation method) with treatment fitted as random effects. Any variables that weren't significant ($P<0.05$) were removed from the final models using a backward elimination procedure. In all cases the adequacy of the final models was assessed by visual inspection of the appropriate residual plots. Analysis were undertaken using Genstat (20th edition; VSN International Limited, Oxford, UK).

Results

Pedometer results Study 1: Cow production data during the four pedometer periods in Study 1 are detailed in Table 3, while the pedometer results for the four periods are detailed in Table 4. As expected, concentrate intake decreased and silage intake increased as the study progressed, while milk yield also declined. Milk fat and protein also showed the normal lactation increase as the study progressed, while energy balance, BCS and live-weight increased. Cow lying and standing bouts remained similar throughout the study, but lying time increased (and standing time decreased) as the study progressed. Daily steps and motion index peaked at 15-18 weeks and then declined.

Within the univariate analysis, lactation number explained most of the variation in performance data with some reasonable correlations ($R^2 < 62$; Table 5). Despite some significant correlations ($P < 0.05$) between pedometer data and production data, due to the poor fit of the equations (as demonstrated by low R^2 values of <40) no pedometer data could be reliably used to predict performance. Multivariate analysis of the pedometer data found that lactation number explained most of the variation in intakes and energy balance. In early lactation (7-10 weeks) standing time had a negative relationship with EB, but R^2 was low, while in mid lactation (15-18 weeks) the number of standing bouts had a positive relationship with DMI (Table 6). In any of these equations it appeared that the higher R^2 were being driven by lactation number (Table 6) rather than pedometer data.

Pedometer results Study 2: Cow production data during the 12 week study are detailed in Table 7, while the pedometer results for the corresponding period are detailed in Table 8. Cows in study 2 had a lower milk yield and therefore a lower DMI compared to cows on Study 1, reflecting the fact that they were in mid-lactation and past peak milk yield. They also had a lower step count and motion index compared to Study 1. Similar to Study 1, none of the pedometer data could be used to predict production variables due to very low correlation (R^2), despite some variables being identified as significant.

RumiWatch results Study 1: Cow production data during the two RumiWatch periods in Study 1 is detailed in Table 9, while the RumiWatch data is summarised in Table 10. Milk yield and total DMI intake where lower in Period 2 compared to Period 1, but energy balance was greater in Period 2. Parameters measured by the RumiWatch system did not differ between Periods.

No variables were significantly correlated with EB within the univariate analysis, and despite some significant correlations between RumiWatch data and milk yield and DMI, none of the equations had a good fit ($R^2 < 50$); therefore, neither lactation number nor any RumiWatch data could reliably predict milk yield, total DMI or energy balance (Table 11). Likewise within the mulitvarate analyses there were no equations strong enough to reliably predict milk yield, total DMI or energy balance (Table 12). No variables were selected by the model for energy balance. However drinking was identified as a positive driver of milk yield and total DMI. Activity index was a negative driver of milk yield in both Periods, and with total DMI in Period 1. Total eat time was a negative driver of total DMI in Period 2. However, the weak R^2 indicates that these equations should be treated with caution as it is unlikely that they will be able to accurately predict any production variables.

Table 1. Chemical composition of silages offered to cows in Studies 1 and 2**.**

	Study 1		Study 2	
	Mean	SD	Mean	SD
Oven dry matter (g/kg)	317	80.0	292	29.2
VCODM (g/kg)	330	78.3	303	28.7
Crude protein (g/kg DM)	151	15.5	130	8.4
Ash (g/kg DM)	88	5.9	95	3.4
Acid detergent fibre (g/kg DM)	267	32.1	286	4.5
Neutral detergent fibre (g/kg DM)	470	53.8	482	9.0
Gross energy (MJ/kg DM)	19.4	2.04	18.5	1.57
Metabolisable energy (MJ/kg DM)	11.6	0.62	11.1	0.26
pH	4.10	2.754	4.01	0.103
Lactic acid (g/kg DM)	77	41.5	97	23.0
Acetic acid (g/kg DM)	18.6	14.16	19.2	4.15
Ethanol (g/kg DM)	5.0	3.64	13.1	3.37
Ammonia (g/kg total N)	75	19.4	75	0.81

VCODM, volatile corrected oven dry matter; DM, dry matter

Table 2. Ingredient list (kg/t) and chemical composition (g/kg) of concentrates offered to cows in studies 1 and 2.

		Study 1				Study 2			
		Pellets (OPF feeder)		Meal (blend concentrate)		Pellets (OPF feeder)		Meal (blend concentrate)	
Ingredients	Maize meal	170		180		175		280	
	Soya bean meal (high protein)	140		140		86		191	
	Soya hulls	140		140		175		254	
	Wheat	130		130		174			
	Sugar beet pulp	100		100		61			
	Rapeseed meal	75		75				190	
	Wheat feed	60		60					
	US distillers grains	50		65		85			
	Maize gluten	40		40		110			
	Molaferm	50		25		80		25	
	Limestone	12.5		12.5		9		6	
	Palm oil	9		9		10			
	Protected fat (Megalac)					15		30	
	Acid buff	8		8					
	Salt	7.4		7.4		6		9	
	Magnesite	4.4		4.4		2		2	
	RumiTech					7		7	
	Mineral/vitamin mix	4		4		7		7	
	Actisaf	0.4		0.4					
Chemical Composition (SD)	Oven dry matter	885	(2.3)	818	(3.6)	894	(4.5)	888	(4.6)
	Starch	209	(10.5)	222	(18.2)	193	(34.0)	262	(8.0)
	Crude protein	206	(7.0)	208	(9.2)	239	(16.8)	169	(2.5)
	Acid detergent fibre	161	(12.3)	155	(9.8)	191	(47.7)	152	(5.8)
	Neutral detergent fibre	343	(38.6)	321	(27.6)	342	(80.0)	295	(24.0)
	Ash	81	(5.6)	81	(6.8)	79	(8.0)	77	(2.0)
	Metabolisable energy (MJ/kg)	13		13		13.2		13.0	

Table 3. Cow production data during the four pedometer periods in Study 1.

	Average	Min	Max
7-10 weeks post-calving			
Silage DMI (kg/day)	10.2	5.8	15.8
Concentrate DMI (kg/day)	12.1	7.8	18.5
Total DMI (kg/day)	22.3	14.3	31.0
Milk yield (kg/day)	38.6	20.2	59.0
Milk fat (g/kg)	40.0	30.3	49.3
Milk protein (g/kg)	31.7	27.2	36.5
Milk lactose (g/kg)	48.3	44.4	51.3
Fat :Protein ratio	1.26	0.95	1.62
Fat + Protein Yield (kg/d)	2.75	1.40	4.22
ME intake (MJ/d)	250	158	348
ME Requirement (MJ/d)	269	163	398
Energy balance (MJ/d)	-18	-75	40
Live-weight (kg)	613	495	785
Body condition score	2.4	1.7	3.4
10-14 weeks post-calving			
Silage DMI (kg/day)	10.6	6.8	15.7
Concentrate DMI (kg/day)	12.1	5.3	20.7
Total DMI (kg/day)	22.7	12.9	32.1
Milk yield (kg/day)	36.8	18.5	56.0
Milk fat (g/kg)	41.1	28.7	52.4
Milk protein (g/kg)	32.2	28.2	36.6
Milk lactose (g/kg)	48.1	42.9	51.9
Fat :Protein ratio	1.28	0.97	1.52
Fat+Protein Yield (kg/d)	2.68	1.19	4.22
ME intake (MJ/d)	252	142	361
ME Requirement (MJ/d)	262	149	394
Energy balance (MJ/d)	-9	-65	34
Liveweight (kg)	617	499	783
Body condition score	2.4	1.7	3.1

Table 3 continued

	Average	Min	Max
15 -18 weeks post-calving			
Silage DMI (kg/day)	11.5	7.9	18.4
Concentrate DMI (kg/day)	11.7	5.7	19.7
Total DMI (kg/day)	23.3	14.9	30.0
Milk yield (kg/day)	35.3	17.2	52.9
Milk fat (g/kg)	43.5	29.8	55.6
Milk protein (g/kg)	33.8	28.5	38.6
Milk lactose (g/kg)	48.0	45.0	51.4
Fat :Protein ratio	1.30	1.00	1.60
Fat+Protein Yield (kg/d)	2.71	1.30	4.16
ME intake (MJ/d)	263	170	400
ME Requirement (MJ/d)	261	151	395
Energy balance (MJ/d)	1	-59	47
Liveweight (kg)	626	498	795
Body condition score	2.4	1.7	2.9
19-22 weeks post-calving			
Silage DMI (kg/day)	12.9	8.3	22.3
Concentrate DMI (kg/day)	10.2	4.7	19.8
Total DMI (kg/day)	23.1	15.7	33.4
Milk yield (kg/day)	33.3	18.0	48.4
Milk fat (g/kg)	44.0	29.9	55.9
Milk protein (g/kg)	34.9	29.9	39.3
Milk lactose (g/kg)	47.9	44.2	51.9
Fat :Protein ratio	1.26	0.89	1.61
Fat+Protein Yield (kg/d)	2.61	1.26	3.71
ME intake (MJ/d)	262	175	390
ME Requirement (MJ/d)	253	150	341
Energy balance (MJ/d)	9	-29	76
Liveweight (kg)	633	506	804
Body condition score	2.3	1.6	2.8

Table 4. Pedometer results during the four pedometer periods in Study 1.

	Average	Min	Max
7-10 weeks post-calving			
Daily Steps	1474	439	2868
Motion index	4983	1656	9454
Lying time (mins)	602	342	843
Lying Bouts	13	5	23
Standing time (mins)	838	597	1098
Standing Bouts	13	5	24
10-14 weeks post-calving			
Daily Steps	1517	544	3096
Motion index	5165	1973	10909
Lying time (mins)	605	302	874
Lying Bouts	12	2	23
Standing time (mins)	835	566	1138
Standing Bouts	12	3	23
15-18 weeks post-calving			
Daily Steps	1418	513	2847
Motion index	4913	2241	9400
Lying time (mins)	656	172	944
Lying Bouts	12	3	24
Standing time (mins)	784	496	1268
Standing Bouts	12	4	25
19-22 weeks post-calving			
Daily Steps	1360	471	3282
Motion index	4735	1826	12046
Lying time (mins)	676	149	1055
Lying Bouts	13	3	24
Standing time (mins)	764	385	1291
Standing Bouts	13	4	24

Table 5. Correlation of pedometer data with animal production values – results of the univariate analysis for Study 1.

