

# A comparison of grazing v. zero-grazing on early-lactation dairy cow performance

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## Animal Research Paper

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### Abstract

To overcome grass supply shortages on the main grazing block, some pasture-based dairy farmers are using zero-grazing (also known as ‘cut and carry’), whereby cows are periodically housed and fed fresh grass harvested from external land blocks. To determine the effect of zero-grazing on cow performance, two early-lactation experiments were conducted with autumn and spring-calving dairy cows. Cows were assigned to one of two treatments in a randomized complete block design. The two treatments were zero-grazing (ZG) and grazing (G). The ZG group were housed and fed zero-grazed grass, while the G group grazed outdoors at pasture. Both treatments were fed perennial ryegrass (*Lolium perenne* L.) from the same paddock. In experiment 1, 24 Holstein Friesian cows ( $n = 12$ ) were studied over a 35-day experimental period in autumn and offered fresh grass, grass silage, ground maize and concentrates. In experiment 2, 30 Holstein Friesian cows ( $n = 15$ ) were studied over a 42-day experimental period and offered fresh grass and concentrates. Average dry matter intake and milk yield was similar for ZG and G in both experiments. Likewise, ZG did not have an effect on milk composition, body condition or locomotion. Zero-grazing had no effect on total nitrogen excretion or nitrogen utilization efficiency in either experiment, or on rumen pH and ammonia concentration in experiment 1. While zero-grazing may enable farmers to supply fresh grass to early-lactation cows in spring and autumn, results from this study suggest that there are no additional benefits to cow performance in comparison to well-managed grazed grass.

## Introduction

In temperate regions such as Ireland, the UK, New Zealand and parts of Australia pasture-based milk production systems predominate due to the abundance of pasture that can be grown (Roche *et al.*, 2017). With future feed costs projected to increase, using more grass in the diet of the lactating cow is a major objective for the Irish dairy industry. While grazed grass is the cheapest feed available (Hanrahan *et al.*, 2018), it has also been shown to increase milk production (Dillon *et al.*, 2002) and milk protein concentration (Kennedy *et al.*, 2005) in early lactation when compared to grass silage feeding. According to McEvoy *et al.* (2008), targeting the early-lactation period for increasing grass input may eliminate the requirement to offer grass silage to animals, and depending on grass availability, concentrate supplementation level may also be reduced.

The variable and seasonal nature of pasture growth and feed quality, however, is a significant challenge in pasture-based farming in temperate regions (Roche *et al.*, 2017). In Ireland there is little net grass growth during the winter period from November to February (Brereton *et al.*, 1985), and subsequently, grass supply in late autumn and early spring is generally not sufficient to meet herd demand (McEvoy *et al.*, 2008). As a result of this grass deficit, grass silage and concentrates have previously constituted a large proportion of the early-lactation diet in spring and autumn-calving dairy cows (Kennedy *et al.*, 2005, 2015). Developments in autumn and spring pasture management have led to improved grass utilization and cow performance (O’Donovan *et al.*, 2015; Claffey *et al.*, 2020); however, grass supply is still limited during these periods, even in an optimal scenario (McEvoy *et al.*, 2008).

A steady increase in the use of zero-grazing has been recently reported especially in the UK, Germany, Holland and the USA (Agrisearch, 2018; Cameron *et al.*, 2018). According to a recent survey (Holohan *et al.*, 2021), an increasing number of dairy farmers in Ireland are choosing to use zero-grazing to overcome grass supply deficits. In this system, grass is cut using a purpose-built machine and transported to the farmyard where it is fed directly to the herd indoors (Agrisearch, 2018). This enables farmers to increase the quantity of grass available to the herd by utilising grass from external land parcels that are detached from

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the main grazing platform. On most of the farms surveyed, zero-grazing was carried out on a short-term basis, typically in spring or autumn, to reduce silage and concentrate feed requirements (Holohan *et al.*, 2021).

Previous studies have suggested that there may be some additional benefits to zero-grazing, in terms of cow performance when compared to conventional grazing, with increases in dry matter intake (DMI) and milk production reported (van Vuuren and van den Pol-van Dasselaar, 2006; Boudon *et al.*, 2009; Dohme-Meier *et al.*, 2014). The potential of zero-grazing to increase DMI is of particular interest in the context of the early-lactation period, when energy demand for production is higher than intake can support, often leading to cow health disorders and reduced fertility and performance (Mulligan and Doherty, 2008; Gilmore *et al.*, 2011). There is however disagreement in the literature around the impact of zero-grazing on cow performance, with some studies noting lower DMI and milk yield in zero-grazed cows compared to grazing cows (Mohammed *et al.*, 2009), and higher incidences of lameness (Haskell *et al.*, 2006) and mastitis (Arnott *et al.*, 2015) with indoor housing systems.

The inconsistency in the current literature and overall lack of research on zero-grazing necessitates further investigation, particularly in an Irish context where interest in this feeding method has increased in recent years. The objective of this research therefore was to determine the effect of zero-grazing on the early-lactation performance of both autumn and spring-calving dairy cows in comparison to conventional pasture grazing. The experimental hypothesis was that zero-grazed cows would have higher DMI and milk yield.

## Materials and methods

### Location and management

Two experiments were carried out at University College Dublin's Lyons Farm, Kildare, Republic of Ireland (53°17'56"N, 6°32'18"W). In both experiments cows were assigned to one of two treatments: zero-grazing (ZG) and grazing (G). The ZG cows were housed full time in a free stall barn and fed zero-grazed grass, while the G cows grazed outdoors at pasture full time. During the experimental periods, grazing and zero-grazing was carried out simultaneously within the same paddock to ensure uniformity of grass quality offered to both groups. Cows in experiment 1 were fed a diet of concentrates, fresh grass and a buffer feed consisting of grass silage and maize meal while cows in experiment 2 were fed concentrates and fresh grass only. These are described in more detail later.

Cows in the G treatment were grazed together in a single group in a strip-grazing system, to enable a fresh allocation of pasture twice daily. Back fences on previously grazed areas were used to prevent cows grazing regrowth. Grass was allocated to achieve a target post grazing sward height of 4.5–5 cm. Herbage growth and supply was estimated twice weekly, using a rising plate meter (diameter 355 mm; 3.2 kg/m<sup>2</sup>; Jenquip, Feilding, New Zealand) by walking in a W shape across the experimental fields and measurements were entered into the PastureBase Ireland software system (Hanrahan *et al.*, 2017), while daily pasture allocations were based on pre-grazing herbage mass as measured daily using the quadrat and shears method. Pasture allowance was adjusted daily to cater for the increasing demand of the cows based on stage of lactation with a continuing target post grazing sward height of 4.5–5 cm. Thus, the +0.5–1.5 cm

additional post grazing residual above the recommended target for the first and last grazing rotation (O'Donovan and McEvoy, 2016) ensured that they were not restricted and was as similar as possible to the *ad libitum* allowance offered to the ZG treatment. In the ZG treatment, grass was harvested to 4 cm at 10:00 h daily using a specialized zero-grazing machine (Zero Grazer, Oldcastle, Ireland), and placed at the feed face where the cows were housed. The grass was manually moved closer to the feed face at regular intervals throughout the day to ensure cows had *ad libitum* access to grass at all times. A feed space allocation of 700 mm per cow was used to enable all cows to feed simultaneously at any one time. The floor surface of the barn was kept clean using an automatic scraper system (CleanSweep; Dairymaster, Kerry, Ireland) which removed dung and urine at regular intervals throughout the day, and free stalls were cleaned and bedded with a mixture of hydrated lime and sawdust twice daily.

