

## Crops and Soils Research Paper

**Cite this article:** Holohan C, Grace C, Bock M, Lynch MB (2022). An assessment of herbage mass, ryegrass cultivar and red clover inclusion on sward productivity, quality and morphology under a cutting protocol. *The Journal of Agricultural Science* **160**, 55–65. <https://doi.org/10.1017/S0021859622000041>

Received: 30 June 2021

Revised: 7 January 2022

Accepted: 12 February 2022

First published online: 21 April 2022


### Key words:

Cut and carry; Nutritive value; Digestibility; Hybrid ryegrass; Perennial ryegrass

### Author for correspondence:

M. B. Lynch, E-mail: [bridget.lynch@teagasc.ie](mailto:bridget.lynch@teagasc.ie)

# An assessment of herbage mass, ryegrass cultivar and red clover inclusion on sward productivity, quality and morphology under a cutting protocol

C. Holohan<sup>1</sup> , C. Grace<sup>2</sup>, M. Bock<sup>1</sup> and M. B. Lynch<sup>1,3</sup>

<sup>1</sup>School of Agriculture and Food Science, University College Dublin, Lyons Farm, Lyons Estate, Celbridge, Naas, Co. Kildare, Ireland; <sup>2</sup>Devenish Nutrition, Dowth, Co. Meath, Ireland and <sup>3</sup>Teagasc, Environment Research Centre, Johnstown Castle, Wexford, Ireland

## Abstract

The use of ‘cut-and-carry’ (the mechanical harvesting and feeding of fresh grass) has increased in some temperate regions in recent years and evidence suggests that sward management practices in this system differ to conventional grazing. In order to investigate this further, a  $2 \times 3 \times 2$  factorial experiment was used to examine the effect of low (1489 kg dry matter (DM)/ha; LHM) and high (2142 kg DM/ha; HHM) pre-cutting herbage mass; three ryegrass cultivars, diploid perennial ryegrass (*Lolium perenne*; DIP), tetraploid perennial ryegrass (TET) and a hybrid ryegrass (*Lolium multiflorum*  $\times$  *L. perenne*; HY); and the inclusion of red clover (*Trifolium pratense*) on sward herbage production, nutritive value and ryegrass morphology. Plots were harvested according to herbage mass from March to November in 2018 and 2019. Annual DM production was 1489 kg DM/ha higher in HHM than in LHM swards. Pre-cutting herbage mass had no effect on organic matter digestibility (OMD) in early season for DIP and TET swards or in late season for all cultivars. There was an interaction between ryegrass cultivar and clover inclusion in annual yield whereby red clover increased DM production in all cultivars however, its effect was largest in HY swards. Red clover inclusion increased DM production but reduced OMD in early and mid-seasons. Overall, TET swards were lowest in neutral detergent fibre and highest in OMD compared to HY and DIP. Pre-cutting herbage mass, ryegrass cultivar and red clover inclusion require careful consideration when establishing and managing pastures in cut-and-carry systems.

## Introduction

In temperate regions such as Ireland, grazed pasture provides a comparatively low-cost, high-quality and sustainable diet for dairy cows, and farmers are encouraged to make as much use as possible of the large amounts of pasture that can be grown (Läpple *et al.*, 2012; O’Brien and Hennessy, 2017). The variable and seasonal nature of pasture growth and quality, however, is a significant challenge to pasture-based farming in temperate regions (Roche *et al.*, 2017). Low growth rates under winter and sporadic drought conditions mean that pasture supply in late autumn, early spring and mid-summer is often not sufficient to meet herd demand. To overcome this, an increasing number of farmers in temperate regions are choosing to incorporate cut-and-carry into their farming systems whereby fresh pasture is cut and fed directly to housed cows (Holohan *et al.*, 2021). Typically this is carried out using a tractor and integrated mower-wagon, and enables farmers to increase the quantity of fresh pasture available to the herd throughout the growing season. Pasture can be harvested ten or more times between early spring and late autumn, which is distinctly different from other cutting systems in which swards are normally harvested 1–3 times per year for ensiled forage production.

According to a survey conducted by Holohan *et al.* (2021) farmers who cut-and-carry require further knowledge on pasture productivity and agronomy practices specifically relating to swards used for cut-and-carry. Their survey also found that the pasture management practices being implemented on farms using cut-and-carry was different from that of best practice conventional grazing (O’Donovan and McEvoy, 2016). The most evident deviation was pre-cutting herbage mass, which ranged from 1350 to 2500 kg dry matter (DM)/ha (>4 cm) (average 1785 kg DM/ha) which is higher than the 1300–1600 kg DM/ha recommended pre-grazing cover for conventional grazing of perennial ryegrass (PRG) swards (O’Donovan and McEvoy, 2016). According to Holohan *et al.* (2021) the two main reasons farmers choose cut-and-carry at higher herbage mass swards were (i) to reduce the distance travelled in the field, particularly when cutting on heavy soils and/or steep gradients, and (ii) to achieve good pasture utilization without impacting cow performance or pasture productivity. While numerous studies (Curran *et al.*, 2010, 1650–2480 kg DM/ha; McEvoy *et al.*, 2009, 1780–2360 kg DM/ha; O’Donovan and

© The Author(s), 2022. Published by Cambridge University Press. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted re-use, distribution and reproduction, provided the original article is properly cited.

**CAMBRIDGE**  
UNIVERSITY PRESS

Delaby, 2008, 2365–3100 kg DM/ha) have investigated the impact of pre-grazing herbage mass on DM intake and milk production of grazing dairy cows, there is little information available in the literature on the effect of varying levels of pre-cutting herbage mass on both pasture production and quality in a cut-and-carry system where grass is mechanically harvested multiple times throughout the year. In terms of sward nutritive value, the aforementioned studies by Curran *et al.* (2010), McEvoy *et al.* (2009) and O'Donovan and Delaby (2008) found that as herbage mass increases, pasture organic matter digestibility (OMD) typically decreases. This reduction in quality has been partly attributed to higher post grazing sward heights in high pre-cutting herbage mass swards which reduces pasture quality in subsequent grazing rotations. The key difference in using cut-and-carry as opposed to conventional grazing in this regard is that swards are consistently cut to the target 4 cm residual, and this may offer potential for farmers to utilize higher herbage mass swards without any negative carryover effects on pasture quality.

Holohan *et al.* (2021) highlighted a knowledge gap regarding the identification of suitable sward species for use in cut-and-carry systems. Ryegrass species and cultivars can vary in terms of their morphology (Beecher *et al.*, 2013), annual and seasonal yield and nutritive value (O'Donovan *et al.*, 2017), and these are important considerations when selecting the appropriate sward type for cut-and-carry. In addition, there is interest in the inclusion of red clover (*Trifolium pratense*) in swards for cut-and-carry due to its upright growth habit and potential to reduce chemical nitrogen input. Use of forage legumes reduces the reliance on imported high-protein feeds and N fertilizer as they are rich in protein and fix atmospheric N (Lüscher *et al.*, 2014; Phelan *et al.*, 2015). As cut-and-carry is typically carried out on external land parcels (often several kilometres away from the farmyard), a reduction in chemical fertilizer spreading may also lead to a reduction in labour and fuel costs associated with travelling to and from these land parcels to apply fertilizer. In addition, freshly cut red clover has been shown by Lee *et al.* (2009) to increase milk yield and milk protein percentage in zero-grazed dairy cows when compared to PRG. It also offers higher forage yield potential and is faster to establish than white clover (Black *et al.*, 2009; Eriksen *et al.*, 2014). Considering the potential that it may offer, the use of mixed ryegrass–red clover swards for cut-and-carry warrants investigation.