Response	Explanatory	P Value	Constant	s.e.	Slope	s.e.	R2
			7-10 weeks post-calving				
Silage DMI (kg/d)	Lactation No	<0.001	8.151	0.3565	0.8999	0.13741	29.4
	Daily Steps	<0.001	13.5	0.589	-0.002184	0.0003831	24.4
	Motion index	<0.001	13.58	0.621	-0.0006627	0.00011993	23.2
	Lying time	0.027	7.781	1.1334	0.004155	0.0018574	4.7
	Lying bouts	0.165	9.405	0.6548	0.06802	0.048651	1.9
	Standing time	0.027	13.76	1.568	-0.004155	0.0018574	4.7
	Standing bouts	0.205	9.441	0.6855	0.06437	0.050415	1.6
Concentrate DMI (kd/d)	Lactation No	<0.001	8.622	0.3916	1.507	0.1509	49.2
	Daily Steps	0.067	13.64	0.862	-0.001037	0.0005608	3.3
	Motion index	0.124	13.46	0.907	-0.0002717	0.0001751	2.3
	Lying time	0.425	13.29	1.498	-0.001966	0.0024556	0.6
	Lying bouts	0.452	11.49	0.853	0.04784	0.06341	0.6
	Standing time	0.425	10.46	2.073	0.001966	0.0024556	0.6
	Standing bouts	0.405	11.39	0.891	0.05477	0.065564	0.7
Total DMI (kd/d)	Lactation No	<0.001	16.77	0.488	2.406	0.1879	61.4
	Daily Steps	<0.001	27.14	1.153	-0.003221	0.0007499	15.5
	Motion index	<0.001	27.05	1.221	-0.0009344	0.00023573	13.5
	Lying time	0.535	21.07	2.146	0.002189	0.0035164	0.4
	Lying Bouts	0.202	20.9	1.214	0.1159	0.09021	1.6
	Standing time	0.535	24.23	2.969	-0.002189	0.0035163	0.4
	Standing Bouts	0.205	20.83	1.269	0.1191	0.09334	1.6
Milk fat (g/kg)	Lactation no.	0.38	40.7	0.937	-0.3182	0.3612	0.7
	Daily Steps	0.015	43.51	1.463	-0.002346	0.000952	5.7
	Motion index	0.016	43.65	1.532	-0.0007231	0.00029596	5.6
	Lying time	0.403	37.92	2.575	0.003546	0.0042199	0.7
	Lying Bouts	0.537	40.92	1.468	-0.06757	0.109104	0.4
	Standing time	0.403	43.02	3.563	-0.003546	0.0042199	0.7
	Standing Bouts	0.454	41.16	1.533	-0.08486	0.112781	0.6
Milk protein (g/kg)	Lactation no.	0.731	31.86	0.441	-0.05861	0.169858	0.1
	Daily Steps	0.035	33.19	0.685	-0.0009512	0.0004457	4.3
	Motion index	0.032	33.29	0.716	-0.0003017	0.00013836	4.5
	Lying time	0.5	30.98	1.198	0.00133	0.001964	0.5
	Lying Bouts	0.669	31.5	0.683	0.02176	0.050766	0.2
	Standing time	0.5	32.9	1.658	-0.00133	0.001964	0.5
	Standing Bouts	0.654	31.48	0.714	0.02359	0.052519	0.2

DMI; dry matter intake

Table 5 continued

Response	Explanatory	P Value	Constant	s.e.	Slope	s.e.	R2
		7-10 weeks post-calving					
Milk lactose (g/kg)	Lactation no.	<0.001	49.46	0.209	-0.5038	0.0804	27.6
	Daily Steps	0.008	47.28	0.383	0.0006797	0.00024933	6.9
	Motion index	0.054	47.52	0.408	0.0001539	0.0000788	3.6
	Lying time	0.211	49.12	0.676	-0.001393	0.0011074	1.5
	Lying Bouts	0.98	48.29	0.388	-0.0007072	0.02881003	0.0
	Standing time	0.211	47.12	0.935	0.001393	0.0011074	1.5
	Standing Bouts	1	48.28	0.405	0.000001866	0.029807701	0.0
Fat:Protein ratio	Lactation no.	0.434	1.28	0.0269	-0.008145	0.0103737	0.6
	Daily Steps	0.228	1.312	0.0433	-0.00003412	0.000028143	1.4
	Motion index	0.254	1.311	0.0453	-0.00001004	0.000008751	1.3
	Lying time	0.622	1.225	0.0746	0.00006049	0.000122315	0.2
	Lying Bouts	0.386	1.297	0.0424	-0.002744	0.0031494	0.7
	Standing time	0.622	1.312	0.1033	-0.00006049	0.000122315	0.2
	Standing Bouts	0.308	1.305	0.0442	-0.003334	0.0032538	1.0
Fat+Protein yield (kg/d)	Lactation no.	<0.001	1.862	0.0836	0.3838	0.03223	57.9
	Daily Steps	<0.001	3.459	0.1922	-0.0004753	0.00012503	12.5
	Motion index	<0.001	3.443	0.2031	-0.0001374	0.00003922	10.8
	Lying time	0.737	2.875	0.3522	-0.0001941	0.00057717	0.1
	Lying Bouts	0.521	2.635	0.2002	0.009591	0.0148767	0.4
	Standing time	0.737	2.596	0.4873	0.0001941	0.00057717	0.1
	Standing Bouts	0.516	2.628	0.2093	0.01002	0.015391	0.4
ME intake (MJ/d)	Lactation no.	<0.001	188.1	5.77	26.62	2.225	58.2
	Daily Steps	<0.001	307.9	12.94	-0.03914	0.00842	17.6
	Motion index	<0.001	307.2	13.72	-0.01142	0.002649	15.6
	Lying time	0.53	235.1	24.41	0.02521	0.040002	0.4
	Lying Bouts	0.206	233.4	13.81	1.306	1.0264	1.6
	Standing time	0.53	271.4	33.77	-0.02521	0.040002	0.4
	Standing Bouts	0.21	232.8	14.44	1.34	1.0621	1.6
ME requirement (MJ/d)	Lactation no.	<0.001	191.7	6.95	33.05	2.668	60.1
	Daily Steps	<0.001	327.8	16.3	-0.03967	0.010585	12.3
	Motion index	<0.001	326.5	17.21	-0.01147	0.003319	10.7
	Lying time	0.755	278.4	29.76	-0.01521	0.048763	0.1
	Lying Bouts	0.578	260.2	16.99	0.7006	1.26002	0.3
	Standing time	0.755	256.5	41.18	0.01521	0.048763	0.1
	Standing Bouts	0.568	259.5	17.76	0.745	1.30339	0.3

ME, metabolisable energy

Table 5 continued

Response	Explanatory	P Value	Constant	s.e.	Slope	s.e.	R2
			7-10 weeks post-calving				
Energy balance (MJ/d)	Lactation no.	<0.001	-3.14	4.4539	-6.47	1.7094	12.3
	Daily Steps	0.979	-18.15	7.618	-0.0001283	0.00494768	0.0
	Motion index	0.91	-17.47	7.969	-0.0001737	0.00153703	0.0
	Lying time	0.058	-42.26	12.804	0.03975	0.02098	3.5
	Lying Bouts	0.332	-25.22	7.414	0.5334	0.54976	0.9
	Standing time	0.058	14.98	17.715	-0.03975	0.02098	3.5
	Standing Bouts	0.357	-25.2	7.751	0.5242	0.56899	0.8
Liveweight (kg)	Lactation no.	<0.001	512	9.96	43.32	3.466	61.2
	Daily Steps	<0.001	703.8	21.27	-0.0605	0.013487	17.7
	Motion index	<0.001	699.3	22.3	-0.01699	0.004256	14.3
	Lying time	0.343	578.4	38.63	0.06004	0.063292	0.9
	Lying Bouts	0.924	612.5	22.18	0.1568	1.64445	0.0
	Standing time	0.343	664.8	53.44	-0.06004	0.063292	0.0
	Standing Bouts	0.927	612.5	23.17	0.1557	1.70121	0.0
Body condition score	Lactation no.	0.013	253.8	4.74	-4.394	1.7462	7.2
	Daily Steps	0.273	236	7.39	0.005257	0.0048004	1.2
	Motion index	0.486	238.6	7.77	0.001047	0.0014966	0.6
	Lying time	0.334	231.7	12.68	0.02011	0.020706	2.0
	Lying Bouts	0.592	247.5	7.3	-0.2892	0.53746	1.1
	Standing time	0.334	260.7	17.52	-0.02011	0.020706	2.0
	Standing Bouts	0.621	247.4	7.62	-0.2759	0.55615	1.1
			11-24 weeks post-calving				
Silage DMI (kg/d)	Lactation no.	<0.001	8.776	0.3277	0.779	0.12067	29.9
	Daily Steps	<0.001	12.48	0.589	-0.001237	0.0003604	12.7
	Motion index	0.004	12.2	0.592	-0.0003109	0.00010646	10.0
	Lying time	0.369	9.775	0.9483	0.001376	0.0015246	3.3
	Lying Bouts	0.353	10.11	0.573	0.04235	0.04538	3.5
	Standing time	0.369	11.76	1.291	-0.001376	0.0015246	3.3
	Standing Bouts	0.426	10.17	0.591	0.03712	0.046433	3.3
Concentrate DMI (kg/d)	Lactation no.	<0.001	8.04	0.5614	1.748	0.2163	38.8
	Daily Steps	0.779	12.42	1.16	-0.0002066	0.00073371	0.1
	Motion index	0.994	12.12	1.153	-0.000001693	0.000213933	0.0
	Lying time	0.664	12.89	1.822	-0.001291	0.0029613	0.2
	Lying Bouts	0.079	10.31	1.063	0.1543	0.08694	3.0
	Standing time	0.664	11.03	2.494	0.001291	0.0029613	0.2
	Standing Bouts	0.059	10.11	1.096	0.1693	0.08865	3.5

DMI; dry matter intake

Table 5 continued

Response	Explanatory	P Value	Constant	s.e.	Slope	s.e.	R2
			11-14 weeks post-calving				
Total DMI (kg/d)	Lactation no.	<0.001	16.81	0.585	2.529	0.2256	55.0
	Daily Steps	0.106	24.89	1.389	-0.001434	0.0008786	2.6
	Motion index	0.231	24.32	1.388	-0.0003103	0.00025758	1.4
	Lying time	0.988	22.68	2.212	0.00005603	0.003594288	0.0
	Lying Bouts	0.067	0.067	1.288	0.1948	0.10529	3.3
	Standing time	0.988	22.76	3.027	-0.00005603	0.003594288	0.0
	Standing Bouts	0.06	20.29	1.329	0.2048	0.1075	3.5
Milk yield (kg/d)	Lactation no.	<0.001	24.12	1.331	5.468	0.5131	52.4
	Daily Steps	0.298	39.95	3.093	-0.002047	0.0019559	1.1
	Motion index	0.499	38.85	3.081	-0.0003883	0.00057184	0.5
	Lying time	0.883	36.14	4.886	0.001171	0.0079401	0.0
	Lying Bouts	0.076	31.99	2.848	0.4168	0.23286	3.1
	Standing time	0.883	37.82	6.686	-0.001171	0.0079401	0.0
	Standing Bouts	0.062	31.55	2.936	0.4481	0.2376	3.4
Milk fat (g/kg)	Lactation no.	0.014	43.07	0.887	-0.8551	0.34178	5.7
	Daily Steps	0.773	41.56	1.476	-0.0002699	0.00093305	0.1
	Motion index	0.468	42.17	1.462	-0.0001977	0.00027135	0.5
	Lying time	0.937	41.33	2.319	-0.0002989	0.00376932	0.0
	Lying Bouts	0.371	42.32	1.368	-0.1004	0.11183	0.8
	Standing time	0.937	40.9	3.174	0.0002989	0.00376932	0.0
	Standing Bouts	0.311	42.52	1.411	-0.1162	0.11417	1.0
Milk protein (g/kg)	Lactation no.	0.851	32.32	0.433	-0.03146	0.166765	0.0
	Daily Steps	0.757	32.07	0.699	0.0001371	0.00044207	0.1
	Motion index	0.67	31.99	0.694	0.00005511	0.000128792	0.2
	Lying time	0.128	33.92	1.086	-0.002708	0.0017656	2.3
	Lying Bouts	0.216	31.51	0.646	0.06569	0.052795	1.5
	Standing time	0.128	30.02	1.487	0.002708	0.0017656	2.3
	Standing Bouts	0.161	31.38	0.665	0.07601	0.053843	1.9
Milk lactose (g/kg)	Lactation no.	<0.001	49.21	0.238	-0.4644	0.09169	19.9
	Daily Steps	0.089	47.42	0.425	0.0004609	0.00026873	2.8
	Motion index	0.281	47.68	0.426	0.00008568	0.000078997	1.2
	Lying time	0.957	48.15	0.677	-0.00005936	0.001100856	0.0
	Lying Bouts	0.552	47.89	0.4	0.01953	0.032732	0.4
	Standing time	0.957	48.07	0.927	0.00005936	0.001100856	0.0
	Standing Bouts	0.543	47.88	0.413	0.0204	0.033452	0.4