### Experiment 1: the effect of zero-grazing on early-lactation performance in autumn-calving cows

This 7-week study was conducted between 1 October and 18 November 2018. Twenty-four autumn-calving Holstein Friesian dairy cows in early lactation were blocked on days in milk ( $28 \pm 13.3$ ), parity, predicted 305-day yield, body condition score (BCS) and body weight (BW), and assigned to one of two treatments in a randomized complete block design ( $n = 12$ ). Prior to being assigned to their respective treatment groups, all cows were fed a diet of grazed grass and 8 kg concentrates, with concentrate feeding stepped up from 4 to 8 kg in the first 7 days post-partum. Cows were offered the experimental diets for a 14-day dietary acclimatization period. Following this, cows remained on their treatments for a further 35-day experimental period. Both treatment groups were offered the same daily diet which consisted of *ad libitum* quantities of perennial ryegrass (*Lolium perenne* L.), 7.2 kg dry matter (DM) concentrates fed in the parlour, 2.5 kg DM grass silage and 1.8 kg DM ground maize. Concentrate ingredients are highlighted in Table 1. The grass silage and ground maize were fed to both G and ZG groups directly before milking each day using individual pre-programmed feed boxes (RIC System; Insentec B.V., Marknesse, the Netherlands). In preparation for the study, paddocks that were previously rotationally grazed by dairy cows were mechanically cut to a height of 4 cm in the previous rotation and grass was harvested for baled silage. This prevented the risk of sward contamination from dung pads left by grazing livestock as per current guidelines (Agrisearch, 2018). Average pre-cutting/pre-grazing yield over the experimental period was 2024 kg DM/ha ( $\pm 557$ ) (>4 cm). Post-cutting sward height for ZG was 4 cm, while post-grazing sward height for G was 5.3 cm. Mean total distance walked per day between paddock and milking parlour for G group was 1.6 km ( $\pm 0.37$ ) for the experimental period.

### Experiment 2: the effect of zero-grazing on early-lactation performance in spring-calving cows

This 7-week study was conducted between 17 March and 6 May 2020. Thirty spring-calving Holstein-Friesian dairy cows in early lactation were blocked on days in milk ( $37 \pm 6.1$ ), parity, pre-experimental milk yield, predicted 305-day yield, BCS, locomotion score and BW, and assigned to one of two treatments in a randomized complete block design ( $n = 15$ ). Cows were offered the experimental diets for a 10-day dietary acclimatization period. Following this, cows remained on their treatments for a further 42-day experimental period. Both treatment groups were offered

**Table 1.** Ingredient composition of concentrate fed in experiments 1 and 2

Ingredients (g/kg)	Experiment 1 (Autumn)	Experiment 2 (Spring)
Barley	217	217
Ground maize	225	225
Soybean meal	210	200
Maize distillers	100	100
Beet pulp	102	100
Soya hulls	55	70
Molasses	45	45
Palm oil	15	15
Mono dicalcium phosphate	8	7
Calcium carbonate	9	8
Magnesium oxide	8	8
Lifeforce MinPlex Pack <sup>a</sup>	1	0.5
Gain cattle premix <sup>b</sup>	4	4
Vitamin E 5% premix	1	0.5

<sup>a</sup>Altech, Nicholasville, KY, USA.

<sup>b</sup>Gain Feeds, Portlaoise, Ireland.

the same diet which consisted of perennial ryegrass (*L. perenne* L.), and 7.2 kg DM concentrates fed in the parlour. Concentrate ingredients are highlighted in Table 1. Average pre-cutting/pre-grazing yield over the experimental period was 1680 kg DM/ha ( $\pm 221$ ) (>4 cm) for both ZG and G. Post-cutting sward height for ZG was 4.5 cm, while post-grazing sward height for G was 4.6 cm. Mean total distance walked per day between paddock and milking parlour for G group was 2.4 km ( $\pm 0.63$ ).

### Animal measurements

All procedures described in this experiment were approved by the Animal Research Ethics Committee of University College Dublin and were conducted under experimental license from the Health Products Regulatory Authority under the European directive 2010/63/EU and S.I. No. 543 of 2012. The respective project licence numbers for experiments 1 and 2 were AE18982/P144 and AE18982/P175. Each person who carried out procedures held an individual authorization from the Health Products Regulatory Authority.

Animals were milked twice daily at 07.00 and 16.00 h. Milk yield and milk sampling were facilitated by using a milk metering and sampling system (Weighall; DairyMaster). Samples of milk were taken weekly during consecutive a.m. and p.m. milkings and pooled according to individual daily milk yield to determine weekly milk composition and quality. Animal BW was measured twice daily after milking using an automatic weighing system (DairyMaster) and averaged on a daily basis. Locomotion scoring was performed on a bi-weekly basis using a five-level ordinal scale (1 = healthy; 5 = severely lame) as described by Sprecher *et al.* (1997). BCS was measured bi-weekly and determined using a five-point scale (1 = emaciated; 5 = obese) with quarter-point increments (Edmonson *et al.*, 1989) and evaluated by the same trained researcher.

Pasture DMI and N excretion was determined over a 6-day period for both treatments during week 4 of experiment 1 ( $48 \pm 13.3$  DIM; mean  $\pm$  SD) and during week 3 in experiment 2 ( $58 \pm 6.1$  DIM; mean  $\pm$  SD). Pasture DMI was determined using the n-alkane technique of Dove and Mayes (2006). Briefly, cows were orally dosed with a paper bolus impregnated with 500 mg of the n-alkane n-dotriacontane (C32) for a period of 12 days following a.m. and p.m. milking. From day 6 to 12, samples of the concentrates, pasture, milk and faeces were collected. Pasture samples were immediately dried at 55°C for 48 h. Faecal samples were collected, whenever possible, when cows naturally defecated, and, if not, samples were collected per rectum and placed in a forced-air oven at 55°C for 72 h or until dry. Samples of milk were collected during a.m. and p.m. milking and pooled according to milk yield.

In experiment 1, blood samples were harvested by jugular venepuncture once weekly for determination of glucose, NEFA and BHB. Blood samples for glucose were harvested into a 4 ml Vacutainer tube containing NaF (6 mg) and Na<sub>2</sub>EDTA (12 mg; Ref. No. 368521; BD, Plymouth, UK) and centrifuged at 2100  $\times$  g for 20 min at 4°C for extraction of plasma. These samples were stored at -20°C pending analysis. Blood samples for other analytes were harvested into a 10 ml Vacutainer (Ref. No. 8303209; BD) and allowed to clot for 16 h at 4°C before centrifuging at 2100  $\times$  g for 20 min at 4°C for extraction of serum. These samples were also stored at -20°C pending analysis. In experiment 1 rumen fluid samples were collected weekly via Flora Rumen scoop oral oesophageal sampler (Prof-Products, Guelph, ON, Canada) and samples were analysed immediately for pH (EC-25 pH/Conductivity Portable Meter, Phoenix Instrument, Garbsen, Germany). Samples were strained through four layers of cheese-cloth. An 8 ml sample was drawn off, mixed with 2 ml of 50% (wt/vol) TCA and stored at -20°C pending determination of NH<sub>3</sub>N concentrations.