The objective of this experiment was to determine the cumulative effect of pre-cutting herbage mass, ryegrass cultivar and red clover inclusion on herbage production, nutritive value and sward morphology when assessed under a cutting protocol for two consecutive growing seasons. The hypotheses of the study were that (a) swards cut at high pre-cutting herbage mass would have higher DM production but may have a higher percentage of stem and lower sward nutritive value; (b) DM production would be highest in hybrid ryegrass, followed by tetraploid ryegrass and diploid ryegrass and (c) clover containing swards would have higher DM production than ryegrass-only swards.

## Materials and methods

### Experimental site preparation

The current study was undertaken at University College Dublin Lyons Farm (53°18'N, 6°32'W, elevation approximately 80 m above sea level). The soil type of the experimental site was a clay loam, classified as a grey brown podzolic soil (Lalor, 2004).

The soil had a pH of 7.3 with Morgan's extractable phosphorus (P) and potassium (K) levels of 7.54 and 51.5 mg/l, respectively. During the previous 4 years, a mixture of perennial ryegrass and red clover had been grown at the site.

In preparation for sowing, the site was sprayed with glyphosate at a rate of 3.0 l/ha (Roundup; Monsanto Meath) to remove the previous PRG and red clover sward and any perennial weeds. It was then ploughed to a depth of 25 cm 3 weeks after herbicide application and tilled using a power-harrow. The seed bed had 10:10:20 fertilizer applied at a rate of 43 kg of nitrogen (N), 43 kg phosphorous (P) and 86 kg potassium (K) per ha, respectively, and was applied uniformly across the experimental site. The seed bed was consolidated using a flat roller after sowing.

### Experimental design

A 2 × 3 × 2 factorial plot experiment was used to investigate the effect of two pre-cutting herbage mass treatments, three ryegrass cultivars and the inclusion of red clover in the sward. The two pre-cutting herbage mass treatments were high herbage mass (1500 kg DM/ha; HHM) and low herbage mass (2000 kg DM/ha; LHM). The three ryegrass cultivars were diploid perennial ryegrass (*Lolium perenne*; Aberchoice; DIP), tetraploid perennial ryegrass (Abergain; TET) and tetraploid hybrid ryegrass (*Lolium multiflorum* × *L. perenne*; Aberecho; HY). These cultivars were selected based on their performance in the Irish Recommended List (DAFM, 2017), in which Aberchoice and Abergain were the highest ranked late-heading diploid and tetraploid ryegrasses respectively in terms of pasture profit index, while Aberecho was the highest ranked hybrid ryegrass on nutritive value. The two clover treatments were ryegrass-only (GO) and ryegrass-red clover (*T. pratense*; Aberchiant; RC). This is a diploid red clover cultivar bred for enhanced persistence under cutting and grazing. The LHM plots were cut at 1489 kg DM/ha ( $n = 24$ , S.D. = 214) and HHM plots were cut at 2142 kg DM/ha ( $n = 24$ , S.D. = 342). Each treatment combination was replicated four times, meaning there were 48 plots in total with each measuring 1.1 m × 7 m (7.7 m<sup>2</sup>). Plots were arranged in a completely randomized block design as per Grace *et al.* (2019). Plots were sown on 19th September 2017 using a plot seeder (Wintersteiger, Ried im Innkreis, Austria) and the monoculture seeding rate for each of the ryegrass cultivars used was as follows: DIP = 34.6 kg/ha, TET = 39.5 kg/ha and HY = 35.0 kg/ha. In the RC swards, ryegrass seeding rates were reduced by 9.7 kg/ha to accommodate the recommended 9.7 kg/ha seeding rate for red clover. The plot seeder was set to sow both grass and clover seeds to a depth of 10 mm and coulter spacing was 50 mm. Germination rates were >90% across each of the three ryegrass cultivars and the red clover cultivar used.

### Harvesting and nutrient management

The study was conducted over two growing seasons (March–November inclusive for 2018 and 2019). Experimental plots were harvested using a Haldrup (Løgstør, Denmark) forage harvester as soon as mean herbage mass across all plots reached the desired target for LHM and HHM treatments (measured non-destructively prior to harvesting by a rising plate meter; Jenquip, New Zealand). Plate meter accuracy was calibrated by comparing readings with actual herbage yield as measured by the Haldrup harvester. The cutting height was mechanically set on the Haldrup harvester at 4 cm to mimic a commercial cut-and-carry

machine. The LHM plots were harvested a total of ten times in 2018 and nine times in 2019, while the HHM plots were harvested eight times in both 2018 and 2019. Fertilizer was applied using a FIONA probe (Fiona Maskinfabrik A/S, DK 5400) following defoliation. Nitrogen fertilizer was applied in equal amounts before harvest 1 and after all subsequent harvests at an annual rate of 250 kg N/ha/year to mimic a conventional high input fertilizer regime. Nitrogen was applied in the form of granulated urea (460 g N/kg) in January, February, March and April and as calcium ammonium nitrate (CAN: 270 g N/kg, 80 g Ca/kg) thereafter. Phosphorous (superphosphate: 160 g P/kg, 110 g S/kg, 210 g Ca/kg) and K (muriate of potash 500 g K/kg) were applied as per recommendations from Wall and Plunkett (2016), at 60 kg P/ha and 375 kg K/ha respectively to ensure P and K were non-limiting.

### Herbage measurements

#### Annual and seasonal DM production

Plots were firstly harvested and a fresh weight yield of each was recorded. A 250 g (fresh weight) sample of herbage was then taken and dried at 45°C for 72 h for DM determination, which was subsequently used to calculate DM yield of each plot. Annual and seasonal cumulative DM production was determined by summing the appropriate pre-cutting herbage mass from each harvest each year. The harvest year was divided into early season (March–May), mid-season (June–August) and late season (September–November).

#### Herbage quality analysis

The dried sample used for DM determination was milled through a 1 mm screen using a hammer mill (Lab Mill, Christy Turner Ltd., Ipswich, UK). Samples from each plot in 2018 and 2019 were later pooled into early, mid and late seasons based on harvest date and according to DM yield of each harvest. The DM content of samples was determined after drying overnight at 105°C (16 h minimum). The ash content was determined following combustion in a muffle furnace (Nabertherm GmbH, Lilienthal, Germany) at 550°C for 5.5 h. The N content of samples was determined by combustion on Leco and crude protein (CP) content calculated ( $N \times 6.25$ ; FP 528 Analyser, Leco Corp., St. Joseph, MI). Neutral detergent fibre (NDF) and acid detergent fibre (ADF) were determined using the method of Van Soest *et al.* (1991) adapted for use in the Ankom 220 Fibre Analyser (Ankom Technology, Macedon, NY). Samples were not subjected to combustion after fibre extraction; therefore, the values reported include ash. The concentration of water soluble carbohydrate (WSC) was determined as described by DuBois *et al.* (1956), while OMD was determined using a modified method of Tilley and Terry (1963) for use in the Ankom Daisy Incubator (Ankom Technology).

#### Plant morphology and clover content

Grab samples were taken from every plot post-harvesting on one occasion in each season (early, mid and late) for both years of the experiment. Samples (30 g fresh weight) were stored in a cold room (4°C) and separated within 48 h of collection. The sample was manually separated into leaf, pseudostem, true stem and dead as per Beecher *et al.* (2013). Leaf blades were detached from the base of the pseudostem or true stem. Leaf sheaths were separated from the true stem and defined and included in the pseudostem fraction. Inflorescences, if present,

were included as true stem. Dead matter was defined as any senesced material that was yellow/brown in colour. The leaf, pseudostem, true stem and dead samples were weighed fresh and oven-dried to determine DM content. Similarly, clover content was measured once in each season (early, mid and late) for both years of the experiment. A 200 g grab sample was taken from each harvested plot and clover, ryegrass and any other fractions (i.e. weeds or dead material) were manually separated. These were weighed fresh and oven-dried to determine DM content.