DMI; dry matter intake

Table 5 continued

Response	Explanatory	P Value	Constant	s.e.	Slope	s.e.	R2
			11-14 weeks post-calving				
Fat :Protein ratio	Lactation no.	0.007	1.336	0.0248	-0.02618	0.009573	6.8
	Daily Steps	0.626	1.295	0.0413	-0.00001276	0.000026108	0.2
	Motion index	0.308	1.316	0.0408	-0.00000776	0.0000075793	1.0
	Lying time	0.326	1.213	0.0646	0.0001036	0.00010505	1.0
	Lying Bouts	0.083	1.339	0.0379	-0.00543	0.0030973	3.0
	Standing time	0.326	1.362	0.0885	-0.0001036	0.00010505	1.0
	Standing Bouts	0.046	1.351	0.0389	-0.006357	0.0031505	3.9
Fat+Protein yield (kg/d)	Lactation no.	<0.001	1.851	0.0941	0.3587	0.03626	48.2
	Daily Steps	0.224	2.935	0.2098	-0.0001622	0.00013265	1.5
	Motion index	0.366	2.871	0.209	-0.00003519	0.00003879	0.8
	Lying time	0.993	2.692	0.332	-0.00000505	0.000539623	0.0
	Lying Bouts	0.062	2.341	0.1932	0.02984	0.015796	3.4
	Standing time	0.993	2.685	0.4544	0.000005051	0.000539623	0.0
	Standing Bouts	0.053	2.316	0.1993	0.03163	0.016123	3.7
ME intake (MJ/d)	Lactation no.	<0.001	186.6	6.8	28.39	2.622	53.2
	Daily Steps	0.145	275.2	15.9	-0.01477	0.010055	2.1
	Motion index	0.312	268.3	15.88	-0.002993	0.0029467	1.0
	Lying time	0.992	252.6	25.25	0.0004357	0.04103479	0.0
	Lying Bouts	0.05	225.1	14.67	2.383	1.199	3.8
	Standing time	0.992	253.2	34.55	-0.0004357	0.04103479	0.0
	Standing Bouts	0.044	223.3	15.13	2.497	1.2242	4.0
ME Requirement (MJ/d)	Lactation no.	<0.001	191.3	7.57	30.52	2.904	52.0
	Daily Steps	0.154	286.6	17.24	-0.01552	0.010888	2.0
	Motion index	0.273	281.1	17.19	-0.003494	0.0031865	1.2
	Lying time	0.812	256.6	27.31	0.01055	0.044403	0.1
	Lying Bouts	0.065	235.1	15.92	2.399	1.3002	3.3
	Standing time	0.812	271.8	37.41	-0.01055	0.044403	0.1
	Standing Bouts	0.058	233.3	16.43	2.513	1.3279	3.5
Energy balance (MJ/d)	Lactation no.	0.086	-3.526	3.6961	-2.458	1.4186	2.9
	Daily Steps	0.966	-9.155	6.0299	-0.0001645	0.00380789	0.0
	Motion index	0.836	-10.59	5.986	0.0002295	0.00110964	0.0
	Lying time	0.606	-4.617	9.4449	-0.007917	0.0153579	0.3
	Lying Bouts	0.886	-8.642	5.604	-0.06546	0.45774	0.0
	Standing time	0.606	-16.02	12.939	0.007917	0.0153579	0.3
	Standing Bouts	0.874	-8.526	5.7881	-0.07436	0.467871	0.0

ME, metabolisable energy

Table 5 continued

Response	Explanatory	P Value	Constant	s.e.	Slope	s.e.	R2
			11-14 weeks post-calving				
Liveweight (kg)	Lactation no.	<0.001	516.5	10.34	43.06	3.575	59.4
	Daily Steps	0.018	669.3	22.48	-0.03365	0.014195	5.3
	Motion index	0.057	659.3	22.54	-0.007943	0.0041772	3.5
	Lying time	0.433	590.4	36.12	0.04602	0.058736	0.6
	Lying Bouts	0.317	597.8	21.36	1.747	1.7451	1.0
	Standing time	0.433	656.6	49.49	-0.04602	0.058736	0.6
	Standing Bouts	0.35	598.5	22.08	1.668	1.7849	0.9
Body condition score	Lactation no.	<0.001	253	4.35	-6.477	1.6694	12.9
	Daily Steps	0.031	223.4	7.18	0.009784	0.0045353	4.4
	Motion index	0.222	229.8	7.24	0.00164	0.0013423	1.5
	Lying time	0.817	235.6	11.52	0.004324	0.0187321	0.1
	Lying Bouts	0.091	249.1	6.73	-0.9307	0.54995	2.8
	Standing time	0.817	241.8	15.78	-0.004324	0.0187321	0.1
	Standing Bouts	0.075	250	6.94	-0.9979	0.56133	3.1
			15 – 18 weeks post-calving				
Silage DMI (kg/d)	Lactation no.	<0.001	9.774	0.4575	0.7659	0.16275	20.2
	Daily Steps	0.01	13.49	0.768	-0.001323	0.0005041	9.0
	Motion index	0.086	12.9	0.794	-0.0002618	0.00015071	5.6
	Lying time	0.553	12.28	1.141	-0.001004	0.0016873	3.4
	Lying Bouts	0.026	10.24	0.668	0.1123	0.04957	7.3
	Standing time	0.553	10.83	1.352	0.001004	0.0016873	3.4
	Standing Bouts	0.021	10.14	0.687	0.1199	0.05101	7.7
Concentrate DMI (kg/d)	Lactation no.	<0.001	8.476	0.6338	1.401	0.2218	30.4
	Daily Steps	0.33	12.8	1.181	-0.0007455	0.00076226	45.0
	Motion index	0.367	12.74	1.192	-0.0002027	0.00022371	4.7
	Lying time	0.749	12.27	1.683	-0.000796	0.00248003	3.9
	Lying Bouts	0.239	10.67	1.002	0.08774	0.074103	4.5
	Standing time	0.749	11.12	1.993	0.000796	0.00248003	3.9
	Standing Bouts	0.207	10.55	1.031	0.09706	0.076322	4.7
Total DMI (kg/d)	Lactation no.	<0.001	18.22	0.607	2.179	0.2337	46.4
	Daily Steps	0.024	26.26	1.366	-0.002045	0.0008927	7.2
	Motion index	0.091	25.58	1.382	-0.0004517	0.00026465	4.7
	Lying time	0.576	24.45	1.981	-0.001661	0.00296	1.1
	Lying Bouts	0.024	20.9	1.133	0.2009	0.08732	5.3
	Standing time	0.576	22.06	2.355	0.001661	0.00296	1.1
	Standing Bouts	0.017	20.69	1.168	0.2171	0.08976	6.0

DMI; dry matter intake

Table 5 continued

Response	Explanatory	P Value	Constant	s.e.	Slope	s.e.	R2
		15-18 weeks post-calving					
Milk yield (kg/d)	Lactation no.	<0.001	24.6	1.304	4.646	0.5039	45.7
	Daily Steps	0.07	40.5	2.824	-0.003502	0.0019139	3.3
	Motion index	0.157	39.5	2.892	-0.0008075	0.0005664	2.0
	Lying time	0.966	35.35	4.231	0.0002705	0.00633656	0.0
	Lying Bouts	0.044	30.82	2.431	0.3839	0.18782	4.1
	Standing time	0.966	35.74	5.032	-0.0002705	0.00633655	0.0
	Standing Bouts	0.04	30.57	2.507	0.4029	0.19354	4.2
Milk fat (g/kg)	Lactation no.	0.116	44.95	1.061	-0.6416	0.4082	2.4
	Daily Steps	0.988	43.44	1.781	0.00001867	0.001213462	0.0
	Motion index	0.857	43.78	1.806	-0.00006436	0.000355129	0.0
	Lying time	0.914	43.74	2.611	-0.0004205	0.00390377	0.0
	Lying Bouts	0.811	43.82	1.529	-0.02849	0.118603	0.1
	Standing time	0.914	43.14	3.096	0.0004205	0.00390377	0.0
	Standing Bouts	0.84	43.77	1.581	-0.02487	0.122662	0.0
Milk protein (g/kg)	Lactation no.	0.28	34.26	0.487	-0.2043	0.18804	1.2
	Daily Steps	0.272	32.93	0.814	0.000609	0.00055166	1.2
	Motion index	0.356	33.06	0.83	0.0001506	0.00016249	0.9
	Lying time	0.009	36.85	1.165	-0.004652	0.001745	6.8
	Lying Bouts	0.513	33.36	0.706	0.03582	0.054578	0.4
	Standing time	0.009	30.15	1.386	0.004652	0.001745	6.8
	Standing Bouts	0.383	33.19	0.728	0.04925	0.056184	0.8
Milk lactose (g/kg)	Lactation no.	<0.001	49.11	0.236	-0.473	0.09123	21.0
	Daily Steps	0.031	47.19	0.413	0.0006107	0.00027987	4.6
	Motion index	0.168	47.48	0.426	0.000116	0.00008344	1.9
	Lying time	0.411	47.55	0.621	0.000767	0.00092984	0.7
	Lying Bouts	0.842	47.98	0.365	0.005653	0.0282347	0.0
	Standing time	0.411	48.65	0.738	-0.000767	0.00092984	0.7
	Standing Bouts	0.712	47.92	0.377	0.01076	0.029101	0.1
Fat :Protein ratio	Lactation no.	0.302	1.316	0.0299	-0.01188	0.011504	1.1
	Daily Steps	0.512	1.319	0.0494	-0.00002218	0.000033678	0.4
	Motion index	0.459	1.324	0.0501	-0.000007331	0.000009817	0.6
	Lying time	0.132	1.181	0.0718	0.0001629	0.00010732	2.3
	Lying Bouts	0.458	1.318	0.0424	-0.00245	0.0032906	0.6
	Standing time	0.132	1.416	0.0851	-0.0001629	0.00010732	2.3
	Standing Bouts	0.395	1.324	0.0438	-0.002907	0.0033998	0.7