### Pasture and feed measurements

Samples of herbage were collected daily and pooled weekly, while concentrate samples were collected weekly during the trial period. In the case of experiment 1, grass silage and ground maize samples were also collected weekly. Pasture and feed samples were dried at 55°C for 72 h in a forced-air oven to determine DM. For chemical composition analysis daily snip samples were taken using a hand-held shears (Gardena Accu 90, Gardena GmbH, Ulm, Germany) to a height of 4 cm at random locations in the paddock. A 100 g subsample was then taken for determination of DM, ash, crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), organic matter digestibility (OMD) and water-soluble carbohydrate (WSC) content (Table 2).

### Meteorological data

Meteorological data on rainfall, air temperature and soil moisture deficit were recorded for the duration of the experiments at Casement Aerodrome (53°30'N, -6°44'W), approximately 5.8 km east of Lyons Farm, by the Irish Meteorological Service.

### Experiment 1

As outlined in Table 3, total rainfall for the period from 1 October to 18 November was 108 mm in 2018, which was 27% lower than the 10-year average for the same period. The number of 'wet days' (>1 mm rainfall) for the period was 16, which was 20% lower than

**Table 2.** Chemical composition of pasture, supplemental concentrates, grass silage and ground maize offered during the experiments 1 and 2

Item	Experiment 1 (autumn)				Experiment 2 (spring)	
	Pasture	Concentrates	Grass silage	Ground maize	Pasture	Concentrates
DM (g/kg)	168	894	359	883	218	902
Chemical composition (g/kg DM)						
CP	250	197	145	78	205	195
NDF	492	154	518	100	428	174
ADF	207	64	269	17	193	64
Ash	96	130	102	13	85	92
WSC	119	–	54	–	133	–
Starch	–	272	–	634	–	292
Digestibility						
OMD	0.70	0.88	0.72	0.87	0.81	0.87

CP, crude protein; WSC, water-soluble carbohydrates; OMD, digestibility of OM.

**Table 3.** Total rainfall, average daily air temperature and daily soil moisture deficit (mm) at the Casement Aerodrome weather station for experiments 1 and 2, and the previous 10-year average for each experimental period

	Experiment 1 (autumn 2018)		Experiment 2 (spring 2020)	
	Experimental period	10-year mean	Experimental period	10-year mean
Total rainfall (mm)	108	137	25	91
Number of wet days (rainfall > 1 mm) <sup>a</sup>	16	20	7	16
Average air temperature (°C)	9.2	9.5	8.5	7.9
Average soil moisture deficit (mm)	15.4	4.5	28.8	11.4

<sup>a</sup>Met Éireann (2022).

the 10-year average. Daily mean air temperature was 9.2°C, marginally lower than the 10-year average of 9.5°C, while soil moisture deficit was 15.41 mm, which was 2.4 times higher than the 10-year average.

### Experiment 2

Total rainfall for the period from 17 March to 6 May was 25 mm in 2020, which was 72% lower than the 10-year average for the same period (Table 3). The number of 'wet days' (>1 mm rainfall) for the period was 7, which was 56% lower than the 10-year average. Daily mean air temperature was 8.5°C, which was marginally higher than the 10-year average of 7.9°C, while soil moisture deficit was 28.5 mm, which was 2.5 times higher than the 10-year average.

### Sample analysis

#### Feed and faecal sample analysis

Dried pasture, concentrate, grass silage, ground maize and faecal samples were ground in a hammer mill fitted with a 1 mm screen (Lab Mill; Christy Turner, Suffolk, UK). The DM content of samples was determined after drying overnight at 105°C (16 h minimum) (AOAC International, 2005, method 930.15). The ash content was determined following combustion in a muffle furnace (Nabertherm GmbH, Lilienthal, Germany) at 550°C for 5.5 h (AOAC International, 2005, method 942.05). The N content of

samples was determined by combustion on Leco and CP content calculated (N × 6.25; FP 528 Analyzer, Leco Corp., St. Joseph, MI, USA; AOAC International, 2005, method 990.03). Neutral detergent fibre and ADF were determined using the method Van Soest *et al.* (1991) adapted for use in the Ankom 220 Fiber Analyzer (Ankom Technology, Macedon, NY, USA). Samples were not subjected to combustion after fibre extraction; therefore, the values reported include ash. No Na<sub>2</sub>SO<sub>4</sub> was used in the procedure. However, a thermostable  $\alpha$ -amylase (FAA, 17 400 Liquefon Units/ml; Ankom Technology) was included when concentrate NDF was determined. Starch was determined using the Megazyme Total Starch Assay Procedure (Product No. K-TSTA; Megazyme International Ireland Ltd., Wicklow, Ireland). The concentration of WSC was determined as described by DuBois *et al.* (1956). *In vitro* digestibility of organic matter of pasture and concentrates offered was determined using a modification of the method of Tilley and Terry (1963) for use in the Ankom Daisy Incubator (Ankom Technology). In experiment 2, NDF, ADF, WSC and starch were determined using near infrared spectrometry (Burns *et al.*, 2011).

#### Milk, blood and rumen sample analysis

Concentrations of milk fat, protein, lactose and SCC were determined in a commercial milk laboratory (Progressive Genetics, Dublin, Ireland) using infrared analysis (CombiFoss 5000, Foss Analytical A/S, Hillerød, Denmark; Soyeyrt *et al.*, 2006). Blood

samples were analysed for NEFA (Kit No. FA115) and BHB (Kit No. RB1007) using enzymatic tests. Glucose (Kit No. GL3816) was analysed using the hexokinase test. All kits were sourced from Randox Laboratories Ltd (Crumlin, County Antrim, UK). All blood analysis was carried out using a clinical blood analyser (RX imola; Randox Laboratories Ltd). Rumen fluid was allowed to thaw for 16 h to 4°C, and then centrifuged at 2100 × g for 10 min at 4°C. One millilitre of supernatant was drawn off and diluted 1:5 with distilled H<sub>2</sub>O, and then centrifuged at 1600 × g for 15 min at 4°C, and 200 µl of supernatant was drawn off and used to determine NH<sub>3</sub>N concentrations according to the phenol-hypochlorite method of Weatherburn (1967).

#### Pasture dry matter intake

Pasture DMI was determined by extracting n-alkanes from pasture, concentrate and faeces samples according to the method of Dove and Mayes (2006). Following extraction, samples were analysed for concentrations of n-alkanes by GC using a Varian 3800 GLC (Varian Inc., California) fitted with a 30 m capillary column with an internal diameter of 0.53 mm, coated with 0.5 µm of dimethyl polysiloxane (SGE Analytical Science Pty Ltd., Ringwood, Australia).

#### Nitrogen partitioning

After DMI was calculated, the data were used to calculate N partitioning as follows: N intake (g) = [(kg of pasture DMI × g of N/kg of DM pasture) + (kg of concentrate DMI × g of N/kg of DM concentrate) + (kg of grass silage DMI × g of N/kg of DM grass silage) + (kg of ground maize DMI × g of N/kg of DM ground maize)]; faecal N (g) = kg of faecal DM excretion × g of N/kg of DM faeces; milk N (g) = kg of milk yield × g of N/kg of milk; and urine N (g) = N intake (g) – faecal N (g) – milk N (g). Faecal excretion was calculated from the indigestibility of the diet fed while urine N was calculated by subtracting N in milk and faeces from N intake (Mulligan *et al.*, 2004).