### Meteorological data

Meteorological data including mean air and soil temperature (°C), mean rainfall (mm/day) and total rainfall for the year were recorded for the duration of the experiment at Casement Aerodrome (53.30°N, 6.44°W), approximately 5.8 km east of Lyons Farm, by the Irish Meteorological Service.

Mean monthly rainfall and air temperature during the experiment and the 10-year average for the experimental site are presented in Table 1. Annual rainfall was 20% lower than the previous 10-year average in 2018 and 6% higher in 2019. Monthly rainfall for 2018 was substantially lower than average for May through to October inclusive, with average rainfall for this 6-month period 53% lower than the 10-year average. Mean monthly air temperatures were below the 10-year average in February and March of 2018 however, temperatures were similar to the long-term mean thereafter. Average soil temperature at 100 mm was higher in 2018 for May, June, July and August than for both 2019 and the 10-year average.

### Statistical analysis

The data were analysed as a  $2 \times 3 \times 2$  factorial using the GLM procedure of the SAS (version 9.4; SAS Inst. Inc.). Individual plot served as the experimental unit. Residuals of data distributions were analysed to fit the assumptions of normality using the UNIVARIATE procedure. All residuals of data distributions were normal and therefore transformations were not required. The statistical model used for all parameters included the fixed effects of cultivar, pre-cutting herbage mass, red clover inclusion and year and the associated interactions. The model used for all variables included year and season as fixed effects and plot as a random effect. Statistically significant differences between least squares means were tested using the PDIF command incorporating the Tukey's test for pairwise comparison of treatment means. All data presented are expressed as least squares means  $\pm$  standard error or estimate (S.E.E.). The probability value which denotes statistical significance is  $P \leq 0.05$ .

## Results

### Herbage production

The effect of pre-cutting herbage mass, ryegrass cultivar and red clover inclusion on annual and seasonal DM production are presented in Table 2. Overall DM production was higher in year 1 than year 2 (15.6 tonnes DM/ha *v.* 13.7 tonnes DM/ha;  $P < 0.01$ ). This reduction in yield was most evident in the ryegrass-only swards which decreased by 3.0 tonnes DM/ha between years 1 and 2, in comparison with the ryegrass–red

**Table 1.** Total monthly rainfall, mean daily air temperature and mean daily soil temperature (at 100 mm) at the Casement Aerodrome weather station for 2018 and 2019 and the previous 10-year (2008–2017) average

	Total rainfall (mm)			Average air temperature (°C)			Average soil temperature (°C)		
	2018	2019	10-year mean	2018	2019	10-year mean	2018	2019	10-year mean
Jan	91.5	33.1	66.5	5.2	5.2	4.9	4.5	5.6	4.9
Feb	25.8	22.2	53.9	3.4	7.2	5.1	3.3	6.2	5.1
Mar	69.1	86.2	50.6	4.5	7.1	6.2	4.7	7.3	6.2
Apr	76.1	69.1	47.6	8.5	8.4	8.2	9.2	9.4	8.2
May	16.8	26.8	62.8	12.0	10.9	11.1	14.6	13.2	11.1
Jun	18.5	92.5	72.7	15.5	12.9	13.7	19.2	14.8	13.7
Jul	30.1	46.7	67.8	16.8	16.3	15.4	20.5	18.6	15.4
Aug	43.3	113	81.2	15.6	15.6	14.8	17.2	16.8	14.8
Sep	37.0	108.7	64.1	12.3	13.0	13.0	13.5	14.5	13.0
Oct	56.0	74.2	81.9	9.2	9.1	10.5	9.8	9.7	10.5
Nov	104.6	143.5	88.5	8.3	6.0	6.9	7.4	6.4	6.9
Dec	88.9	49.3	81.1	7.9	6.1	5.0	7.1	5.2	5.0
Average/total	657.7	865.3	818.6	9.9	9.8	9.6	10.9	10.6	9.6

clover swards which decreased by 792 kg DM/ha. There was an interaction between ryegrass cultivar and red clover ( $P < 0.01$ ) in annual DM production, whereby the addition of red clover to the sward increased DM production in HY more than DIP or TET. Regarding pre-cutting herbage mass, HHM swards produced 1489 kg DM/ha more than LHM swards annually ( $P < 0.001$ ).

In mid and late seasons there was an interaction between red clover and ryegrass cultivar ( $P < 0.05$ ), which resulted in an increase in DM production in HY compared to DIP and TET when red clover was included in the sward. There was also an interaction between herbage mass and red clover inclusion in late season DM production ( $P < 0.01$ ), whereby the addition of red clover resulted in a greater increase in DM production in HHM swards than LHM swards. There was a significant effect of ryegrass cultivar on early season DM production ( $P < 0.01$ ). The HY ryegrass produced more herbage than the DIP (+333 kg DM/ha) and TET (+168 kg DM/ha) perennial ryegrass varieties. Herbage mass had a significant effect in mid-season ( $P < 0.01$ ) with HHM swards yielding 614 kg DM/ha more than LHM swards.

### Ryegrass morphology and sward clover content

The effects of pre-cutting herbage mass, clover and ryegrass cultivar on seasonal leaf, pseudostem, true stem and dead content are presented in Fig. 1. There was an effect of year ( $P < 0.001$ ) on leaf, true stem, dead and clover percentage.

#### Leaf

Herbage mass had a significant effect in early season ( $P < 0.001$ ) with LHM swards having higher leaf percentage than HHM. Ryegrass cultivar had a significant effect in early season ( $P < 0.001$ ), with leaf percentage similar in DIP and TET but lower in HY. In late season TET had a higher leaf percentage, than HY and DIP ( $P < 0.001$ ).

#### Pseudostem

Herbage mass had a significant effect in early season ( $P < 0.001$ ), with pseudostem higher in HHM swards compared to LHM swards. Ryegrass cultivar also had an effect in early season ( $P < 0.001$ ), with pseudostem percentage highest in HY, and lowest in DIP.

#### True stem

Herbage mass had a significant effect in mid-season ( $P < 0.05$ ) with HHM swards having more true stem than LHM. In early and mid-seasons ryegrass cultivar had a significant effect ( $P < 0.001$ ), with HY having the highest true stem percentage, and DIP and TET similar to each other.

#### Dead material

Herbage mass had a significant effect on the percentage of dead material in the sward ( $P < 0.05$ ), with HHM swards having a higher percentage of dead material in mid and late seasons. Ryegrass cultivar also had a significant effect on dead material ( $P < 0.001$ ), with DIP swards having the highest percentage of dead material in mid and late seasons.

#### Clover

The effects of pre-cutting herbage mass and ryegrass cultivar on seasonal clover content are presented in Fig. 2. Herbage mass had a significant effect on early, mid and late season clover percentage ( $P < 0.05$ ), with clover content highest in HHM swards in early season, and highest in LHM swards in mid and late seasons. Ryegrass cultivar also had a significant effect on mid and late season clover percentage ( $P < 0.05$ ), with HY swards having higher clover content than DIP and TET, which were similar. Average sward clover content across all treatments increased from 9.5% in year 1 to 21% in year 2. Clover content varied between LHM and HHM swards in year 1 (12 v. 7% respectively), however in year 2 LHM and HHM swards both had a clover content of 21%.