DMI; dry matter intake

Table 5 continued

Response	Explanatory	P Value	Constant	s.e.	Slope	s.e.	R2
		15-18 weeks post-calving					
Fat+Protein yield (kg/d)	Lactation no.	<0.001	1.958	0.0965	0.3248	0.03713	43.4
	Daily Steps	0.051	3.118	0.2083	-0.0002761	0.00013949	5.1
	Motion index	0.123	3.04	0.2107	-0.0000638	0.000041052	3.3
	Lying time	0.723	2.835	0.3046	-0.0001621	0.00045547	0.1
	Lying Bouts	0.03	2.364	0.1743	0.02981	0.013516	4.8
	Standing time	0.723	2.601	0.3613	0.0001621	0.00045547	0.1
	Standing Bouts	0.024	2.337	0.1799	0.03193	0.013951	5.1
ME intake (MJ/d)	Lactation no.	<0.001	205.6	7	24.72	2.703	45.3
	Daily Steps	0.024	297.3	15.62	-0.02354	0.01025	7.1
	Motion index	0.097	288.9	15.82	-0.005095	0.0030403	4.3
	Lying time	0.534	277.8	22.72	-0.02119	0.033973	0.8
	Lying Bouts	0.016	234	12.94	2.441	0.9999	5.7
	Standing time	0.534	247.3	27.01	0.02119	0.033973	0.8
	Standing Bouts	0.012	231.4	13.33	2.643	1.0276	6.4
ME Requirement (MJ/d)	Lactation no.	<0.001	196.7	7.69	27.95	2.958	47.2
	Daily Steps	0.041	296.6	17.1	-0.02373	0.01148	5.3
	Motion index	0.103	290.3	17.3	-0.005558	0.0033789	3.3
	Lying time	0.869	267.2	25.13	-0.006233	0.0375795	0.0
	Lying Bouts	0.035	234	14.39	2.381	1.1163	4.5
	Standing time	0.869	258.2	29.81	0.006232	0.0375795	0.0
	Standing Bouts	0.03	232	14.86	2.535	1.1528	4.7
Energy balance (MJ/d)	Lactation no.	0.094	7.157	3.8761	-2.496	1.4914	2.7
	Daily Steps	0.935	0.2925	6.44443	0.0003609	0.00439098	0.0
	Motion index	0.662	-1.956	6.5288	0.0005637	0.00128404	0.2
	Lying time	0.295	10.51	9.395	-0.01478	0.014047	1.1
	Lying Bouts	0.866	-0.08389	5.534669	0.07252	0.429251	0.0
	Standing time	0.295	-10.77	11.142	0.01478	0.014047	1.1
	Standing Bouts	0.762	-0.8493	5.72135	0.1347	0.44376	0.1
Liveweight (kg)	Lactation no.	<0.001	533.3	10.5	39.91	3.593	55.7
	Daily Steps	0.01	683.3	23.04	-0.03949	0.015084	8.7
	Motion index	0.027	676.6	23.22	-0.01003	0.004459	6.5
	Lying time	0.625	643.5	33.77	-0.02473	0.050455	1.0
	Lying Bouts	0.353	609.9	19.8	1.42	1.5198	1.4
	Standing time	0.625	607.9	40.14	0.02473	0.050455	1.0
	Standing Bouts	0.348	609.1	20.43	1.476	1.5671	1.5

ME, metabolisable energy

Table 5 continued

Response	Explanatory	P Value	Constant	s.e.	Slope	s.e.	R2
		15-18 weeks post-calving					
Body condition score	Lactation no.	<0.001	251	4.07	-7.012	1.5708	16.5
	Daily Steps	0.083	223.3	7.04	0.008353	0.0047703	3.0
	Motion index	0.537	230.8	7.26	0.0008811	0.00142154	0.4
	Lying time	0.643	239.9	10.52	-0.007333	0.0157546	0.2
	Lying Bouts	0.151	243.5	6.11	-0.6829	0.47235	2.1
	Standing time	0.643	229.4	12.51	0.007333	0.0157546	0.2
	Standing Bouts	0.159	243.6	6.31	-0.692	0.48727	2.0
		19 – 22 weeks post-calving					
Silage DMI (kg/d)	Lactation no.	<0.001	10.92	0.495	0.8595	0.19108	17.1
	Daily Steps	0.535	12.37	0.889	0.0003902	0.00062639	0.4
	Motion index	0.097	11.52	0.858	0.0002908	0.00017331	2.9
	Lying time	0.885	13.07	1.189	-0.0002498	0.00171929	0.0
	Lying Bouts	0.084	11.68	0.742	0.09573	0.054732	3.2
	Standing time	0.885	12.71	1.338	0.0002497	0.00171928	0.0
	Standing Bouts	0.087	11.68	0.749	0.09552	0.055274	3.1
Concentrate DMI (kg/d)	Lactation no.	<0.001	7.785	0.6608	1.064	0.2247	21.3
	Daily Steps	0.272	11.38	1.058	-0.0007999	0.00072407	4.2
	Motion index	0.148	11.69	1.027	-0.0002953	0.00020228	4.7
	Lying time	0.794	10.64	1.403	-0.0005219	0.00198883	3.9
	Lying Bouts	0.644	9.909	0.9133	0.02992	0.0645	3.8
	Standing time	0.794	9.892	1.5719	0.0005219	0.00198883	3.9
	Standing Bouts	0.567	9.814	0.9202	0.0374	0.065116	3.8
Total DMI (kg/d)	Lactation no.	<0.001	18.71	0.619	1.922	0.2409	38.9
	Daily Steps	0.62	23.81	1.284	-0.0004506	0.00090519	0.3
	Motion index	0.94	23.28	1.257	-0.00001904	0.000253976	0.0
	Lying time	0.763	23.7	1.717	-0.0007494	0.00248175	0.1
	Lying Bouts	0.108	21.55	1.073	0.1286	0.07921	2.7
	Standing time	0.763	22.62	1.931	0.0007493	0.00248174	0.1
	Standing Bouts	0.092	21.46	1.082	0.1361	0.07985	3.0
Milk yield (kg/d)	Lactation no.	<0.001	24.07	1.261	4.011	0.4906	40.1
	Daily Steps	0.634	34.62	2.678	-0.0009023	0.00188733	0.2
	Motion index	0.99	33.36	2.621	0.000006485	0.000529504	0.0
	Lying time	0.651	31.81	3.577	0.002343	0.0051708	0.2
	Lying Bouts	0.099	29.88	2.236	0.2751	0.16501	2.9
	Standing time	0.651	35.18	4.024	-0.002344	0.0051708	0.2
	Standing Bouts	0.096	29.81	2.256	0.2801	0.16653	2.9

DMI; dry matter intake

Table 5 continued

Response	Explanatory	P Value	Constant	s.e.	Slope	s.e.	R2
			19-22 weeks post-calving				
Milk fat (g/kg)	Lactation no.	0.173	45.42	1.221	-0.6199	0.45147	3.5
	Daily Steps	0.858	44.35	1.945	-0.0002462	0.001371	1.8
	Motion index	0.338	45.75	1.906	-0.0003672	0.00038105	2.5
	Lying time	0.307	46.61	2.581	-0.003813	0.0037104	1.5
	Lying Bouts	0.283	45.68	1.635	-0.1303	0.12069	1.3
	Standing time	0.307	41.11	2.884	0.003813	0.0037104	1.5
	Standing Bouts	0.31	45.61	1.654	-0.1248	0.12229	1.2
Milk protein (g/kg)	Lactation no.	0.058	35.71	0.473	-0.3483	0.18402	3.5
	Daily Steps	0.882	34.85	0.782	0.00008193	0.000550808	0.0
	Motion index	0.713	35.23	0.764	-0.00005689	0.000154252	0.1
	Lying time	<0.001	38.28	0.983	-0.004918	0.0014213	11.3
	Lying Bouts	0.974	34.98	0.661	-0.001574	0.0488097	0.0
	Standing time	<0.001	31.2	1.106	0.004918	0.0014212	11.3
	Standing Bouts	0.803	34.8	0.667	0.01234	0.049258	0.1
Milk lactose (g/kg)	Lactation no.	<0.001	49.1	0.244	-0.505	0.09334	23.0
	Daily Steps	0.153	47.35	0.435	0.0004423	0.00030673	2.2
	Motion index	0.713	47.8	0.43	0.00003199	0.000086833	0.1
	Lying time	0.666	47.7	0.587	0.0003673	0.00084865	0.2
	Lying Bouts	0.497	47.71	0.371	0.01867	0.027409	0.5
	Standing time	0.666	48.23	0.66	-0.0003673	0.00084865	0.2
	Standing Bouts	0.446	47.68	0.375	0.02115	0.027652	0.6
Fat :Protein ratio	Lactation no.	0.645	1.274	0.035	-0.005517	0.0119232	4.9
	Daily Steps	0.67	1.281	0.0532	-0.00001532	0.000035797	5.0
	Motion index	0.318	1.308	0.0524	-0.00001	0.000009964	5.9
	Lying time	0.473	1.213	0.0692	0.00006991	0.000096907	5.1
	Lying Bouts	0.331	1.3	0.0453	-0.003085	0.0031578	5.1
	Standing time	0.473	1.314	0.077	-0.00006991	0.000096907	5.1
	Standing Bouts	0.289	1.304	0.0457	-0.003407	0.003197	5.2
Fat+Protein yield (kg/d)	Lactation no.	<0.001	1.973	0.0926	0.2757	0.03572	37.8
	Daily Steps	0.551	2.732	0.1882	-0.0000798	0.000133473	0.4
	Motion index	0.704	2.691	0.1837	-0.00001422	0.000037301	0.2
	Lying time	0.716	2.714	0.2526	-0.0001329	0.00036381	0.1
	Lying Bouts	0.147	2.406	0.1584	0.0171	0.011706	2.3
	Standing time	0.716	2.523	0.2824	0.0001329	0.00036381	0.1
	Standing Bouts	0.128	2.392	0.16	0.01819	0.011839	2.5

Table 5 continued

Response	Explanatory	P Value	Constant	s.e.	Slope	s.e.	R2
		19-22 weeks post-calving					
ME intake (MJ/d)	Lactation no.	<0.001	211.2	7.14	21.97	2.779	38.5
	Daily Steps	0.64	269	14.82	-0.004905	0.0104405	0.2
	Motion index	0.931	261.1	14.5	0.0002541	0.00292891	0.0
	Lying time	0.799	267.2	19.8	-0.007325	0.0286243	0.1
	Lying Bouts	0.076	241.5	12.34	1.632	0.9107	3.3
	Standing time	0.799	256.7	22.28	0.007324	0.0286242	0.1
	Standing Bouts	0.067	240.6	12.44	1.702	0.9183	3.5
ME Requirement (MJ/d)	Lactation no.	<0.001	197.9	7.19	23.87	2.774	43.0
	Daily Steps	0.464	265	15.26	-0.00795	0.0108182	0.6
	Motion index	0.657	260.6	14.9	-0.001348	0.0030254	0.2
	Lying time	0.793	259.5	20.5	-0.007786	0.029527	0.1
	Lying Bouts	0.146	236.5	12.85	1.393	0.9496	2.3
	Standing time	0.793	248.3	22.92	0.007786	0.0295269	0.1
	Standing Bouts	0.129	235.5	12.98	1.471	0.9606	2.5
Energy balance (MJ/d)	Lactation no.	0.306	12.55	4.281	-1.699	1.6513	1.2
	Daily Steps	0.421	3.127	6.8621	0.003932	0.0048659	0.7
	Motion index	0.168	-0.3844	6.64537	0.001874	0.001349	2.1
	Lying time	0.876	9.849	9.2272	-0.002077	0.0132922	0.0
	Lying Bouts	0.696	6.28	5.8458	0.1695	0.432	0.2
	Standing time	0.876	6.857	10.3168	0.002077	0.0132922	0.0
	Standing Bouts	0.697	6.259	5.9128	0.1711	0.43743	0.2
Liveweight (kg)	Lactation no.	<0.001	548.3	11.28	36.71	3.767	50.3
	Daily Steps	0.052	674.6	21.93	-0.0297	0.015096	6.1
	Motion index	0.135	664.7	21.59	-0.006446	0.004271	4.4
	Lying time	0.273	665.3	29.39	-0.04609	0.041797	4.0
	Lying Bouts	0.508	622.7	19.11	0.9047	1.36182	3.3
	Standing time	0.273	599	32.95	0.04609	0.041797	4.0
	Standing Bouts	0.464	621.3	19.27	1.01	1.3748	3.4
Body condition score	Lactation no.	<0.001	250	4.19	-7.018	1.6298	15.6
	Daily Steps	0.146	224.5	7.23	0.007479	0.0050986	2.2
	Motion index	0.73	232.3	7.15	0.0005007	0.00144406	0.1
	Lying time	0.451	241.8	9.74	-0.01065	0.014083	0.6
	Lying Bouts	0.854	235.7	6.19	-0.08425	0.456823	0.0
	Standing time	0.451	226.5	10.96	0.01065	0.014083	0.6
	Standing Bouts	0.829	235.9	6.25	-0.0997	0.461138	0.0

DMI; dry matter intake, ME; metabolisable energy

Table 6. Correlation of pedometer data with animal production data - results of a multivariate analysis for Study 1.