#### Statistical analysis

Data were analysed as a complete randomized block design using the mixed model procedure (PROC MIXED) in SAS (SAS, version 9.4, Inst. Inc., Cary, NC, USA). The natural logarithm transformation of milk SCC was used to normalize the distribution. The transformed data were used to calculate *P* values. Data distributions were analysed to fit the assumptions of normality using the UNIVARIATE procedure of SAS. Individual cow was the experimental unit. Analysis included tests for the fixed effects of treatment and week, and their interactions. The following model was used:

$$Y_{ijklm} = \mu + T_i + W_j + TW_{ij} + \varepsilon_{ijklm}$$

where  $Y_{ijklm}$  is the variable of interest,  $\mu$  is the overall mean,  $T_i$  is the fixed effect of treatment  $i$ ,  $W_j$  is the fixed effect of week  $j$ ,  $TW_{ij}$  is the fixed interaction of treatment  $i$  and week  $j$ , and  $\varepsilon_{ijklm}$  is the residual error.

Statistically significant differences between least squares means were tested using the PDIF command incorporating the Tukey test for pairwise comparison of treatment means. Statistical significance was assumed at a value of  $P < 0.05$  and a tendency towards significance assumed at a value of  $P > 0.05$  but  $< 0.10$ .

## Results

### Experiment 1: the effect of zero-grazing on early-lactation performance in autumn-calving cows

#### Pasture and feed quality

Chemical composition of pasture, supplemental concentrates, grass silage and ground maize offered during the experimental period is outlined in Table 2. Average grass DM content was 168 g/kg, with OMD of 0.70, CP of 250 g/kg DM and NDF of 482 g/kg DM. Average grass silage DM was 349 g/kg, with OMD of 0.72, CP of 145 g/kg DM and NDF of 518 g/kg DM.

#### DMI, milk production, milk composition

The effects of grazing method on DMI, milk production, milk composition, animal BW, BCS and locomotion score are shown in Table 4. Zero-grazing did not have a significant effect on DMI in this study. Similarly, it had no effect on milk yield or milk composition.

#### Cow BW, BCS and locomotion

As outlined in Table 4, there was no significant difference in BW and BCS between the ZG and G treatments. In addition, treatment had no effect on locomotion score.

#### Nitrogen partitioning

The effects of grazing method on nitrogen partitioning are shown in Table 5. Dietary N intake did not differ significantly between treatments. Zero-grazed cows partitioned a greater proportion of N to faeces compared to G cows ( $P = 0.009$ ); however, N percentage in urine and milk was similar for both treatments. In addition, zero-grazing had no effect on total N excretion or NUE.

#### Blood metabolites and rumen fermentation

The effects of grazing method on blood metabolites and rumen fermentation are shown in Table 6. Treatment had no effect on blood glucose, NEFA or BHB concentrations. Similarly, there were no significant differences between treatments for rumen pH or ammonia levels.

### Experiment 2: the effect of zero-grazing on early-lactation performance in spring-calving cows

#### Pasture and feed quality

Chemical composition of pasture and supplemental concentrates offered during the experimental period is outlined in Table 2. Average grass DM content was 218 g/kg, with OMD of 0.81, CP of 205 g/kg DM and NDF of 428 g/kg DM.

#### DM intake, milk production and milk composition

The effects of grazing method on DMI, milk production and milk composition are shown in Table 4. Grass and total DMI tended to be higher in the ZG than G cows (13.07 v. 12.66 kg/day and 20.27 v. 19.86 kg/day;  $P = 0.081$  respectively). Average daily milk production did not significantly differ. In terms of milk composition (milk fat, protein and lactose percentage and yield) there was no significant difference between treatments. Energy corrected milk (ECM) yield was also similar between treatments. Somatic cell count was similar in both ZG and G (31 600 v. 32 400 cells per ml).

#### Cow BW, BCS and locomotion

Average BW was not significantly different between treatments, while daily BW change between the start and end of the

**Table 4.** Effects of grazing method on DM intake, milk production, milk composition, animal BW, body condition and locomotion in comparison to in pasture grazing

Item	Experiment 1 (autumn)				Experiment 2 (spring)			
	Zero-graze	Graze	S.E.M.	P value	Zero-graze	Graze	S.E.M.	P value
DM intake								
Grass (kg/day)	6.9	6.8	0.36	0.882	13.1	12.7	0.22	0.084
Total <sup>a</sup> (kg/day)	18.4	18.3	0.36	0.882	20.3	19.9	0.22	0.084
Yield (kg/day)								
Milk	32	31	2.1	0.703	35	33	2.3	0.601
Fat	1.3	1.3	0.13	0.717	1.24	1.23	0.060	0.966
Protein	1.09	1.06	0.080	0.790	1.18	1.15	0.046	0.743
Milk solids (F + P)	2.4	2.3	0.21	0.764	2.4	2.4	0.12	0.846
Lactose	1.42	1.37	0.031	0.608	1.59	1.54	0.076	0.635
ECM <sup>b</sup>	36	34	2.1	0.801	26.2	25.9	0.88	0.858
Milk composition								
Fat (g/kg)	41.1	41.1	0.12	0.997	36.5	37.7	0.18	0.523
Protein (g/kg)	35.0	34.8	0.08	0.878	34.4	34.8	0.07	0.680
Lactose (g/kg)	44.8	44.9	0.03	0.675	46.1	46.3	0.01	0.743
SCC ( $\times 10^3$ cells/ml)	57	72	23.0	0.655	32	32	3.1	0.794
Animal variable								
Mean BW (kg)	639	601	24.2	0.136	606	589	22.5	0.414
Mean BCS <sup>c</sup>	2.97	2.90	0.082	0.581	3.06	2.99	0.044	0.284
BW change (kg/day)	+0.6	+0.7	0.15	0.513	+1.0	+0.8	0.16	0.225
BCS change <sup>d</sup>	-0.06	+0.03	0.087	0.334	+0.10	-0.02	0.061	0.061
Locomotion <sup>e</sup>	1.8	1.6	0.19	0.403	1.2	1.2	0.19	0.410

<sup>a</sup>Total DM intake = grass + 7.2 kg concentrates + 2.5 kg silage + 1.8 maize meal for experiment 1; grass + 7.2 kg concentrates for experiment 2.

<sup>b</sup>Energy corrected milk calculated as per Tyrrell and Reid (1965).

<sup>c</sup>BCS was on a scale of 1–5 in 0.25 increments (Edmonson *et al.*, 1989).

<sup>d</sup>BCS change from beginning to end of experimental period.

<sup>e</sup>Locomotion was on a scale of 1–5 (Sprecher *et al.*, 1997).

experiment was similar. Mean BCS was similar; however, BCS change between the start and end of the experimental period tended to be higher in ZG than G cows (+0.10 *v.* -0.02;  $P = 0.061$ ). Average locomotion score was the same for both treatments.

### Nitrogen partitioning

The effects of grazing method on nitrogen partitioning are shown in Table 5. Dietary N intake did not differ significantly between treatments. Zero-grazed cows partitioned a greater proportion of N in faeces (0.21 *v.* 0.19;  $P = 0.024$ ) and subsequently excreted a higher amount of N to faeces than G cows (0.134 *v.* 0.120 kg/day;  $P = 0.011$ ). The proportion of N partitioned in milk and urine was similar for both treatments. The kilograms of N excreted in milk and urine were also similar. In addition, zero-grazing did not have an effect on total N excretion or nitrogen utilization efficiency.