**Table 2.** Effect of pre-cutting herbage mass, ryegrass cultivar and red clover inclusion on annual and seasonal DM production (kg DM/ha; least square means  $\pm$  S.E.E.)

Time period	Herbage mass (HM)		Ryegrass cultivar (RT)				Red clover inclusion (CL)				Level of significance					
	High	Low	S.E.E.	DIP	TET	HY	S.E.E.	GO	RC	S.E.E.	HM	RT	CL	HM $\times$ RT	HM $\times$ CL	RT $\times$ CL
Annual	15 381	13 892	160.21	14 453 <sup>a</sup>	14 348 <sup>a</sup>	15 236 <sup>b</sup>	196.21	13 879	15 480	160.21	***	***	***	NS	NS	**
Early season	6961	7001	81.03	6815 <sup>a</sup>	6980 <sup>a</sup>	7148 <sup>b</sup>	99.24	6985	6977	81.03	NS	**	NS	NS	NS	NS
Mid-season	4456	3824	75.56	4047 <sup>a</sup>	3825 <sup>b</sup>	4548 <sup>c</sup>	96.68	3703	4577	78.94	***	***	***	NS	NS	***
Late season	3964	3152	62.18	3591	3543	3540	76.15	3191	3925	68.02	***	NS	***	NS	**	*

DIP, diploid perennial ryegrass; TET, tetraploid perennial ryegrass; HY, hybrid ryegrass; GO, ryegrass-only sward; RC, ryegrass-red clover sward; CL, clover inclusion; HM, herbage mass; S.E.E., standard error of estimate. Within rows, means with differing superscripts (a–c) differ significantly. Tukey's test used for post-hoc means comparisons.

### Sward nutritive value

The effects of pre-cutting herbage mass, ryegrass cultivar and red clover on seasonal nutritive value are presented in Table 3. Year had an effect ( $P < 0.01$ ) on all sward nutritive value characteristics.

### Dry matter

DM content was highest in LHM swards in early and late seasons, while it was highest in HHM swards in mid-season ( $P < 0.04$ ). In terms of ryegrass cultivar, DM was highest in DIP and lowest in HY swards across all seasons ( $P < 0.001$ ). Red clover inclusion had a significant effect on mid and late season DM ( $P < 0.001$ ), whereby ryegrass-only swards were higher in DM content than ryegrass-red clover swards.

### Crude protein

There was an interaction between ryegrass cultivar and red clover ( $P < 0.001$ ) in mid and late seasons, with the effect of red clover on CP greatest in HY swards and similar in DIP and TET swards. There was also an interaction between herbage mass and red clover in mid-season ( $P < 0.001$ ), whereby the effect of red clover inclusion on CP content was greater in HHM than LHM swards. In addition there was an interaction between herbage mass and ryegrass cultivar in early season ( $P < 0.001$ ). While TET and HY swards had lower CP when cut at HHM, CP levels in DIP swards were similar when cut at LHM or HHM. There was an effect of herbage mass in late season ( $P < 0.001$ ), with LHM swards having higher CP content than HHM (206 v. 201 g/kg DM). Red clover inclusion increased sward CP content by 3.6% ( $P < 0.004$ ).

### Ash

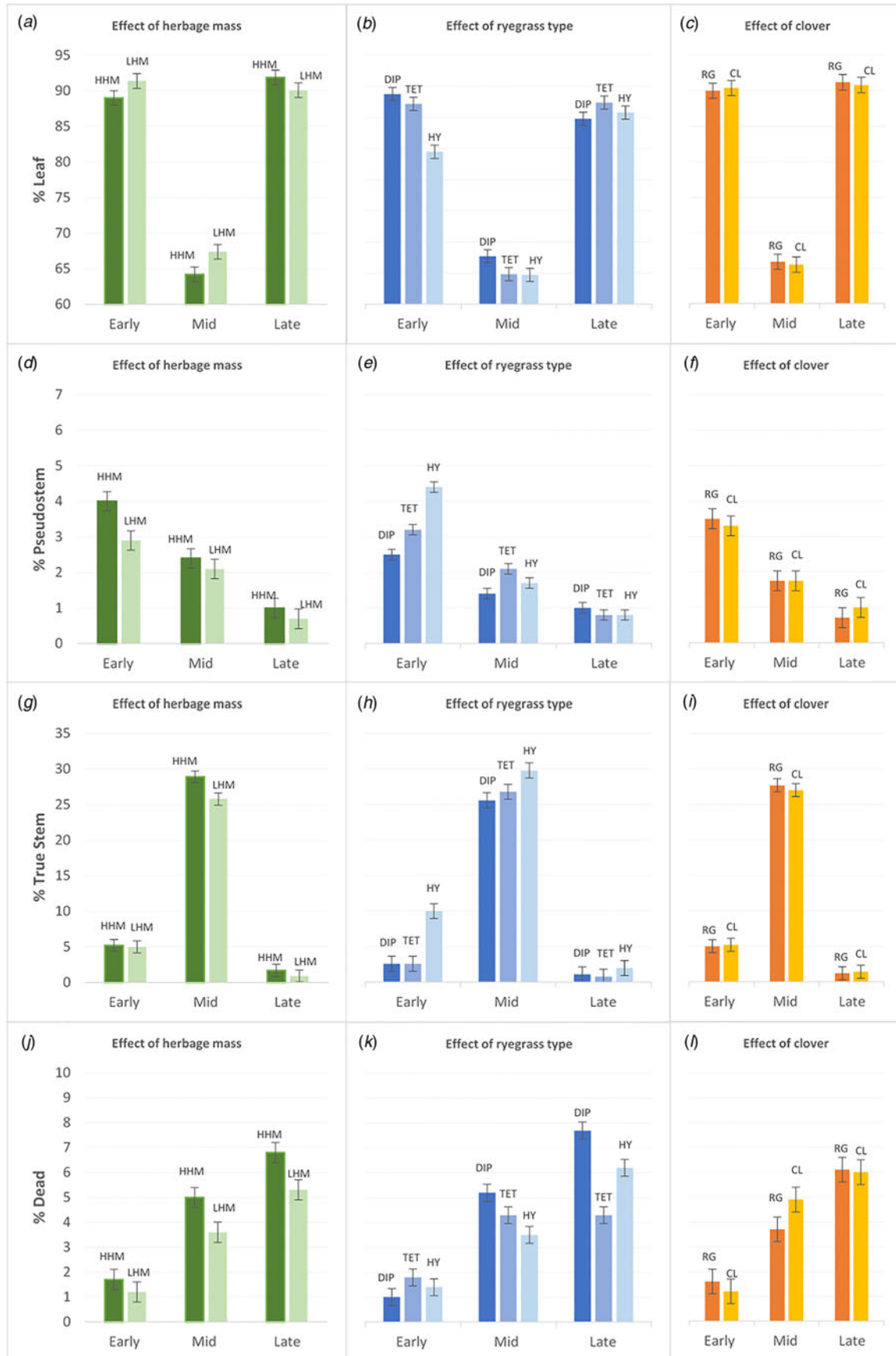
The LHM swards had lower ash content in mid ( $P < 0.001$ ) and late seasons ( $P = 0.002$ ). There was a significant effect of ryegrass cultivar on ash content in all seasons ( $P < 0.001$ ). In early and late seasons, TET and HY swards were similar while DIP swards had significantly lower ash content. In early season, all three ryegrass cultivars were different from each other, with DIP swards having the lowest ash content and HY having highest. The inclusion of red clover increased ash content in mid and late seasons ( $P < 0.001$ ).