Response	Constant	Explanatory							R2
		Lactation no.	Daily Steps	Motion index	Lying time (mins)	Lying Bouts	Standing time (mins)	Standing Bouts	
Week 7-10 post-calving									
Silage DMI (kg/day)	3.506 (1.3935)	-	-0.001068 (0.0003494)	-	-	-	-	-	55.1
Conc DMI (kg/day)	11.48 (1.020)	1.608 (0.1445)	-	-	-0.008264 (0.0019737)	-	-	0.1425 (0.05249)	57.4
Total DMI (kg/day)	12.33 (1.882)	2.048 (0.2281)	-	-	-	-	-	-	64.8
Milk yield (kg/day)	35.03 (3.339)	5.948 (0.4731)	-	-	-0.02658 (0.006463)	-	-	0.437 (0.17186)	62.8
Milk fat (g/kg)	46.69 (2.067)	-0.8258 (0.38183)	-0.003213 (0.0010293)	-	-	-	-	-	10.1
Milk protein (g/kg)	33.24 (0.730)	-	-	-0.0002908 (0.00014177)	-	-	-	-	4.2
Milk lactose (g/kg)	49.44 (0.218)	-0.5027 (0.08270)	-	-	-	-	-	-	27.4
Fat :Protein ratio	-	-	-	-	-	-	-	-	-
Fat+Protein yield (kg/day)	2.412 (0.2218)	0.3526 (0.03841)	-	-	-0.001625 (0.0004367)	0.02510 (0.011244)	-	-	64.0
ME intake (MJ/d)	131.4 (21.92)	21.47 (2.657)	-	-	-	-	-	-	63.1
ME Reqt. (MJ/d)	235.5 (18.29)	30.63 (3.174)	-	-	-0.1336 (0.03513)	-	-	2.122 (0.9377)	66.1
Energy balance (MJ/d)	46.63 (18.137)	-7.301 (1.7387)	-	-	-	-	-0.05698 (0.020056)	-	18.7
Liveweight (kg)	509.3 (9.90)	36.91 (4.290)	-	-	-	-	-	-	61.3
BCS	254.1 (4.78)	-4.366 (1.7675)	-	-	-	-	-	-	6.7

DMI; dry matter intake, ME, metabolisable energy, BCS; body condition score

Table 6 continued

Response	Constant	Explanatory							R2
		Lactation no.	Daily Steps	Motion index	Lying time (mins)	Lying Bouts	Standing time (mins)	Standing Bouts	
Week 11- 14 post-calving									
Silage DMI (kg/day)	4.061 (1.0806)	0.4531 (0.15563)	-	-	-	-	-	-	44.0
Conc DMI (kg/day)	8.183 (1.5157)	1.801 (0.2222)	0.001461 (0.0005736)	-	-	-	-	-	47.9
Total DMI (kg/day)	16.87 (0.595)	2.508 (0.2278)	-	-	-	-	-	-	54.6
Milk yield (kg/day)	23.43 (3.681)	5.619 (0.5383)	0.003175 (0.0013899)	-	-	-	-	-	57.5
Milk fat (g/kg)	43.21 (0.896)	-0.8825 (0.34335)	-	-	-	-	-	-	6.1
Milk protein (g/kg)	-	-	-	-	-	-	-	-	-
Milk Lactose (g/kg)	49.19 (0.243)	-0.4586 (0.09290)	-	-	-	-	-	-	19.4
Fat :Protein ratio	1.336 (0.0250)	-0.02592 (0.009583)	-	-	-	-	-	-	6.8
Fat+Protein Yield (kg/d)	1.864 (0.0952)	0.3543 (0.03648)	-	-	-	-	-	-	48.3
ME intake (MJ/d)	210.1 (13.16)	27.11 (2.663)	-	-	-	-	-	-	54.7
ME Reqt. (MJ/d)	192.4 (7.66)	30.16 (2.922)	-	-	-	-	-	-	51.6
Energy Balance (MJ/d)	-43.24 (11.700)	-3.858 (1.8275)	-	-	-	-	-	-	13.8
Liveweight (kg)	518.6 (10.32)	42.51 (3.599)	-	-	-	-	-	-	58.9
BCS	253.5 (4.32)	-6.513 (1.6474)	-	-	-	-	-	-	13.5

DMI; dry matter intake, ME, metabolisable energy, BCS; body condition score

Table 6 continued

Response	Constant	Explanatory							R2
		Lactation no.	Daily Steps	Motion index	Lying time (mins)	Lying Bouts	Standing time (mins)	Standing Bouts	
					week 15- 18 post-calving				
Silage DMI (kg/day)	5.199 (1.0823)	0.4451 (0.17438)	-	-	-	-	-	-	55.6
Conc DMI (kg/day)	13.61 (1.568)	1.673 (0.2944)	-	-	-	-	-	-	37.0
Total DMI (kg/day)	19.69 (1.451)	1.717 (0.2775)	-	-	-	-	-	0.2275 (0.06739)	56.3
Milk yield (kg/day)	26.85 (3.109)	3.892 (0.5763)	0.003463 (0.0015822)	-	-	-	-	-	51.3
Milk fat (g/kg)	-	-	-	-	-	-	-	-	-
Milk protein (g/kg)	34.75 (0.429)	-	-	-	-	-	-	-	12.6
Milk lactose (g/kg)	48.99 (0.238)	-0.6038 (0.11223)	-	-	-	-	-	-	24.5
Fat :Protein ratio	-	-	-	-	-	-	-	-	-
Fat+Protein Yield (kg/day)	2.611 (0.3053)	0.2524 (0.04247)	-	-	-0.0009562 (0.00036096)	-	-	0.03477 (0.011131)	51.5
ME intake (MJ/d)	223.2 (16.61)	19.08 (3.172)	-	-	-0.08372 (0.025087)	-	-	2.823 (0.7704)	56.7
ME Reqt. (MJ/d)	178.8 (12.37)	27.01 (2.951)	-	-	-	-	-	1.732 (0.8512)	49.2
Energy Balance (MJ/d)	-20.92 (10.181)	-	-	-	-	-	-	-	23.6
Liveweight (kg)	535.6 (10.84)	39.56 (3.723)	-	-	-	-	-	-	54.7
BCS	250 (4.11)	-6.403 (1.5856)	-	-	-	-	-	-	14.3

DMI; dry matter intake, ME, metabolisable energy, BCS; body condition score

Table 6 continued

Response	Constant	Explanatory: Lactation no.	Daily Steps	Motion index	Lying time (mins)	Lying Bouts	Standing time (mins)	Standing Bouts	R2
				Week 19- 22 post-calving					
Silage DMI (kg/day)	8.386 (0.9699)	1.015 (0.1954)	-	0.0004572 (0.00015671)	-	-	-	-	24.8
Conc DMI (kg/day)	7.895 (0.6719)	1.035 (0.2305)	-	-	-	-	-	-	20.6
Total DMI (kg/day)	18.42 (0.644)	1.494 (0.3171)	-	-	-	-	-	-	42.2
Milk yield (kg/day)	24.11 (1.330)	4.012 (0.5143)	-	-	-	-	-	-	39.3
Milk fat (g/kg)	-	-	-	-	-	-	-	-	-
Milk protein (g/kg)	38.28 (0.983)	-	-	-	-0.004918 (0.0014213)	-	-	-	11.3
Milk lactose (g/kg)	49.15 (0.246)	-0.5166 (0.09432)	-	-	-	-	-	-	24.4
Fat :Protein ratio	-	-	-	-	-	-	-	-	-
Fat+Protein Yield (kg/day)	1.975 (0.0961)	0.2773 (0.03681)	-	-	-	-	-	-	38.2
ME intake (MJ/d)	207.2 (7.43)	17.17 (3.659)	-	-	-	-	-	-	42.1
ME Reqt. (MJ/day)	198.4 (7.49)	23.86 (2.870)	-	-	-	-	-	-	42.9
Energy Balance (MJ/d)	-	-	-	-	-	-	-	-	-
Liveweight (kg)	596.4 (22.92)	36.01 (3.862)	-	-	-0.06739 (0.030174)	-	-	-	50.9
BCS	280.9 (11.27)	-	-	-	-	-	-	-	23.6

DMI; dry matter intake, ME, metabolisable energy, BCS; body condition score

Table 7. Mid lactation **c**ow performance data during Study 2 (12 week period).

	Average	Min	Max
Silage DMI (kg/day)	11.8	9.7	21.5
Concentrate DMI (kg/day)	9.7	5.7	16.4
Total DMI (kg/day)	21.5	16.4	27.1
Milk yield (kg)	34.0	23.2	48.9
Milk fat (g/kg)	44.1	34.2	56.6
Milk protein (g/kg)	33.0	29.4	39.2
Milk lactose (g/kg)	48.1	45.6	50.3
Fat plus protein yield (kg/day)	2.61	1.72	3.73
Energy balance (MJ/day)	10.4	-21.1	63.8
Body condition score	2.3	1.8	2.6
Liveweight (kg)	637	526	813

DMI; dry matter intake

Table 8. Mid lactation cow pedometer results during Study 2 (12 week period).

	Average	Min	Max
Daily steps	1314	630	2436
Motion Index	4661	2207	9163
Lying Time (mins)	540	346	742
Standing Time (mins)	460	258	654
Transitions	21	8	44
Transitions Down	11	4	22
Transitions Up	11	4	22

Table 9. Correlation of pedometer data with animal production values – results of the univariate analysis for Study 2.