### Discussion

In Ireland, some dairy farmers choose to use zero-grazing to supply the herd with fresh grass from land parcels that are outside of

the main grazing block during seasonal shortages or when *in situ* grazing is not possible due to adverse weather conditions (Holohan *et al.*, 2021). Given the lack of understanding on the effect that this feeding method has on cow performance, the objective of the current study was to determine the effect of zero-grazing on cow performance in early-lactation dairy cows during both the autumn and spring, in comparison to conventional grazing. The experimental hypothesis was that zero-grazed cows would have higher DMI and milk yield. The results of the study show that cows offered zero-grazed grass had similar DMI and milk production compared to conventionally grazed cows; therefore, the hypothesis can be rejected.

### DM intake, milk production, milk composition, animal BW, BCS and locomotion

It is recognized that DMI is the primary factor governing the ability of cows to meet their nutritional needs, particularly in early lactation (Allen, 2000; Jorritsma *et al.*, 2003; Jouany, 2006). While grazing plays an important role in Ireland's pasture-based dairy production model, achieving high levels of DMI can be challenging (Wilkinson *et al.*, 2019). According to Bargo *et al.*

**Table 5.** Effects of grazing method on nitrogen (N) partitioning in comparison to in pasture grazing

Item	Experiment 1 (autumn)				Experiment 2 (spring)			
	Zero-graze	Graze	S.E.M.	P value	Zero-graze	Graze	S.E.M.	P value
<b>N intake</b>								
Feed kg/day	0.59	0.59	0.021	0.883	0.7	0.6	0.10	0.512
<b>N output</b>								
Milk kg/day	0.17	0.17	0.014	0.923	0.189	0.19	0.011	0.733
Faeces kg/day	0.19	0.18	0.065	0.194	0.134	0.12	0.051	0.011
Urine kg/day	0.24	0.24	0.010	0.684	0.325	0.34	0.011	0.429
<b>N partitioning<sup>a</sup> (proportion)</b>								
Milk	0.28	0.29	0.018	0.835	0.29	0.29	0.017	0.792
Faeces	0.32	0.30	0.004	0.009	0.21	0.19	0.008	0.024
Urine	0.40	0.41	0.017	0.569	0.50	0.52	0.019	0.226
N excreted <sup>b</sup>	0.72	0.71	0.018	0.835	0.71	0.71	0.017	0.799
NUE <sup>c</sup>	0.28	0.29	0.018	0.835	0.29	0.29	0.017	0.790

<sup>a</sup>N partitioning = N out {[faeces, urine, milk (kg/day)]/N intake (kg/day)}.

<sup>b</sup>N excreted = N out {[faeces + urine output (kg/day)]/N intake (kg/day)}.

<sup>c</sup>Nitrogen utilization efficiency = N out {[milk output (kg/day)]/N intake (kg/day)}.

**Table 6.** Effect of grazing method on blood metabolites and rumen fermentation in comparison to in pasture grazing in experiment 1

Item	Zero-graze	Graze	S.E.M.	P value
<b>Blood metabolites</b>				
Glucose (mM/l)	3.10	2.99	0.082	0.191
NEFA (mM/l)	0.15	0.16	0.017	0.656
BHB (mM/l)	0.97	1.02	0.083	0.609
<b>Rumen fermentation</b>				
pH <sup>a</sup>	6.37	6.36	0.058	0.869
Ammonia (mM/l)	8.0	8.1	0.48	0.865

<sup>a</sup>Mean pH taken once weekly post afternoon milking.

(2003), if the aim is to maximize pasture DMI of high producing dairy cows, management must ensure unrestricted pasture quality and quantity; however, this is not always possible during the autumn and spring periods. Zero-grazing has previously been reported to increase DMI in comparison to grazing cows (van Vuuren and van den Pol-van Dasselaar, 2006; Boudon *et al.*, 2009; Dohme-Meier *et al.*, 2014). The reason, according to Oshita *et al.* (2008) and Dohme-Meier *et al.* (2014), is that cows grazing pasture require more time to ingest the same amount of herbage as zero-grazed cows, and this can therefore limit DMI when the diet largely consists of fresh grass. Dohme-Meier *et al.* (2014) fed a diet consisting of 0.78 grass and found significantly higher DMI in zero-grazed cows. In the current study, fresh grass made up 0.37 of the diet in experiment 1 and 0.65 in experiment 2, and DMI was similar and not statistically different between ZG and G cows in either experiment. In both experiments the cows were offered 7.2 kg DM concentrate per day. These levels are consistent with the energy requirements of the herd, expected grass intake of pasture and fed to meet

energy requirements. Such daily feed allowances include approximately 15 UFL to come from grass and 7 UFL to come from concentrate with typical energy requirements in early lactation of 22 UFL per day. Such early-lactation concentrate allowances have been found to be consistent with good pasture utilization in high output grazing systems. There was however, a tendency in experiment 2 for higher DMI in ZG cows, which may indicate a potentially positive relationship between the proportion of grass in the diet and DMI in zero-grazed cows compared to grazing cows. Thus, lower concentrate allowances may induce an increase in DMI in ZG cows compared to conventionally grazed cows as previously reported (van Vuuren and van den Pol-van Dasselaar, 2006; Boudon *et al.*, 2009; Dohme-Meier *et al.*, 2014).

Another reason for the tendency for a higher DMI in ZG cows in experiment 2 maybe due to the lower post grazing sward height for the grazing treatment (4.5 v. 4.6 cm for ZG and G) in comparison to experiment 1 (4.0 v. 5.3 cm for ZG and G) respectively. Previous research by Ganche *et al.* (2013) reported an effect of post grazing sward height in the first 10 weeks of lactation in Ireland on grass DMI. Albeit, the treatment differences reported were a post grazing sward height of 2.7 (severe) having an impact on grass DMI in comparison to 3.5 (low) and 4.2 (moderate), which were unaffected.

For experiment 1, all the experimental paddocks were cut and baled for grass silage in the rotation prior to the start of the experiment. The current recommendation (Agrisearch, 2018) is to avoid zero-grazing pastures grazed within the previous month in order to prevent the risk of sward contamination from dung pads left by grazing livestock. For experiment 2, the experimental paddocks were ungrazed since the previous autumn. Thus, it is unlikely a longer rest period (as was the case in experiment 2) after grazing and prior to the onset of experiment 1, instead of cutting, would have resulted in a different outcome in the results.

It is worth noting that weather conditions during both experiments 1 and 2 were unseasonably mild for those particular

periods in Ireland. In experiment 1 in autumn 2018, rainfall levels were 27% lower than the 10-year average. In addition, the average soil moisture deficit was 2.4 times higher than the 10-year average. In experiment 2 in spring 2020, rainfall was 72% lower than the 10-year average for the same period, and average soil moisture deficit was 2.5 times higher than the 10-year average. The low levels of rainfall and soil moisture provided more favourable grazing conditions than would be expected in the late autumn and early spring periods, and it is possible that less favourable conditions could have resulted in lower performance in the grazing cows. During inclement weather, grazing cows experience behavioural changes (Redbo *et al.*, 2001; Webster *et al.*, 2008), and spend less time lying and have shorter and fewer daily lying bouts when exposed to wet and cold conditions (Hendriks *et al.*, 2019). Leso *et al.* (2018) concluded that rainfall in particular reduces both lying and rumination time in grazing cows in Ireland which could have implications for milk production.