### Neutral detergent fibre

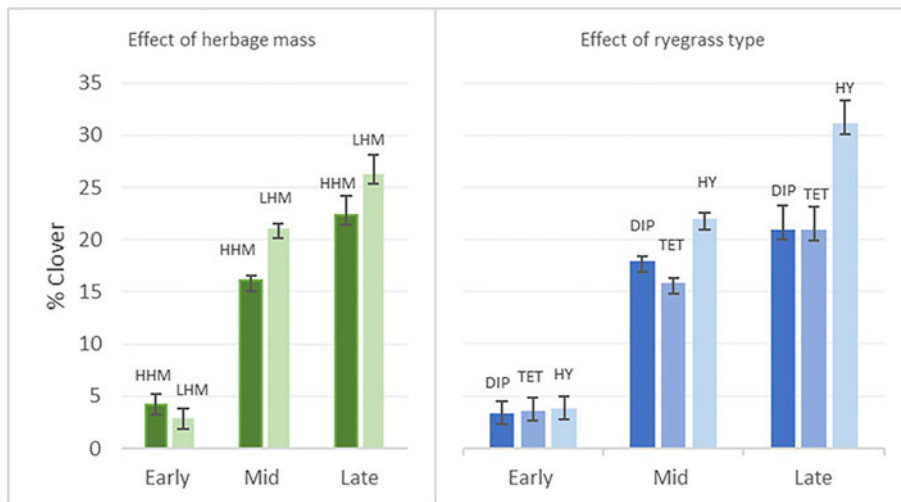
There was an interaction between herbage mass and ryegrass cultivar in mid and late season NDF contents ( $P < 0.001$ ). Sward NDF content in mid-season was higher in HY swards when harvested at HHM compared to LHM, while in late season HY and DIP swards had higher NDF content when harvested at HHM. In early season, LHM swards had 2.2% lower NDF than HHM swards on average ( $P < 0.001$ ), while NDF highest in HY and lowest in TET ( $P < 0.001$ ).

### Acid detergent fibre

There was an interaction between herbage mass and ryegrass cultivar on mid-season ADF content ( $P < 0.001$ ). When swards were cut at HHM, ADF content increased at a higher rate in HY swards, than in DIP and TET swards which were both similar. In early season the LHM swards had lower ADF than ( $P < 0.0001$ ), while DIP and TET swards had higher ADF (221 g/kg DM) than HY (215 g/kg DM) ( $P < 0.001$ ). Late season ADF was highest in DIP (231 g/kg DM) and lowest in TET (213 g/kg DM;  $P < 0.001$ ). The inclusion of red clover increased sward ADF content in mid and late seasons ( $P < 0.001$ ).



**Fig. 1.** (Colour online) Effect of pre-cutting herbage mass, ryegrass cultivar and clover on seasonal leaf, pseudostem, true stem and dead percentage of ryegrass (% DM; least square means  $\pm$  s.e.e. as error bars). HHM, high pre-cutting herbage mass; LHM, low pre-cutting herbage mass; DIP, diploid perennial ryegrass; TET, tetraploid perennial ryegrass; HY, hybrid ryegrass; RG, ryegrass-only; CL, clover inclusion.



**Fig. 2.** (Colour online) Effect of pre-cutting herbage mass and ryegrass cultivar on seasonal red clover content (% DM; least square means  $\pm$  s.e.e. as error bars). HHM, high pre-cutting herbage mass; LHM, low pre-cutting herbage mass; DIP, diploid perennial ryegrass; TET, tetraploid perennial ryegrass; HY, hybrid ryegrass; RG, ryegrass-only; CL, clover inclusion.

### Water soluble carbohydrates

The LHM swards had higher WSC in early and late seasons, while HHM was higher in mid-season ( $P < 0.001$ ). The HY swards had significantly lower WSC (135 g/kg DM) than DIP and TET swards (160 g/kg DM on average) in late season ( $P < 0.001$ ). Swards containing red clover had 16.4% lower WSC than ryegrass-only swards on average ( $P < 0.001$ ).

### Organic matter digestibility

There was an interaction between herbage mass and ryegrass cultivar in early and mid-season ( $P < 0.001$ ) OMD contents. In early season HY swards had lower OMD when cut at HHM, while in mid-season the reduction in OMD was largest in DIP and HY swards cut at HHM. There was also an interaction between herbage mass and clover inclusion in early and mid-seasons ( $P < 0.001$ ). Swards containing red clover had higher OMD than ryegrass-only swards when cut at LHM, however the opposite was true when cut at HHM, with lower levels of OMD when red clover was included in the sward. There was also an interaction between ryegrass cultivar and red clover in late season ( $P < 0.001$ ) whereby OMD was lower in HY swards with red clover included.

## Discussion

The hypotheses of the study were that (a) swards cut at high pre-cutting herbage mass would have higher DM production but may have a higher percentage of stem and lower sward nutritive value, (b) DM production would be highest in hybrid ryegrass, followed by tetraploid ryegrass and diploid ryegrass and (c) clover containing swards would have higher DM production than ryegrass-only swards.

### Herbage production

The quantity of herbage produced and utilized annually is one of the key factors influencing profitability of dairy farms (Hanrahan *et al.*, 2018). According to Kennedy *et al.* (2005) the greatest potential to increase the proportion of grass in the dairy cow diet exists at the beginning and end of the grass-growing season. Holohan *et al.* (2021) showed that cut-and-carry is mostly carried out in early and late seasons by farmers aiming to capitalize on this potential and provide additional grass to the dairy herd.

Therefore, maximizing herbage production in these seasons is particularly important.

Higher DM production was achieved from high pre-cutting herbage mass (HHM) swards compared to those harvested at low pre-cutting herbage mass (LHM), as was hypothesized. This is in line with the findings of Wims *et al.* (2014), who also observed an increase in annual DM production of 1.45 tonnes in swards grazed at high pre-cutting herbage mass (2000 kg DM/ha, >4 cm) *v.* medium herbage (1400 kg DM/ha, >4 cm). The primary reason for this is the longer regrowth interval in the HHM swards. Short regrowth intervals reduce pasture growth rates (Parsons and Penning, 1988; McKenzie, 1996) and annual pasture production (MacDonald *et al.*, 2008). As PRG pastures follow a sigmoidal pattern of growth, beginning slowly before increasing exponentially, short regrowth intervals do not allow PRG plants to reach maximum average growth rate (Parsons and Penning, 1988) and consequently depress DM production.

As hypothesized, the impact of red clover inclusion in the current study was an increase in DM production annually and in mid and late seasons across all three ryegrass cultivars, with the largest increase seen in HY and smaller rates of increase in DIP and TET. This variation would suggest that the increase in DM production is dependent on the companion ryegrass with which red clover is sown. Hybrid ryegrass swards typically have a lower tiller density than PRG swards (Wilman and Gao, 1996; Gilliland and Mann, 2001) and according to Annicchiarico and Tomasoni (2010), that increased space between ryegrass plants reduces grass-clover competition and increases clover content. It is believed that this additional space in the HY swards was more complementary to red clover growth than the DIP and TET swards in the current study as it allowed for increased light interception and more efficient use of sunlight. This is evidenced in the higher clover percentage in HY swards in the current study. These swards may have benefited from additional N supply, given the ability of clover to utilize atmospheric N (Phelan *et al.*, 2015). In addition, red clover is deep rooted and offers improved water extraction capacity under moisture-limited conditions (Brown *et al.*, 2005). This would be advantageous to red clover-ryegrass swards during periods of low soil moisture particularly in the summer months. The increases in DM production from clover inclusion in the current study have also been previously reported (Frame and Karkess, 1987; Elgersma and Søgaard, 2016; Clavin *et al.*, 2017).