		P Value	Constant	s.e.	Slope	s.e.	R2
Silage DMI (kg/d)	Motion index	0.023	13.59	0.813	-0.03786	0.016212	12.0
	Lying time	0.694	12.41	1.518	-0.00077	0.001933	0.3
	Standing time	0.705	11.33	1.292	0.000732	0.001921	0.3
	Daily steps	0.008	13.97	0.828	-0.00164	0.000591	14.8
	Transitions (n/d)	0.401	12.38	0.702	-0.02644	0.031225	1.2
Concentrate DMI (kg/d)	Motion index	0.245	10.94	1.154	-0.02701	0.022973	8.6
	Lying time	0.640	10.64	2.092	-0.00123	0.002625	8.2
	Standing time	0.616	8.808	1.7901	0.001317	0.002607	8.3
	Daily steps	0.366	10.71	1.208	-0.00078	0.000856	8.2
	Transitions (n/d)	<0.001	6.775	0.96	0.1361	0.03848	24.6
Total DMI (kg/d)	Motion index	0.014	24.48	1.216	-0.06387	0.025086	10.2
	Lying time	0.543	22.95	2.392	-0.00186	0.003046	0.7
	Standing time	0.529	20.24	2.035	0.001915	0.003025	0.7
	Daily steps	0.013	24.68	1.275	-0.00242	0.000937	10.5
	Transitions (n/d)	0.030	19.25	1.069	0.106	0.04758	8.0
Milk yield (kg/d)	Motion index	0.112	38.93	3.21	-0.1069	0.06624	4.4
	Lying time	0.615	37.02	6.126	-0.00395	0.0078	0.4
	Standing time	0.589	31.16	5.212	0.004209	0.007748	0.5
	Daily steps	0.130	38.97	3.378	-0.00382	0.002483	4.0
	Transitions (n/d)	0.003	26.12	2.634	0.3672	0.11723	14.7
Milk fat (g/kg)	Motion index	0.771	44.71	2.117	-0.01278	0.043697	0.1
	Lying time	0.886	44.68	3.963	-0.00073	0.005046	0.0
	Standing time	0.884	43.63	3.373	0.000735	0.005014	0.0
	Daily steps	0.823	43.63	2.225	0.000368	0.001635	0.1
	Transitions (n/d)	0.966	44.19	1.841	-0.00354	0.081939	0.0
Milk protein (g/kg)	Motion index	0.924	32.92	0.874	0.001731	0.018032	0.0
	Lying time	0.252	31.16	1.616	0.002379	0.002057	2.3
	Standing time	0.250	34.58	1.375	-0.00238	0.002044	2.3
	Daily steps	0.456	32.34	0.913	0.000504	0.000671	1.0
	Transitions (n/d)	0.107	34.16	0.742	-0.05412	0.033021	4.5

DMI, dry matter intake

Table 9 continued

		P Value	Constant	s.e.	Slope	s.e.	R2
Milk lactose (g/kg)	Motion index	0.097	47.21	0.532	0.01851	0.01098	4.7
	Lying time	0.803	47.82	1.019	0.000325	0.001298	0.1
	Standing time	0.798	48.29	0.867	-0.00033	0.001289	0.1
	Daily steps	0.097	47.16	0.559	0.000692	0.000411	4.7
	Transitions (n/d)	0.535	48.35	0.472	-0.01312	0.021008	0.7
Fat:protein ratio	Motion index	0.074	1.357	0.0529	-0.00045	0.001091	0.3
	Lying time	0.347	1.429	0.0983	-0.00012	0.000125	1.6
	Standing time	0.343	1.258	0.0836	0.000119	0.000124	1.6
	Daily steps	0.834	1.348	0.0556	-0.000009	0.0000409	0.1
	Transitions (n/d)	0.274	1.289	0.0455	0.002236	0.002026	2.1
Fat+Protein yield (kg/d)	Motion index	0.074	3.006	0.2281	-0.00857	0.004708	5.5
	Lying time	0.636	2.813	0.4381	-0.00027	0.000558	0.4
	Standing time	0.607	2.417	0.3727	0.000286	0.000554	0.5
	Daily steps	0.136	2.959	0.2417	-0.00027	0.00017763	3.9
	Transitions (n/d)	0.003	2.054	0.1903	0.02587	0.00839	15.2
Liveweight (kg)	Motion index	0.009	712	28.51	-1.588	0.5884	11.3
	Lying time	0.513	674.7	56.42	-0.04734	0.071847	0.8
	Standing time	0.531	608.1	48.04	0.04497	0.071412	0.7
	Daily steps	0.01	715.6	29.97	-0.0591	0.022023	11.2
	Transitions (n/d)	0.112	598.5	25.73	1.848	1.145	4.4
Body condition score	Motion index	0.014	207.6	8.01	0.429	0.16275	11.6
	Lying time	0.289	210.6	15.26	0.02081	0.019437	2.0
	Standing time	0.291	240.4	12.99	-0.02057	0.019315	2.0
	Daily steps	<0.001	198.4	7.96	0.02164	0.005722	21.7
	Transitions (n/d)	0.553	230.9	7.14	-0.1897	0.31773	0.6
Energy balance (MJ/d)	Motion Index	0.407	15.59	6.512	-0.1124	0.13439	1.2
	Lying time (minutes)	0.504	2.242	12.2076	0.01044	0.015544	0.8
	Standing time (minutes)	0.464	17.9	10.38	-0.01139	0.015433	0.9
	Steps per day	0.149	19.91	6.756	-0.00727	0.004965	3.6
	Transitions per day	0.003	26.02	5.256	-0.7345	0.23394	14.8

DMI, dry matter intake

Table 10. Cow milk yield, DMI and energy balance during the two RumiWatch periods.

	Average	Min	Max
Period 1 (10- 15 weeks post-calving)			
Milk yield (kg/d)	41.0	25.8	56.4
Total DMI (kg/day)	24.6	17.5	31.7
Energy balance (MJ/d)	-14	-59	56
Period 2 (16 - 21 weeks post calving)			
Milk yield (kg/d)	37.8	25.1	48.5
Total DMI (kg/day)	25.0	18.6	30.9
Energy balance (MJ/d)	2	-21	58

DMI, dry matter intake

Table 11. RumiWatch data during the two periods.

	Average	Min	Max
Period 1 (10- 15 weeks post-calving)			
Other activity time (min/h)	21	16	30
Ruminate time (min/h)	22	17	27
Total Eat time (min/h)	16	11	24
Drink time (min/h)	1	0	2
Other chew (n/h)	113	58	192
Ruminate chew (n/h)	1433	1138	1690
Total Eat chew (n/h)	1126	809	1568
Drink gulp (n/h)	11	3	42
Bolus (n/h)	24	19	29
Chews / min	63	52	77
Chews / bolus	52	42	62
Activity	99	55	177
Uptime (min/h)	30	12	42
Downtime (min/h)	30	18	48
Temp average (°C)	15	7	23
Activity change (n/h)	8	6	11
Period 2 (16 - 21 weeks post calving)			
Other activity time (min/h)	22	17	28
Ruminate time (min/h)	21	16	25
Total Eat time (min/h)	16	11	25
Drink time (min/h)	1	0	2
Other chew (n/h)	111	59	163
Ruminate chew (n/h)	1413	1134	1649
Total Eat chew (n/h)	1082	733	1787
Drink gulp (n/h)	12	3	31
Bolus (n/h)	23	19	28
Chews / min	63	53	77
Chews / bolus	52	42	59
Activity	91	62	150
Uptime (min/h)	30	10	42
Downtime (min/h)	30	18	50
Temp average (°C)	15	6	23
Activity change (n/h)	8	5	12

Table 12. The correlation of RumiWatch data with milk yield, DMI and energy balance – results of a univariate analysis

Response	Explanatory	P Value	Constant	s.e.	Slope	s.e.	R2
		Period 1 (10-15 weeks post calving)					
Milk yield (kg/d)	Lactation no.	0.006	31.95	3.226	3.087	1.0512	18.1
	Other activity time (min/hr)	<0.001	14.37	6.879	1.257	0.322	28.1
	Ruminate time (min/hr)	0.505	49.33	12.443	-0.3858	0.5734	1.1
	Total Eat time (min/hr)	<0.001	64.11	5.617	-1.402	0.3363	30.8
	Drink time (min/hr)	0.013	36.85	1.88	6.201	2.3951	14.7
	Other chew (n/hr)	0.236	35.28	4.853	0.05071	0.042105	3.6
	Ruminate chew (n/hr)	0.026	67.22	11.371	-0.01831	0.007907	12.1
	Total Eat chew (n/hr)	<0.001	63.61	5.639	-0.02009	0.004945	29.8
	Drink gulp (n/hr)	0.007	36.71	1.782	0.3865	0.1351	17.4
	Bolus (n/hr)	0.006	69.68	9.945	-1.21	0.4174	17.7
	Chews /min	<0.001	76.25	9.338	-0.5578	0.147	27.0
	Chews / bolus	0.279	53.81	11.726	-0.2454	0.22354	3.0
	Activity index	<0.001	62.77	3.891	-0.2208	0.03853	46.0
	Uptime (min/hr)	0.155	34.4	4.657	0.2181	0.15028	5.1
	Downtime (min/hr)	0.155	47.5	4.605	-0.2181	0.15028	5.1
	Temperature (°C)	0.195	35.69	4.149	0.3551	0.26923	4.3
	Activity change (n/hr)	0.848	42.07	5.712	-0.1368	0.70713	0.1
Total DMI (kg/d)	Lactation no.	<0.001	19.21	1.517	1.844	0.4946	26.3
	Other activity time (min/hr)	0.004	13.73	3.618	0.5137	0.16936	19.1
	Ruminate time (min/hr)	0.951	24.23	6.205	0.01775	0.285948	0.0
	Total Eat time (min/hr)	<0.001	35.31	2.862	-0.6491	0.17121	27.3
	Drink time (min/hr)	0.094	23.19	0.973	2.13	1.2395	7.0
	Other chew (n/hr)	0.082	20.5	2.356	0 0.03650	0.020443	7.6
	Ruminate chew (n/hr)	0.302	30.79	5.931	-0.00432	0.004124	2.7
	Total Eat chew (n/hr)	<0.001	35.29	2.851	-0.00949	0.0025	27.0
	Drink gulp (n/hr)	0.045	23.01	0.923	0.1446	0.06995	9.9
	Bolus (n/hr)	0.32	29.99	5.368	-0.2267	0.22526	2.5