Milk production and composition were similar in experiments 1 and 2 between the ZG and G treatments, and this was likely due to DMI and sward nutritive value being similar across treatments in both experiments. While there was a tendency in experiment 2 for higher grass DMI in ZG cows, this did not significantly increase milk production or composition. There was however a tendency for ZG cows to increase BCS at a higher rate than G cows in experiment 2. While not statistically significant, this may have been caused by increased DMI or possible differences in energy expenditure between G and ZG cows, or a combination of these factors. It has been previously reported that animals at pasture walk longer distances and spend considerably more time eating and foraging for food than conventionally housed animals (Osuji, 1974), while Dohme-Meier *et al.* (2014) found that grazing cows can consume up to 19% more energy than cows fed the same herbage in the barn (Dohme-Meier *et al.*, 2014).

While housing cows indoors may offer some benefit to the animal, such as reduced exposure to extreme weather conditions (Schütz *et al.*, 2010), there are also a number of challenges associated with the housed environment. According to Arnott *et al.* (2015) confined cows typically have higher SCC and higher levels of clinical mastitis compared to grazing cows, while Haskell *et al.* (2006) reported higher risk of lameness and leg injury in confined systems. In the current study however, zero-grazing did not have an effect on SCC, with SCC across both treatments in experiments 1 and 2 averaging 64 500 and 32 000 cells/ml respectively. This is well within the target industry threshold of <200 000 cells/ml (Schukken *et al.*, 2003). Locomotion score, which is an estimate of the prevalence of lame cows in the herd (Whay, 2002), was similar for both ZG and G cows, in the current study. According to Tadich *et al.* (2010) cows with scores of 1 or 2 are not usually considered lame. Mean locomotion scores across treatments in the current study were 1.7 and 1.2 in experiments 1 and 2 respectively, which were within acceptable levels. Results from the current study suggest that good udder and hoof health can be maintained when cows are housed indoors for a short period during spring or autumn.

### Nitrogen partitioning

Large amounts (0.70–0.80) of ingested N are excreted from dairy cows, which can have a detrimental effect on the environment (Tamminga, 1992; Ryan *et al.*, 2011). A greater problem in pasture-based systems, compared with confinement systems, is that a large proportion of N is lost to the environment through

volatilization and leaching when cows are grazing outdoors (Hyde *et al.*, 2003; Casey and Holden, 2005; Ryan *et al.*, 2011). In the current study, total N excretion and N use efficiency did not significantly differ between G and ZG cows in either experiment 1 or 2. The partitioning of N into milk and urine was similar; however, the percentage of ingested N excreted in faeces was higher in ZG cows in both experiments 1 and 2. According to Huhtanen *et al.* (2008), faecal N is derived from excretion of undigested feed N, undigested microbial N and endogenous N. It is possible that the excretion of one or more of these was higher in ZG; however, it is difficult to pinpoint which, if either, was the contributory factor, particularly given that there was no significant difference between total ingested N and total excreted N. From an environmental perspective, an increased faecal:urinary N ratio is desirable in grazing cows because large amounts of ammonia in urine are lost to volatilization after a urination event as well as losses of N<sub>2</sub>O during the denitrification process (Totty *et al.*, 2013). Faecal N is also more stable than urinary N and is less susceptible to leaching (Powell *et al.*, 2009). It must be noted however, that an increased faecal:urinary N ratio may not translate to lower ammonia emissions in zero-grazed cows. According to Moraes *et al.* (2017) the enzyme urease (which is found in faeces) causes rapid conversion of urea in urine to ammonia and CO<sub>2</sub> when urine and faeces mix together on the floor surface of indoor housing. As a result, ammonia volatilization is typically higher when cows are housed indoors than grazing outdoors (Hennessy *et al.*, 2020). Advancements in manure handling such as low-emission slurry spreading may however reduce ammonia volatilization and N leaching from indoor housing.

### Blood metabolites and rumen fermentation

Measurement of blood metabolites allows for the determination of discrete differences in the energy status of cows (Al Ibrahim *et al.*, 2010). In experiment 1, blood glucose levels (averaging 3.05 mmol/l) in both treatments were above the value of 2.2 mmol/l, below which indicates hypoglycaemia (Ruoff *et al.*, 2017). Blood concentrations of NEFA (averaging 0.16 mmol/l) across both treatments were within the acceptable values of <0.6 mmol/l after calving (Adewuyi *et al.*, 2005), and were not affected by grass feeding method. Plasma concentrations of BHB in both treatments (averaging 1.0 mmol/l) were above the range of normal values which is typically between 0.1 and 0.6 mmol/l in early lactation (Raboisson *et al.*, 2014). However, according to Mulligan *et al.* (2006) the alarm level threshold for negative energy balance in lactating cows is a BHB concentration in excess of 1.4 mmol/l. Both treatment groups in experiment 1 were below this threshold. It is probable that no differences were observed in NEFA and BHB concentrations between treatments because DMI was similar and there was no difference in BW or BCS.

Rumen fluid ammonia concentrations of G and ZG cows in experiment 1 were not significantly different. Rumen ammonia concentration between both treatments averaged 8.07 mmol/l, which was just within the optimum range of 3.0–8.5 mmol/l (McDonald *et al.*, 2012). Rumen pH of 6.37 and 6.36 for ZG and G respectively indicates that both treatment groups were not experiencing acidosis at the time of sampling. According to Kleen *et al.* (2003) sub acute ruminal acidosis (SARA) occurs when rumen pH is depressed for prolonged periods each day, e.g. <5.6 for >3 h/day (Kleen *et al.*, 2003), and it has been

previously highlighted by farmers as a potential issue when using ZG (Holohan *et al.*, 2021). The occurrence of SARA in cows is linked to the feeding of high amounts of ryegrass pasture (O'Grady *et al.*, 2008), and it is likely that the percentage of fresh grass in the diet in experiment 1 (0.37 of total diet DM) was not large enough to induce acidosis. It is possible that feeding higher proportions of grass than the current study may have negative consequences for rumen pH. According to Kolver and de Veth (2002), rumen pH is positively related to pasture NDF, meaning that as NDF increases so too does rumen pH. Given that rumen pH remained unchanged between treatments in this experiment, it provides further indication that dietary NDF was similar for both treatments.

## Conclusion

The majority of dairy farmers in Ireland that use zero-grazing do so on a short-term basis in spring and autumn. While zero-grazing may enable them to supply fresh grass to early-lactation cows, in replacement of other conserved forages, this study found no additional benefits to cow performance when comparing zero-grazing to well-managed grazed grass.

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**Conflict of interest.** None.

**Ethical standards.** All procedures described in this study were approved by the Animal Research Ethics Committee (AREC) of University College Dublin (UCD) and were conducted under the experimental license from the Health Products Regulatory Authority (HPRA) under the European directive 2010/63/EU and S.I. No. 543 of 2012. Each person who carried out procedures during these experiments held an individual authorization from the HPRA.