**Table 3.** Effect of pre-cutting herbage mass, ryegrass cultivar and red clover inclusion on seasonal sward chemical composition

	Herbage mass (HM)			Ryegrass cultivar (RT)				Red clover inclusion (CL)			Level of significance					
	High	Low	S.E.E.	DIP	TET	HY	S.E.E.	GO	RC	S.E.E.	HM	RT	CL	HM × RT	HM × CL	RT × CL
DM (g/kg)																
Early	173	193	1.9	203 <sup>a</sup>	183 <sup>b</sup>	162 <sup>c</sup>	1.7	184	182	1.9	***	***	NS	NS	NS	NS
Mid	202	196	2.6	212 <sup>a</sup>	196 <sup>b</sup>	190 <sup>c</sup>	3.0	204	194	2.6	*	***	***	NS	NS	NS
Late	217	235	1.7	242 <sup>a</sup>	223 <sup>b</sup>	214 <sup>c</sup>	2.0	233	219	1.7	***	***	***	NS	NS	NS
CP (g/kg DM)																
Early	219	232	2.1	222 <sup>a</sup>	223 <sup>a</sup>	231 <sup>b</sup>	2.6	221	229	2.1	***	***	***	***	NS	NS
Mid	165	186	1.4	174	176	177	1.4	165	186	1.1	***	NS	***	NS	***	***
Late	201	206	0.3	199 <sup>a</sup>	198 <sup>a</sup>	212 <sup>b</sup>	0.4	187	220	0.3	***	***	***	NS	NS	***
Ash (g/kg DM)																
Early	92	93	0.8	84 <sup>a</sup>	94 <sup>b</sup>	99 <sup>c</sup>	1.0	93	92	0.8	NS	***	NS	NS	NS	NS
Mid	80	75	0.8	75 <sup>a</sup>	81 <sup>b</sup>	76 <sup>a</sup>	1.0	76	79	0.8	***	***	**	NS	NS	NS
Late	85	82	0.6	80 <sup>a</sup>	85 <sup>b</sup>	86 <sup>b</sup>	0.8	81	86	0.6	**	***	***	NS	NS	NS
NDF (g/kg DM)																
Early	448	438	0.9	441	432	455	1.1	442	445	0.9	***	***	NS	NS	NS	NS
Mid	483	477	2.1	475	465	501	2.7	468	472	3.6	*	***	NS	***	NS	NS
Late	445	431	1.8	450 <sup>a</sup>	431 <sup>b</sup>	435 <sup>b</sup>	3.5	441	436	1.8	***	***	NS	***	NS	NS
ADF (g/kg DM)																
Early	225	212	1.1	220 <sup>a</sup>	221 <sup>a</sup>	215 <sup>b</sup>	1.4	218	219	1.1	***	***	NS	NS	NS	NS
Mid	259	235	2.3	246 <sup>ab</sup>	244 <sup>a</sup>	251 <sup>b</sup>	2.9	241	252	2.3	***	*	***	***	NS	NS
Late	223	221	1.9	231	213	223	1.6	213	231	1.9	NS	***	***	NS	NS	NS
WSC (g/kg DM)																
Early	87	106	3.4	96	92	101	4.2	98	95	3.4	***	NS	NS	NS	NS	NS
Mid	146	116	2.6	131	131	130	3.2	140	121	2.6	***	NS	***	NS	NS	NS
Late	145	158	2.8	159 <sup>a</sup>	160 <sup>a</sup>	135 <sup>b</sup>	3.4	166	136	2.8	***	***	***	NS	NS	NS
OMD (g/kg DM)																
Early	863	870	0.8	880 <sup>a</sup>	863 <sup>b</sup>	856 <sup>c</sup>	1.0	869	864	0.8	***	***	***	***	***	NS
Mid	807	837	2.6	821 <sup>a</sup>	835 <sup>b</sup>	811 <sup>c</sup>	3.2	825	819	2.6	***	***	*	***	***	NS
Late	839	844	2.2	829 <sup>a</sup>	859 <sup>b</sup>	837 <sup>a</sup>	2.7	845	839	2.2	NS	***	NS	NS	NS	***

DIP, diploid perennial ryegrass; TET, tetraploid perennial ryegrass; HY, hybrid ryegrass; GO, ryegrass-only sward; RC, ryegrass-red clover sward; RT, ryegrass cultivar; CL, clover inclusion; HM, herbage mass; S.E.E., standard error of estimate. Within rows, means with differing superscripts (a-c) differ significantly.



### Ryegrass morphology and clover content

The grass plant comprises leaf, pseudostem, true stem and dead material. These components differ in digestibility, and variations in their relative percentage can affect sward quality (Beecher *et al.*, 2013). In the current study, these percentages varied throughout the growing season, with leaf percentage higher across all experimental treatments in early and late seasons, than in mid-season. This reduction in leaf and increase in pseudostem and true stem percentage in mid-season is characteristic of the reproductive stage of the ryegrass plant which occurs during this time (Minson, 1990; McDonald *et al.*, 2002). Differences in leaf and stem proportions between cultivars have previously been reported by Beecher *et al.* (2013), and this was the case in the current study whereby leaf percentage was similar in DIP and TET swards but lower in HY in early and late seasons. The DIP swards had the highest percentage of dead material in mid and late seasons which has also been previously observed by Garry *et al.* (2020) and Tubritt *et al.* (2020), however the reasons for this are unclear.

Clover proportion is considered one of the main drivers in grass-clover sward performance (Camlin, 1981). Ford and Barrett (2011) suggested that persistence may differ with contrasting managements (e.g. defoliation method and frequency) or different suites of biotic and abiotic stress factors. According to Black *et al.* (2009) red clover yield and persistence typically decreases with increased defoliation frequency, however in the current study, clover content was highest in LHM swards which would suggest that the shorter regrowth interval of the LHM treatment did not have a detrimental effect on clover content, or possibly suppressed the yield of the ryegrass more than red clover. Ryegrass cultivar also had an effect on sward clover content, with HY having a significantly higher percentage of clover than DIP and TET in mid and late seasons. The reason for this possibly relates to the lower sward density characteristics of hybrid ryegrass which could complement clover growth and persistency. It is important to note that while red clover had a positive effect on DM production in the current study, annual yields from red clover-based swards typically decline after 3 years from sowing (Black *et al.*, 2009). Improved plant persistency has however been a major objective of red clover breeding programmes in recent years (Řepková and Nedělník, 2014) and it is possible that new varieties may have greater persistency under frequent defoliation systems. A long-term study using a regular cutting protocol would therefore be beneficial.

### Sward nutritive value

The effects of pre-grazing herbage mass on sward nutritive value have been previously studied by Curran *et al.* (2010), McEvoy *et al.* (2009) and O'Donovan and Delaby (2008), who found that as herbage mass increases, sward nutritive value typically decreases. Similarly, in the current study, OMD was lower in HHM swards than LHM swards in early and mid-seasons. According to McEvoy *et al.* (2009) the extent to which quality differs depends on stage of the growing season. They reported similar OMD values in medium (1700 kg DM/ha) and high (2200 kg DM/ha) herbage mass swards throughout the spring period until early June, after which OMD declined in high pre-cutting herbage mass treatments. In the current study, herbage mass did not have a significant effect on DIP or TET swards in early season, while HY swards had significantly lower OMD when cut at HHM. The higher stem percentage in HY HHM swards during this

period and in all HHM swards during mid-season is suspected to be the main contributory factor to the reduced OMD values. Contrary to the study hypothesis, similar OMD values were observed between LHM and HHM swards in late season and leaf and stem measurements corresponded with this.