DMI, dry matter intake

Table 12 continued

Response	Explanatory	P Value	Constant	s.e.	Slope	s.e.	R2
		Period 1 (10-15 weeks post calving)					
Total DMI (kg/d)	Chews /min	0.027	36.25	5.084	-0.1841	0.08003	11.9
	Chews / bolus	0.284	30.9	5.816	-0.1204	0.11088	2.9
	Activity index	<0.001	35.19	2.11	-0.1076	0.01957	47.7
	Uptime (min/hr)	0.323	22.33	2.341	0.07555	0.075538	2.5
	Downtime (min/hr)	0.323	26.87	2.315	-0.07555	0.075538	2.5
	Temperature (ºC)	0.388	22.85	2.087	0.1181	0.1352	2.4
	Activity change (n/hr)	0.943	24.81	2.833	-0.02512	0.350773	0.0
Energy balance (MJ/d)	Lactation no.	0.634	-19.27	12.226	1.911	3.9846	0.6
	Other activity time (min/hr)	0.795	-6.439	27.8824	-0.342	1.30515	0.2
	Ruminate time (min/hr)	0.522	-41.22	42.828	1.274	1.9735	1.1
	Total Eat time (min/hr)	0.977	-13.02	23.234	-0.0402	1.391006	0.0
	Drink time (min/hr)	0.476	-9.423	6.9564	-6.376	8.8612	1.3
	Other chew (n/hr)	0.528	-24.2	16.916	0.09348	0.146761	1.0
	Ruminate chew (n/hr)	0.620	-34.39	41.589	0.01446	0.028918	0.6
	Total Eat chew (n/hr)	0.916	-11.25	23.143	-0.00216	0.020293	0.0
	Drink gulp (n/hr)	0.395	-8.871	6.6808	-0.4352	0.50646	1.9
	Bolus (n/hr)	0.306	-52.07	37.213	1.619	1.5617	2.7
	Chews /min	0.506	-38.65	37.376	0.395	0.58835	1.1
	Chews / bolus	0.812	-23.44	40.928	0.1868	0.78025	0.1
	Activity index	0.619	-22.51	18.011	0.08955	0.178765	0.7
	Uptime (min/hr)	0.470	-2.074	16.3366	-0.3843	0.52719	1.3
	Downtime (min/hr)	0.470	-25.16	16.156	0.3843	0.52719	1.3
	Temperature (ºC)	0.434	-2.599	14.472	-0.7432	0.93912	1.6
	Activity change (n/hr)	0.903	-11.31	19.655	-0.2986	2.43341	0.0

DMI, dry matter intake

Table 12 continued

Response	Explanatory	P Value	Constant	s.e.	Slope	s.e.	R2
Period 2 (16-21 weeks post-calving)							
Milk yield (kg/d)	Lactation no.	0.076	32.81	2.972	1.767	0.9967	8.0
	Other activity time (min/hr)	0.041	23.78	6.923	0.6387	0.31201	10.4
	Ruminate time (min/hr)	0.406	29.67	9.852	0.3841	0.46194	1.9
	Total Eat time (min/hr)	0.008	50.32	4.515	-0.7796	0.27683	18.1
	Drink time (min/hr)	0.126	35.34	1.828	3.54	2.2595	6.4
	Other chew (n/hr)	0.492	40.64	4.163	-0.02532	0.036497	1.3
	Ruminate chew (n/hr)	0.794	40.54	10.416	-0.00192	0.007339	0.2
	Total Eat chew (n/hr)	0.018	48.13	4.437	-0.00952	0.004021	13.5
	Drink gulp (n/hr)	0.085	35.42	1.667	0.2087	0.12134	7.6
	Bolus (n/hr)	0.211	49.41	9.3	-0.4949	0.39564	4.2
	Chews /min	0.129	53	9.817	-0.2406	0.15502	6.3
	Chews / bolus	0.328	27.18	10.786	0.2057	0.20757	2.7
	Activity index	<0.001	55.68	4.575	-0.1958	0.04944	30.4
	Uptime (min/hr)	0.115	31.71	3.892	0.2065	0.12783	6.8
	Downtime (min/hr)	0.115	44.12	3.995	-0.2065	0.12783	6.8
	Temperature (^{o}C)	0.156	32.6	3.723	0.3379	0.2331	5.5
	Activity change (n/hr)	0.176	44.2	4.703	-0.7965	0.57697	5.0
Total DMI (kg/d)	Lactation no.	0.093	22.42	1.587	0.9177	0.53224	7.6
	Other activity time (min/hr)	0.105	18.98	3.762	0.2751	0.16958	6.8
	Ruminate time (min/hr)	0.412	20.74	5.251	0.202	0.24621	1.8
	Total Eat time (min/hr)	0.016	31.11	2.449	-0.3797	0.15016	15.1
	Drink time (min/hr)	0.016	23	0.928	2.896	1.147	15.0
	Other chew (n/hr)	0.625	23.97	2.226	0.00955	0.019512	0.7
	Ruminate chew (n/hr)	0.696	22.88	5.544	0.001524	0.003906	0.4
	Total Eat chew (n/hr)	0.015	30.63	2.357	-0.00518	0.002136	14.0
	Drink gulp (n/hr)	0.007	23.03	0.835	0.173	0.06077	18.4
	Bolus (n/hr)	0.974	24.86	5.062	0.007097	0.215351	0.0

DMI, dry matter intake

Table 12 continued

Response	Explanatory	P Value	Constant	s.e.	Slope	s.e.	R2
		Period 2 (16-21 weeks post-calving)					
Total DMI (kg/d)	Chews /min	0.382	29.74	5.345	-0.07469	0.084409	2.1
	Chews / bolus	0.875	24.12	5.823	0.01764	0.112065	0.0
	Activity index	0.01	31.85	2.684	-0.07481	0.028999	15.6
	Uptime (min/hr)	0.332	23.03	2.12	0.06756	0.069639	2.5
	Downtime (min/hr)	0.332	27.09	2.177	-0.06756	0.069639	2.5
	Temperature (ºC)	0.04	21.18	1.93	0.2488	0.12087	10.5
	Activity change (n/hr)	0.76	25.8	2.568	-0.0962	0.315072	0.3
Energy balance (MJ/d)	Lactation no.	0.916	2.696	10.075	-0.3458	3.28864	8.5
	Other activity time (min/hr)	0.939	3.488	23.6704	-0.08125	1.062864	8.8
	Ruminate time (min/hr)	0.464	24.87	31.436	-1.09	1.4708	7.1
	Total Eat time (min/hr)	0.727	-3.827	16.1965	0.344	0.97929	9.1
	Drink time (min/hr)	0.187	-5.086	6.3232	9.654	7.1759	11.3
	Other chew (n/hr)	0.184	-15.44	13.11	0.1551	0.1144	7.4
	Ruminate chew (n/hr)	0.727	13.34	33.163	-0.00822	0.023313	7.2
	Total Eat chew (n/hr)	0.782	5.913	15.4923	-0.00387	0.013888	7.3
	Drink gulp (n/hr)	0.154	-4.798	5.7869	0.5634	0.38656	11.3
	Bolus (n/hr)	0.398	-23.56	29.758	1.079	1.2608	9.6
	Chews /min	0.914	5.207	32.1657	-0.05531	0.506526	8.2
	Chews / bolus	0.068	63.68	33.075	-1.196	0.6354	13.3
	Activity index	0.182	-21.14	17.216	0.2504	0.18406	11.2
	Uptime (min/hr)	0.246	15.97	12.724	-0.4827	0.40907	10.8
	Downtime (min/hr)	0.246	-12.99	13.058	0.4827	0.40907	10.8
	Temperature (ºC)	0.442	-7.369	12.3026	0.5841	0.751	9.7
	Activity change (n/hr)	0.157	-19.27	14.978	2.623	1.8153	11.2

DMI; dry matter intake

Table 13. Using RumiWatch data to predict milk yield, DMI or energy balance – results of the multivariate analysis.

Response	Constant	Explanatory				R2
		Total Eat time (min/h)	Drink gulp (n/h)	Chews/ bolus	Activity index	
Period 1 (10-15 weeks post-calving)						
Milk yield (kg/d)	58.42 (3.731)		0.3352 (0.09638)		-0.2144 (0.03415)	60.4
Total DMI (kg/d)	33.5 (2.144)	-	0.1224 (0.05181)	-	-0.1041 (0.01855)	54.8
Energy balance (MJ/d)	*No explanatory variables selected by the model*					
Period 2 (16-21 weeks post-calving)						
Milk yield (kg/d)	36.89 (8.513)		0.2365 (0.09318)	0.365 (0.15831)	-0.2268 (0.04498)	49.6
Total DMI (kg/d)	29.98 (2.118)	-0.4546 (0.13010)	0.2018 (0.05370)	-	-	39.5
Energy balance (MJ/d)	*No explanatory variables selected by the model*					

DMI; dry matter intake

Discussion

Energy balance in dairy cows is defined as the difference between energy consumed from feed (energy input) and energy expended for maintenance, production, activity and pregnancy (energy output). In early lactation, high yielding dairy cows are often unable to consume sufficient nutrients to meet their energy requirements for milk production, and consequently enter a period of negative EB which leads to the mobilisation of body tissue reserves. Severe negative EB can have a negative impact on fertility and health. Being able to predict EB at an individual cow level is important as this will allow farmers to intervene before cows are negatively affected by metabolic diseases, ill health or poor fertility.

The most accurate approach to measure EB in dairy cows is through respiration chambers, but this is costly, labour-intensive and not practical for on-farm use. The next best option is to calculate EB by gathering data on DMI, milk production, milk composition, BW, and the energy contents of feeds to estimate the difference between energy intakes and energy requirements. However, reliable feed intake measurements at an individual animal level are not available in commercial dairy herds, therefore some research has been carried out using other parameters such as body weight change, blood metabolites and milk composition have been investigated as a proxy for EB with pros and cons to each method. However, little, if any, research has been conducted to investigate if any behaviour measures could serve as a proxy for EB. As DMI is closely linked to EB the aim of this study was to investigate if there was potential for cow behaviour to be used as a proxy for DMI and/or EB.

***Pedometer results**:* Lactation number explained most of the variation in both DMI and EB which is unsurprising as older animals will have greater DMI, and therefore, more capacity to reduce the effects of negative EB. While not always significant, there were negative correlations between intakes and the activity of the animal. It is likely that cows with lower intakes are smaller or lower ranking animals which will have higher activity or number of steps if they are bullied out of the feed boxes or spend time looking for a space to feed. Similarly, BW was negatively related to intakes which confirms the assumption that older/heavier cow do not need to work as hard as younger cows to achieve their feed intake. As milk production parameters are linked to intakes, any correlations observed in the intake data followed a similar pattern in the milk production parameters. In early lactation, standing bouts were positively related to concentrate DMI, likely due to the fact that cows were fed a majority of their concentrates through OPF. As cows were fed concentrates in relation to milk yield, milk yield was also correlated with standing bouts. Despite many of the correlations being significant, the fit of the relationship was low, as demonstrated by the R^2. The R^2 is a descriptive statistic indicating the proportion of variance explained by the variables in question. Therefore, as pedometer data could not explain a reasonable percentage of variation in DMI or EB, it provides no useful basis for predicting performance, DMI and EB of dairy cows.

***RumiWatch results**:* Surprisingly, most eating/chewing parameters captured by the RumiWatch halters had a negative relationship with milk yield and DMI within the univariate analysis, however, because R^2 were low so this observation should be treated with caution.

As none of the variables were significantly correlated with EB in the univariate analysis it is not surprising that the multivariate analysis could not yield any equation to explain EB. Drinking was identified as a positive driver of milk yield and total DMI, which is unsurprising as higher yielding cows have greater DMI and water requirements. Activity index was also negative driver of milk yield and total DMI, again likely due to older/heavier cows having advantage at the feed boxes and therefore do not need to work as hard as younger cows to achieve their feed intake.

***Implications**:* Attempting to use behaviour data as a proxy for DMI or EB is a new concept and this study was a pilot to see if any value could be found in monitoring behaviour for the purposes of predicting DMI or EB. However, these studies comprised low numbers of cows with relatively normal energy balance curves. Future research may seek to include data from a larger number of studies, including those which may have restricted energy intakes to achieve extremes of EB.

Conclusions

Despite some significant correlations between behaviour parameters and production data, the fit of these relationships were too low to provide any useful value. Therefore, parameters derived from feeding behaviour halters and a pedometer systems were unable to make any practical contribution to predicting DMI or EB in dairy cows.