## References

- Adewuyi A, Gruys E and van Eerdenburg F (2005) Non esterified fatty acids (NEFA) in dairy cattle. A review. *Veterinary Quarterly* **27**, 117–126.
- Agrisearch** (2018) *Zero-Grazing – A Best Practice Guide*. Hillsborough: Agrisearch.
- Al Ibrahim R, Kelly A, O'Grady L, Gath V, McCarney C and Mulligan F (2010) The effect of body condition score at calving and supplementation with *Saccharomyces cerevisiae* on milk production, metabolic status, and rumen fermentation of dairy cows in early lactation. *Journal of Dairy Science* **93**, 5318–5328.
- Allen M (2000) Effects of diet on short-term regulation of feed intake by lactating dairy cattle. *Journal of Dairy Science* **83**, 1598–1624.
- AOAC (2005) *Official Method of Analysis*, 18th edn, Washington DC: Association of Official Analytical Chemists.
- Arnott G, Ferris C and O'Connell N (2015) *A Comparison of Confinement and Grazing Systems for Dairy Cows: What Does the Science Say?* Belfast: AgriSearch.
- Bargo F, Muller L, Kolver E and Delahoy J (2003) Invited review: production and digestion of supplemented dairy cows on pasture. *Journal of Dairy Science* **86**, 1–42.
- Boudon A, Peyraud J, Faverdin P, Delagarde R, Delaby L and Chaves A (2009) Effect of rumen fill on intake of fresh perennial ryegrass in young and mature dairy cows grazing or zero-grazing fresh perennial ryegrass. *Animal* **3**, 1706–1720.
- Brereton A, Carton O and O'Keeffe W (1985) Tissue turnover in perennial ryegrass (*Lolium perenne* L.) during winter. *Irish Journal of Agricultural Research* **24**, 49–62.
- Burns G, Gilliland T, Grogan D and O'Kiely P (2011) Using chemometrics to develop near infrared spectroscopy (NIRS) calibrations to predict ryegrass quality. In *Agricultural Research Forum 2011*. Carlow: Teagasc, p. 135.
- Cameron L, Chagunda MGG, Roberts DJ and Lee MA (2018) A comparison of milk yields and methane production from three contrasting high-yielding dairy cattle feeding regimes: cut-and-carry, partial grazing and total mixed ration. *Grass and Forage Science* **73**, 789–797.
- Casey J and Holden N (2005) Analysis of greenhouse gas emissions from the average Irish milk production system. *Agricultural Systems* **86**, 97–114.
- Claffey A, Delaby L, Boland T and Egan M (2020) Implications of adapting autumn grazing management on spring herbage production – the effect on late lactation milk production and the subsequent response in early lactation animal performance. *Livestock Science* **231**.
- Dillon P, Crosse S, O'Brien B and Mayes R (2002) The effect of forage type and level of concentrate supplementation on the performance of spring-calving dairy cows in early lactation. *Grass and Forage Science* **57**, 212–223.
- Dohme-Meier F, Kaufmann L, Görs S, Junghans P, Metges C, van Dorland H and Münger A (2014) Comparison of energy expenditure, eating pattern and physical activity of grazing and zero-grazing dairy cows at different time points during lactation. *Livestock Science* **162**, 86–96.
- Dove H and Mayes R (2006) Protocol for the analysis of n-alkanes and other plant-wax compounds and for their use as markers for quantifying the nutrient supply of large mammalian herbivores. *Nature* **1**, 1680–1697.
- DuBois M, Gilles K, Hamilton J, Rebers P and Smith F (1956) Colorimetric method for determination of sugars and related substances. *Analytical Chemistry* **28**, 350–356.
- Edmonson A, Lean I, Weaver L, Farver T and Webster G (1989) A body condition scoring chart for Holstein dairy cows. *Journal of Dairy Science* **72**, 68–78.
- Ganche E, Delaby L, O'Donovan M, Boland TM, Galvin N and Kennedy E (2013) Post-grazing sward height imposed during the first 10 weeks of lactation: influence on early and total lactation dairy cow production, and spring and annual sward characteristics. *Livestock Science* **157**, 299–311.
- Gilmore H, Young F, Patterson D, Wylie G, Law R, Kilpatrick DE and Mayne C (2011) An evaluation of the effect of altering nutrition and nutritional strategies in early lactation on reproductive performance and estrous behavior of high-yielding Holstein-Friesian dairy cows. *Journal of Dairy Science* **94**, 3510–3526.
- Hanrahan L, Geoghan A, O'Donovan M, Griffith V, Ruelle E and Shaloo L (2017) PastureBase Ireland: a grassland decision support system and national database. *Computers and Electronics in Agriculture* **136**, 193–201.
- Hanrahan L, McHugh N, Hennessy T, Moran B, Kearney R, Wallace M and Shaloo L (2018) Factors associated with profitability in pasture-based systems of milk production. *Journal of Dairy Science* **101**, 5474–5485.
- Haskell M, Rennie L, Bowell V, Bell M and Lawrence A (2006) Housing system, milk production, and zero-grazing effects on lameness and leg injury in dairy cows. *Journal of Dairy Science* **89**, 4259–4266.
- Hendriks S, Phyn CVC, Turner S, Mueller KR, Kuhn-Sherlock B, Donaghy D, Huzzey JM and Roche J (2019) Effect of weather on activity and lying behaviour in clinically healthy grazing dairy cows during the transition period. *Animal Production Science* **60**, 148–153.
- Hennessy D, Delaby L, van den Pol-van Dasselaar A and Shaloo L (2020) Increasing grazing in dairy cow milk production systems in Europe. *Sustainability* **12**, 1–15.
- Holohan C, Russell T, Mulligan F, Pierce K and Lynch M (2021) A survey analysis of farmer practices and perceptions of zero-grazing on Irish dairy farms. *Journal of Dairy Science* **104**, 5665–5674.
- Huhtanen P, Nousiainen J, Rinne M, Kytölä K and Khalili H (2008) Utilization and partition of dietary nitrogen in dairy cows fed grass silage-based diets. *Journal of Dairy Science* **91**, 3589–3599.
- Hyde B, Carton O, O'Toole P and Misselbrook T (2003) A new inventory of ammonia emissions from Irish agriculture. *Atmospheric Environment* **37**, 55–62.