It has been previously reported by Jacobs *et al.* (1998) that increased herbage mass is also associated with decreased CP and increased NDF content, particularly in mid-season. CP and NDF results in the current study correspond with this. In terms of clover inclusion, CP levels were higher in ryegrass-clover than ryegrass-only swards, similar to Ribeiro Filho *et al.* (2003) and Enriquez-Hidalgo *et al.* (2014). The effect of clover on mid and late season CP content however depended on the ryegrass cultivar with which it was sown. As previously outlined, clover content was highest in HY swards, and this subsequently translated to higher CP levels in hybrid ryegrass-red clover swards than perennial ryegrass-red clover swards.

Previous studies have highlighted lower concentrations of NDF in red clover compared with grasses (Bertilsson and Murphy, 2003; Dewhurst *et al.*, 2003), however the inclusion of clover in the current study did not reduce NDF as might have been expected. Furthermore, its inclusion significantly increased sward ADF content in mid and late seasons. The increased levels of NDF and ADF may explain the low OMD levels in the swards containing red clover as both are associated with reduced digestibility (Hopkins and Wilkins, 2006; Stergiadis *et al.*, 2015). Elgersma and Søgaard (2018) reported that ADF and NDF increases at a faster rate in legumes than grasses, particularly in mid-season, and this may have contributed to the reduced digestibility in clover-ryegrass swards in the current study. According to Beecher *et al.* (2013), digestibility is linked to the morphological composition of the sward. Stem has a higher lignin content (Laredo and Minson, 1975) and lower digestibility than leaf (Buxton, 1996). The morphological measurements in the current study show ryegrass leaf and stem percentage were similar in ryegrass-only and ryegrass-red clover swards, which therefore suggests that the higher NDF and ADF, and lower OMD observed in ryegrass-clover swards was likely caused by the stem percentage in the red clover plants. According to Taylor and Quesenberry (1996) red clover digestibility decreases with plant maturity, and also with cutting height. The base of the stem in red clover is less digestible than the upper stem parts, and subsequently cutting height impacts sward digestibility. Therefore, it is possible that the cutting height of 4 cm may have played a part in the lower OMD in swards containing clover. The exact impact of regular cutting on the morphological characteristics of red clover however requires further study.

WSC levels were variable across the seasons with LHM swards highest in early and late seasons and HHM swards highest in mid-season. Prevailing weather conditions have a major influence on WSC values (Roche *et al.*, 2009), and may have contributed to WSC variability between seasons in the current study, particularly given that LHM and HHM swards were not harvested on the same days (due to different regrowth intervals). The reduction in WSC in the clover-containing swards in this study is reflective of the lower WSC content typically found in red clover in comparison with ryegrass (McDonald *et al.*, 1991; Evans *et al.*, 1996).

### Conclusion

Cutting swards at high pre-cutting herbage mass, rather than low pre-cutting herbage mass, increased annual DM production. The

effect on herbage nutritive value however varied depending on season and ryegrass cultivar, with a relatively small reduction in digestibility in HY HHM swards in early season and no reduction in late season across all cultivars. This could present an opportunity for improved sward productivity in early and late seasons when the majority of cut-and-carry is carried out on temperate dairy farms. While hybrid ryegrass was the highest yielding ryegrass cultivar, it had the lowest digestibility and highest NDF content. Therefore, the use of hybrid ryegrass needs to be considered carefully as its lower sward quality may negate the advantage of any increase in DM production. Tetraploid ryegrass was the most balanced in terms of yield and quality in the current study. The inclusion of red clover had a positive effect on production, and increased sward CP content, however mixed ryegrass–red clover swards had higher NDF and ADF and lower digestibility than ryegrass-only swards. Results from this study suggest there is scope to optimize sward performance through the adoption of sward management practices specific to cut-and-carry systems.

**Financial support.** This study was funded by the Irish Department of Agriculture, Food and the Marine Research Stimulus Fund under the NutriGen project (15S675).

**Conflict of interest.** None.

## References

- Annicchiarico P and Tomasoni C** (2010) Optimizing legume content and forage yield of mown white clover–Italian ryegrass mixtures through nitrogen fertilization and grass row spacing. *Grass and Forage Science* **65**, 220–226.
- Beecher M, Hennessy D, Boland T, McEvoy M, O'Donovan M and Lewis E** (2013) The variation in morphology of perennial ryegrass cultivars throughout the grazing season and effects on organic matter digestibility. *Grass and Forage Science* **70**, 19–29.
- Bertilsson J and Murphy M** (2003) Effects of feeding clover silages on feed intake, milk production and digestion in dairy cows. *Grass and Forage Science* **58**, 309–322.
- Black A, Laidlaw A, Moot D and O'Kiely P** (2009) Comparative growth and management of white and red clovers. *Irish Journal of Agricultural and Food Research* **48**, 149–166.
- Brown H, Moot D and Pollock K** (2005) Herbage production, persistence, nutritive characteristics and water use of perennial forages grown over 6 years on a Wakanui silt loam. *New Zealand Journal of Agricultural Research* **48**, 423–439.
- Buxton D** (1996) Quality-related characteristics of forages as influenced by plant environment and agronomic factors. *Animal Feed Science and Technology* **59**, 37–49.
- Camlin M** (1981) Competitive effects between ten cultivars of perennial ryegrass and three cultivars of white clover grown in association. *Grass and Forage Science* **36**, 169–178.
- Clavin D, Crossan P, Grant J and O'Kiely P** (2017) Red clover for silage: management impacts on herbage yield, nutritive value, ensilability and persistence, and relativity to perennial ryegrass. *Journal of Dairy Science* **72**, 414–431.
- Curran J, Delaby L, Kennedy E, Murphy J, Boland T and O'Donovan M** (2010) Sward characteristics, grass dry matter intake and milk production performance are affected by pre-grazing herbage mass and pasture allowance. *Livestock Science* **127**, 144–154.
- DAFM** (2017) Grass and White Clover Varieties – Irish Recommended List 2017. Department of Agriculture, Food and the Marine. Available at <https://agritech.ie/wp-content/uploads/2017/04/GrassandWhiteCloverRecommendedListVarietiesforIreland2017210317.pdf>.
- Dewhurst R, Evans R, Scollan ND, Moorby J, Merry R and Wilkins R** (2003) Comparison of grass and legume silages for milk production. 2. *In vivo* and *in sacco* evaluations of rumen function. *Journal of Dairy Science* **86**, 2612–2262.
- 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.
- Elgersma S and Søegaard K** (2016) Effects of species diversity on seasonal variation in herbage yield and nutritive value of seven binary grass-legume mixtures and pure grass under cutting. *European Journal of Agronomy* **78**, 73–83.
- Elgersma A and Søegaard K** (2018) Changes in nutritive value and herbage yield during extended growth intervals in grass–legume mixtures: effects of species, maturity at harvest, and relationships between productivity and components of feed quality. *Grass and Forage Science* **73**, 78–93.
- Enriquez-Hidalgo D, Gilliland TJ, Deighton MH, O'Donovan M and Hennessy D** (2014) Milk production and enteric methane emissions by dairy cows grazing fertilized perennial ryegrass pasture with or without inclusion of white clover. *Journal of Dairy Science* **97**, 1400–1412.
- Eriksen J, Askegaard M and Søegaard K** (2014) Complementary effects of red clover inclusion in ryegrass–white clover swards for grazing and cutting. *Grass and Forage Science* **69**, 241–250.
- Evans D, Humphreys M and Williams T** (1996) Forage yield and quality interactions between white clover and contrasting ryegrass varieties in grazed swards. *Journal of Agricultural Science* **126**, 295–299.
- Ford J and Barrett B** (2011) Improving red clover persistence under grazing. *Proceedings of the New Zealand Grassland Association* **73**, 119–124.
- Frame J and Karkess R** (1987) The productivity of four forage legumes sown alone and with each of five companion grasses. *Grass and Forage Science* **42**, 213–223.
- Garry B, McGovern F, Boland T, Baumont R, Lewis E and O'Donovan M** (2020) Effects of perennial ryegrass variety and ploidy on voluntary dry matter intake and *in vivo* digestibility in sheep. *Livestock Science* **240**, 104–164.
- Gilliland T and Mann R** (2001) The silage yield potential of hybrid ryegrass over a 5-year period in Northern Ireland relative to other ryegrasses and timothy. *Grass and Forage Science* **56**, 305–310.
- Grace C, Boland T, Sheridan H, Brennan E, Fritch R and Lynch M** (2019) The effect of actual versus simulated grazing on dry matter production of multispecies and perennial ryegrass only swards. *Grass and Forage Science* **74**, 437–449.
- Hanrahan L, McHugh N, Hennessy T, Moran B, Kearney R, Wallace M and Shalloo L** (2018) Factors associated with profitability in pasture-based systems of milk production. *Journal of Dairy Science* **101**, 5474–5485.
- 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. <https://doi.org/10.3168/jds.2020-19164>.
- Hopkins A and Wilkins R** (2006) Temperate grassland: key developments in the last century and future perspectives. *Journal of Agricultural Science* **144**, 503–523.
- Jacobs J, Rigby S, McKenzie F, Ward G and Kearney G** (1998) Effect of lock up and harvest dates on dairy pasture dry matter yield and quality for silage in south-western Victoria. *Australian Journal of Experimental Agriculture* **38**, 131–138.
- 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.
- Lalor S** (2004) *Soils of UCD Research Farm, Lyons Estate, Celbridge, Co., Kildare*. Dublin: University College Dublin.
- Läpple D, Hennessy T and O'Donovan M** (2012) Extended grazing: a detailed analysis of Irish dairy farms. *Journal of Dairy Science* **95**, 188–195.
- Laredo M and Minson D** (1975) The voluntary intake and digestibility by sheep of leaf and stem fractions of *Lolium perenne*. *Grass and Forage Science* **30**, 73–77.
- Lee M, Theobald V, Tweed J, Winters A and Scollan N** (2009) Effect of feeding fresh or conditioned red clover on milk fatty acids and nitrogen utilization in lactating dairy cows. *Journal of Dairy Science* **92**, 2008–1692.
- Lüscher A, Mueller-Harvey I, Soussana F, Rees R and Peyraud J** (2014) Potential of legume-based grassland-livestock systems in Europe. *Grass and Forage Science* **69**, 206–228.