SECTION 5

The potential of MIR analysis of milk to predict individual dairy cow energy balance

Introduction

'MIR', or mid-infrared spectroscopy, is the technique used by milk processors and milk recording organisation to predict the fat and protein content of bulk tank milk samples, and milk samples from individual cows. The technique, which is used throughout the world to analyse milk samples, involves shining a light (within the mid-infrared range) through a small sample of milk using a MIR instrument (see photo). Some of the light is absorbed by the molecules in the milk and some is reflected, and a 'spectra' is produced. Using these spectra we are able to predict the fat, protein, lactose and urea content of milk with a high degree of accuracy using a series of calibration equations. For example, Figure 1 shows the spectra for two different cows, and while the lines are similar, there are subtle differences, which indicate different milk compositions. More recently, MIR has been used to predict the type of fat in milk, allowing processor to identify how much of the fat in milk is unsaturated (more health) and how much is saturated (less healthy). Research is also underway using MIR to identify the diet a cow is being offered (i.e. grass vs. silage). This could be used to validate the 'providence' of milk from a farm, i.e. 'grass fed' milk.

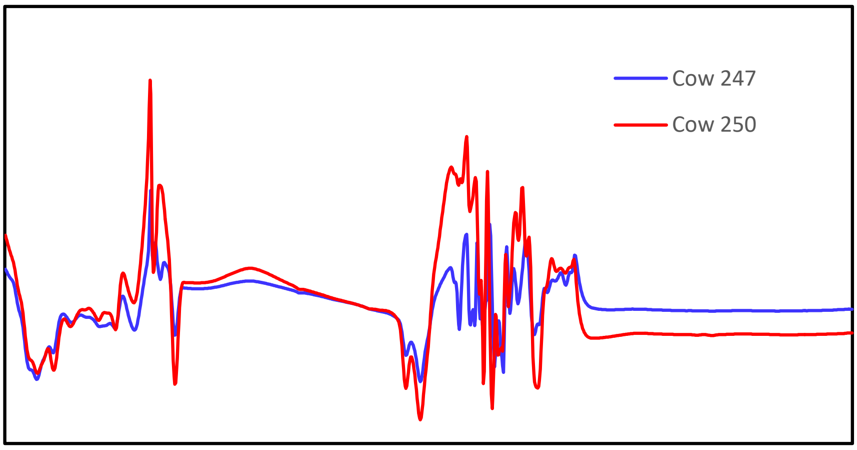

Figure 1. Typical MIR spectra for milk samples from two dairy cows.

However, over the last decade research has increasingly examined what MIR can tell us about the cow that is producing the milk (and not just about the milk). This was examined in a major EU project called GplusE, in which AFBI was a partner, and more recently within the current project. Within these and other projects, MIR has been used to predict a number of 'difficult-to-measure' traits in cows, including energy balance of individual cows. In addition, MIR has been used identify cows in a herd that are 'metabolically at risk', and which may need special attention. MIR also offers potential to help lessen the environmental footprint of dairying. For example, MIR can be used to predict the methane production of individual cows, and to identify cows which are using nitrogen efficiency (or inefficiently). While most of these predictions equations are still in the development stage, a number of research groups throughout the world, including at AFBI, are currently working in this area.

AFBI Research

Since 2017, all milk samples analysed at AFBI have been analysed using a MIR milk analyser. This instrument shines light within the MIR range at the sample, and measures the reflectance from the sample, with this captured in the form of a spectra. The spectra for each sample comprises 1060 data points, and using a calibration contained within the instrument, the fat and protein content of the milk is predicted. This process is used in laboratories throughout the world to predict the fat and protein content of milk.

Within this project, milk spectra data was sourced from 217 sampling occasions (spectra from am and pm samples weighted according to am and pm milk yields on each occasion), representing different stages of lactation. A range of production traits for the 7 day period around which the milk samples were taken were subsequently determined, as shown below:

Days in milk
Daily milk yield (kg)
Dry matter intake (kg DM/d)
Forage % of ration (DM basis)
Concentrate % of ration (DM basis)
Total milk energy output (MJ)
Milk energy /kg metabolic LW (MJ/kg0.75)
Total ME intake (MJ)
Daily energy balance (MJ/d)

Daily energy balance values were determined using the equations outlined in Feed-into-Milk, the UK dairy cow rationing system. Basic chemometrics were then run using WinISI software (using first derivative equations) to identify relationships between these 9 production traits and the milk spectra, as summarised in Table 6.

Table 1. Mean, minimum, maximum of production data used, and statistics describing the relationships identified.

Constituent	Mean	SD	Est. Min	Est. Max	SEC	RSQ	SECV	1-VR
Days in Milk	83.8	33.0	0.0	182.9	10.68	0.90	15.87	0.77
Daily milk yield (kg)	32.7	8.2	8.1	57.4	6.87	0.30	7.64	0.14
Dry Matter Intake (kg DM/d)	26.6	7.4	4.5	48.8	6.42	0.24	6.98	0.10
Forage %	0.6	0.1	0.3	0.9	0.10	0.08	0.10	0.07
Concentrate %	0.4	0.1	0.1	0.7	0.10	0.08	0.10	0.07
Total milk energy output (MJ)	103.7	25.6	26.8	180.6	18.37	0.49	21.59	0.29
Milk energy /kg metabolic LW (MJ/	0.8	0.2	0.3	1.4	0.14	0.40	0.15	0.29
Total ME intake (MJ)	267.5	37.6	154.7	380.4	29.31	0.39	33.29	0.21
Daily energy balance (MJ/d)	24.5	36.5	0.0	134.1	23.88	0.57	28.01	0.42

Good relationships were identified for ‘days in milk’ and ‘daily energy balance’ (relationships in Figures 2 and 3, respectively). While the former is not a trait that we would need to predict, the relationships shows that there is a strong relationship between MIR spectra and time of lactation, reflecting changes in milk composition that takes place over the lactation. With regards daily energy balance the MIR calibration had a standard error of calibration (SEC) of 23.88, a SECV or 28.013, and a variance ratio (1-VR) of 0.415. Mean value for Energy balance for the data set was 24.5 with correlation coefficient of calibration squared (RSQ) 0.573 and r value 0.757. While this equation, developed with a limited data set is still not adequate for prediction purposes, it is strongly indicative that a relationship exists. Undoubtedly this equation can be further developed as more diverse datasets are incorporated into the dataset, and this work is part of an ongoing process.

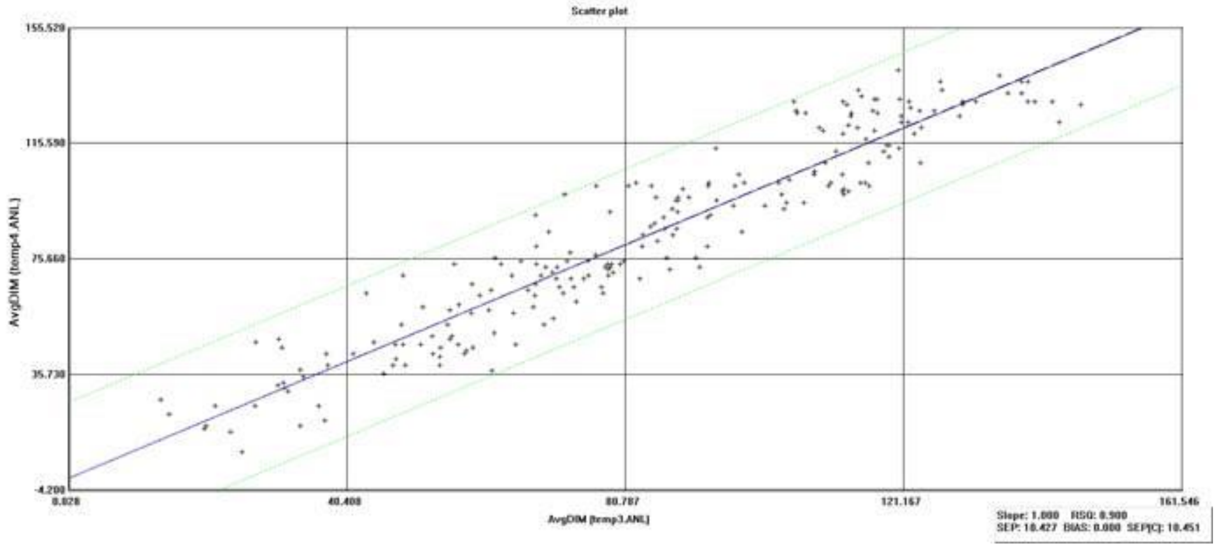

Figure 2. Average ‘days in milk’ prediction by NIRS, for milk yield adjusted spectral data.

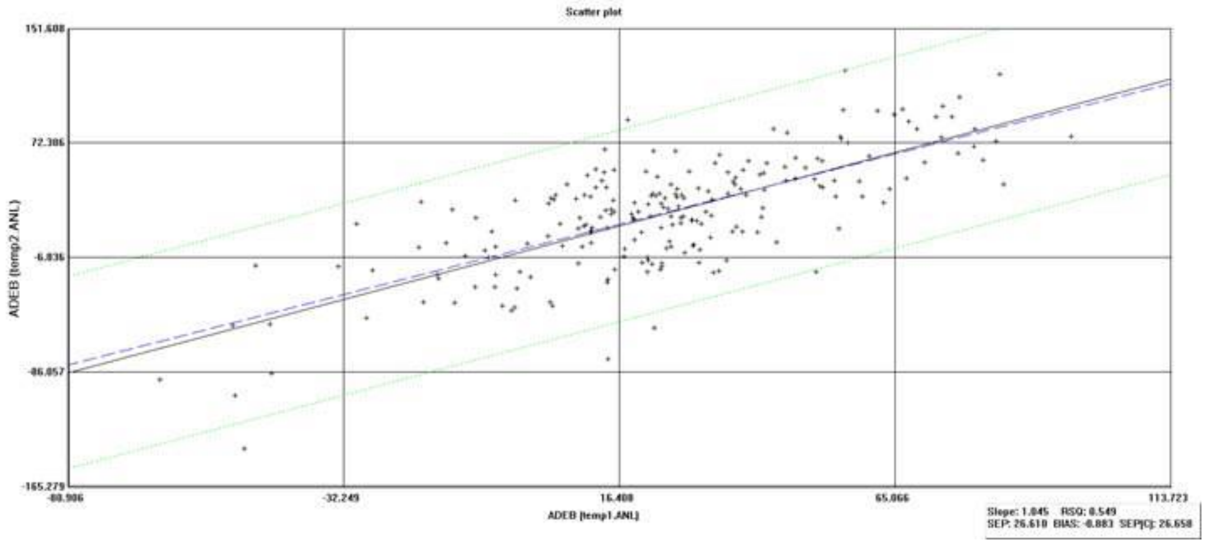

Figure 3. Average daily energy balance data prediction by NIRS, for milk yield adjusted spectral data.

Conclusions

MIR has a number of benefits, including that it is 'non-invasive' (unlike a blood sample) and that milk samples are readily available from farms (monthly for those involved in milk recording). It looks likely that in the near future information obtained from MIR analysis of milk samples will become increasing useful and important in helping farmers manage the nutrition of their herds, and indeed individual cows, and to help farmers reduce the environmental impact of dairy farming.

SECTION 6

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