- Jorritsma R, Wensing T, Krui A, Lam P, Vos J and Noordhuizen P (2003) Metabolic changes in early lactation and impaired reproductive performance in dairy cows. *Veterinary Research* **34**, 11–26.
- Jouany J (2006) Optimizing rumen functions in the close-up transition period and early lactation to drive dry matter intake and energy balance in cows. *Animal Reproduction Science* **96**, 250–264.
- Kennedy E, O'Donovan M, Murphy J, Delaby L and O'Mara F (2005) Effects of grass pasture and concentrate-based feeding systems for spring-calving dairy cows in early spring on performance during lactation. *Grass and Forage Science* **60**, 310–318.
- Kennedy E, Lewis E, Murphy J, Galvin N and O'Donovan M (2015) Production parameters of autumn-calving cows offered either a total mixed ration or grazed grass plus concentrate during early lactation. *Journal of Dairy Science* **98**, 7917–7929.
- Kleen J, Hooijer G, Rehage J and Noordhuizen J (2003) Subacute ruminal acidosis (SARA): a review. *Journal of Veterinary Medicine. A, Physiology, Pathology, Clinical Medicine* **50**, 406–414.
- Kolver E and de Veth M (2002) Prediction of ruminal pH from pasture-based diets. *Journal of Dairy Science* **85**, 1255–1266.
- Leso L, O'Leary N, Werner J, Kennedy E, Geoghegan A and Shalloo L (2018) Associations between cow behaviour at pasture, weather conditions and day length. *Sustainable meat and milk production from grasslands. Proceedings of the 27th General Meeting of the European Grassland Federation*, Cork, Ireland, pp. 870–872. Available at [https://www.european-grassland.org/fileadmin/documents/Infos/Printed\\_Matter/Proceedings/EGF2018.pdf#page=717](https://www.european-grassland.org/fileadmin/documents/Infos/Printed_Matter/Proceedings/EGF2018.pdf#page=717).
- McDonald P, Edwards R, Greenhalgh J, Morgan C, Sinclair L and Wilkinson R (2012) *Animal Nutrition*, 7th Edn. Harlow: Prentice Hall.
- McEvoy M, Kennedy E, Murphy J, Boland T, Delaby L and O'Donovan M (2008) The effect of herbage allowance and concentrate supplementation on milk production performance and dry matter intake of spring-calving dairy cows in early lactation. *Journal of Dairy Science* **91**, 1258–1269.
- Met Éireann (2022) *Past Weather Statements*. Ireland: Met Éireann. 26 February 2022. Available at <https://www.met.ie/climate/past-weather-statements>.
- Mohammed R, Stanton C, Kennelly J, Kramer JM, Glimm D, O'Donovan M and Murphy J (2009) Grazing cows are more efficient than zero-grazed and grass silage-fed cows in milk rumenic acid production. *Journal of Dairy Science* **92**, 3874–3893.
- Moraes L, Burgos S, DePeters E, Zhang R and Fadel JG (2017) Short communication: urea hydrolysis in dairy cattle manure. *Journal of Dairy Science* **100**, 2388–2394.
- Mulligan F and Doherty M (2008) Production diseases of the transition cow. *The Veterinary Journal* **176**, 3–9.
- Mulligan F, Dillon P, Callan J, Rath M and O'Mara F (2004) Supplementary concentrate type affects nitrogen excretion of grazing dairy cows. *Journal of Dairy Science* **87**, 3451–3460.
- Mulligan F, O'Grady L, Rice D and Doherty M (2006) A herd health approach to dairy cow nutrition and production diseases of the transition cow. *Animal Reproduction Science* **96**, 331–353.
- O'Donovan M and McEvoy M (2016) Managing your grass. In *Teagasc Dairy Manual*. Carlow: Teagasc, pp. 227–238.
- O'Donovan M, Geoghegan A, Hennessy D and O'Leary M (2015) Lessons from PastureBase Ireland – improving our focus on spring grass. *Proceedings from the Irish Grassland Association Dairy Conference*, Limerick, Ireland, pp. 5–22.
- O'Grady L, Doherty M and Mulligan F (2008) Subacute ruminal acidosis (SARA) in grazing Irish dairy cows. *The Veterinary Journal* **176**, 44–49.
- Oshita T, Sudo K, Nonaka K, Kume S and Ochiai K (2008) The effect of feed regimen on chewing time, digesta passage rate and particle size distribution in Holstein non-lactating cows fed pasture ad libitum. *Livestock Science* **113**, 243–250.
- Osuji P (1974) The physiology of eating and the energy expenditure of the ruminant at pasture. *Journal of Range Management* **27**, 437–443.
- Powell J, Broderick G, Grabber J and Hymes-Fecht U (2009) Effects of forage protein-binding polyphenols on chemistry of dairy excreta. *Journal of Dairy Science* **92**, 1765–1769.
- Raboisson D, Mounié M and Maigné E (2014) Diseases, reproductive performance, and changes in milk production associated with subclinical ketosis in dairy cows: a meta-analysis and review. *Journal of Dairy Science* **97**, 7547–7563.
- Redbo I, Ehrlemark A and Redbo-Torstensson P (2001) Behavioural responses to climatic demands of dairy heifers housed outdoors. *Canadian Journal of Animal Science* **81**, 9–15.
- Roche J, Berry D, Bryant A, Burke C, Butler S, Dillon P, Donaghy DJ, Horan B, Macdonald KA and Macmillan K (2017) A 100 year review: a century of change in temperate grazing systems. *Journal of Dairy Science* **100**, 10189–10233.
- Ruoff J, Borchardt S and Heuwiese W (2017) Short communication: associations between blood glucose concentration, onset of hyperketonemia, and milk production in early lactation dairy cows. *Journal of Dairy Science* **100**, 5462–5467.
- Ryan W, Hennessy D, Murphy J, Boland T and Shalloo L (2011) A model of nitrogen efficiency in contrasting grass-based dairy systems. *Journal of Dairy Science* **94**, 1032–1044.
- Schukken Y, Wilson D, Welcome F, Garrison-Tikofsky L and Gonzalez R (2003) Monitoring udder health and milk quality using somatic cell counts. *Veterinary Research* **34**, 579–596.
- Schütz K, Clark K, Cox N, Matthews L and Tucker C (2010) Responses to short-term exposure to simulated rain and wind by dairy cattle: time budgets, shelter use, body temperature and feed intake. *Animal Welfare* **19**, 375–383.
- Soyeurt H, Dardenne P, Dehareng F, Lognay G, Veselko D, Marlier M, Bertozzi C, Mayeres P and Gengler N (2006) Estimating fatty acid content in cow milk using mid-infrared spectrometry. *Journal of Dairy Science* **89**, 3690–3695.
- Sprecher D, Hostetler DE and Kaneene J (1997) A lameness scoring system that uses posture and gait to predict dairy cattle reproductive performance. *Theriogenology* **47**, 1179–1187.
- Tadich N, Flor E and Green L (2010) Associations between hoof lesions and locomotion score in 1098 unsound dairy cows. *The Veterinary Journal* **184**, 60–65.
- Tamminga S (1992) Nutrition management of dairy cows as a contribution to pollution control. *Journal of Dairy Science* **75**, 345–357.
- Tilley J and Terry R (1963) A two-stage technique for the in vitro digestion of forage crops. *Grass and Forage Science* **18**, 104–111.
- Totty V, Greenwood S, Bryant R and Edwards G (2013) Nitrogen partitioning and milk production of dairy cows grazing simple and diverse pastures. *Journal of Dairy Science* **96**, 141–149.
- Tyrrell HF and Reid JT (1965) Prediction of the energy value of cow's milk. *Journal of Dairy Science* **48**, 1215–1223.
- Van Soest P, Robertson J and Lewis B (1991) Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *Journal of Dairy Science* **74**, 3583–3597.
- van Vuuren A and van den Pol-van Dasselara A (2006) Grazing systems and feed supplementation. In Elgersma A, Dijkstra J and Tamminga S (eds), *Fresh Herbage for Dairy Cattle*. Wageningen: Springer, pp. 85–101.
- Weatherburn M (1967) Phenol-hypochlorite reaction for determination of ammonia. *Analytical Chemistry* **39**, 971–974.
- Webster J, Stewart M, Rogers A and Verkerk G (2008) Assessment of welfare from physiological and behavioural responses of New Zealand dairy cows exposed to cold and wet conditions. *Animal Welfare* **17**, 19–26.
- Whay H (2002) Locomotion scoring and lameness detection in dairy cattle. *In Practice* **24**, 444–449.
- Wilkinson M, Lee M, Rivero J and Chamberlain T (2019) Some challenges and opportunities for grazing dairy cows on temperate pastures. *Grass and Forage Science* **75**, 1–17.