- MacDonald K, Penno J, Lancaster J and Roche J** (2008) Effect of stocking rate on pasture production, milk production, and reproduction of dairy cows in pasture-based systems. *Journal of Dairy Science* **91**, 2151–2163.
- McDonald P, Henderson A and Heron S** (1991). *The Biochemistry of Silage*. Abersytwyth, UK: Chalcombe Publications.
- McDonald P, Edwards R, Greenhalgh J and Morgan C** (2002) *Grass and Forage Crops*. Essex, England: Pearson Education Limited.
- Mcevoy M, O'Donovan M, Kennedy E, Murphy J, Delaby L and Boland T** (2009) Effect of pregrazing herbage mass and pasture allowance on the lactation performance of Holstein–Friesian dairy cows. *Journal of Dairy Science* **92**, 414–422.
- McKenzie F** (1996) The influence of grazing frequency and intensity on the vigour of *Lolium perenne* under subtropical conditions. *Australian Journal of Agricultural Research* **47**, 975–983.
- Minson D** (1990) *Digestible Energy of Forage*. San Diego: Academic Press Inc.
- O'Brien B and Hennessy D** (2017) Scientific appraisal of the Irish grass-based milk production system as a sustainable source of premium quality milk and dairy products. *Irish Journal of Agricultural and Food Research* **56**, 120–129.
- O'Donovan M and Delaby L** (2008) Sward characteristics, grass dry matter intake and milk production performance is affected by timing of spring grazing and subsequent stocking rate. *Livestock Science* **115**, 158–168.
- O'Donovan M and McEvoy M** (2016) Managing your grass. In Moore M (ed). *Teagasc Dairy Manual*. Oakpark: Teagasc, pp. 227–238.
- O'Donovan M, McHugh N, McEvoy M, Grogan D and Shalloo L** (2017) Combining seasonal yield, silage dry matter yield, quality and persistency in an economic index to assist perennial ryegrass variety selection. *The Journal of Agricultural Science* **155**, 556–568.
- Parsons A and Penning P** (1988) The effect of the duration of regrowth on photosynthesis, leaf death and the average rate of growth in a rotationally grazed sward. *Grass and Forage Science* **43**, 15–27.
- Phelan P, Moloney A, McGeough E, Humphreys J, Bertilsson J, O'Riordan E and O'Kiely P** (2015) Forage legumes for grazing and conserving in ruminant production systems. *Critical Reviews in Plant Sciences* **34**, 281–326.
- Řepková J and Nedělník J** (2014) Modern methods for genetic improvement of *Trifolium pratense*. *Czech Journal of Genetics and Plant Breeding* **50**, 92–99.
- Ribeiro Filho HM, Delagarde R and Peyraud JL** (2003) Inclusion of white clover in strip-grazed perennial ryegrass swards: herbage intake and milk yield of dairy cows at different ages of sward regrowth. *Animal Science* **77**, 499–510.
- Roche J, Turner L, Lee J, Edmeades D and Donaghy D** (2009) Weather, herbage quality and milk production in pastoral systems. Interrelationships and associations between weather variables and herbage growth rate, quality and mineral concentration. *Animal Production Science* **49**, 211–221.
- Roche J, Berry D, Bryant A, Burke C, Butler S, Dillon P, Donaghy DJ, Horan B, MacDonald KA and MacMillan KL** (2017) A 100 year review: a century of change in temperate grazing systems. *Journal of Dairy Science* **100**, 10189–10233.
- Stergiadis S, Allen M, Chen X and Wills DY** (2015) Prediction of nutrient digestibility and energy concentrations in fresh grass using nutrient composition. *Journal of Dairy Science* **98**, 3257–3273.
- Taylor N and Quesenberry K** (1996) *Red Clover Science*. Dordrecht: Springer Science & Business Media.
- 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.
- Tubritt T, Delaby L, Gilliland TJ and O'Donovan M** (2020) The relationship between the grazing efficiency and the production, morphology and nutritional traits of perennial ryegrass varieties. *Journal of Agricultural Science* **158**, 583–593.
- 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.
- Wall D and Plunkett M** (2016) *Major and Micronutrient Advice for Productive Agricultural Crops*. Environment Research Centre, Johnstown Castle, Wexford: Teagasc.
- Wilman D and Gao Y** (1996) Herbage production and tiller density in five related grasses, their hybrids and mixtures. *The Journal of Agricultural Science* **127**, 57–65.
- Wims CM, Delaby L, Boland TM and O'Donovan M** (2014) Effect of pre-grazing herbage mass on dairy cow performance, grass dry matter production and output from perennial ryegrass (*Lolium perenne* L.) pastures. *Animal: An International Journal of Animal Bioscience* **8**, 141–151.