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The effect of altering autumn grazing management on sward structural characteristics, morphology and nutritive value

Thesis presented by

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for the degree of

Doctor of Philosophy

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2021

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Declaration

"This is to certify that the work I am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism and intellectual property."

Signed: **Caitlin Looney, 30th September 2021**

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Glossary of Terms

ADF - Acid detergent fibre

CD – Closing date

CP - Crude protein

Cm – centimetre

DD – Defoliation date

DM - Dry matter

ESH – Extended sheath height

ETH – Extended tiller height

FLL – Free leaf lamina

g – gram

Ha - Hectare

Kg - Kilogram

K - Phosphorus

LAI - Leaf area index

LAR – Leaf appearance rate

LER – Leaf extension rate

LSR –Leaf senescence rate

LU – Livestock units

M – metre

MD – Measurement date

Min - minute

Ml - millilitre

Mm - Millimetre

N - Nitrogen

NDF - Neutral detergent fibre

NS - not significant

OMD - Organic matter digestibility

P - Potassium

PRG - Perennial ryegrass

RNA – Ribonucleic acid

t - Tonne(s)

THM – Target herbage mass

WSC – Water soluble carbohydrates

°C - Degrees Celsius

Thesis abstract

Altering grazing management practices to increase the amount of herbage available on farm can help extend the grazing season, improve herbage utilization and, in turn, improve the sustainability and efficiency of pasture based dairy systems. Extended grazing happens at two pivotal time points - autumn and spring. Management for both incorporates building herbage masses; in autumn, the grazing rotation is extended from August to a peak in October, which in turn increases pre-grazing herbage mass. Increasing herbage in spring relies on accumulating herbage, over winter achieved by autumn closing date (CD). Accumulating herbage mass has the potential to impact various factors of sward production, morphology and physiology. The current thesis evaluated how management practices in autumn and spring affect the perennial ryegrass (*Lolium perenne*, L; PRG) plant. This research is important to identify areas where management can be improved which will allow for the increase in herbage available to be utilised, improve efficiencies, profitability and sustainability. The objective of this thesis was to investigate the impact of accumulating herbage masses for the extension of the grazing season in autumn, over winter and spring. Herbage masses in autumn were investigated at different defoliation dates (DD) across the final rotation (chapter 2 and 3). The effect of final defoliation in autumn (CD) over winter and into spring was investigated (chapter 4 and 5).

It was found accumulating herbage should begin in August and herbage masses > 2000 kg DM ha^{-1} should be defoliated before 7th November, as there is a large decline in herbage mass and sward quality. Low target herbage mass (THM; 500 kg DM ha^{-1}) should have a later DD, as swards continue to accumulate herbage, while maintaining sward quality, however, low THM, can potentially be carried over winter, average farm cover is below farm targets for spring demand (i.e. above 750 kg DM ha^{-1}; S.R. > 2.9 livestock units (LU) ha^{-1}). Carrying swards with lower herbage masses over winter was demonstrated successfully in chapter 4 and 5. The medium THM, can maintain sward quality across the autumn period, despite losing herbage, so can be grazed later in the final rotation. Sward morphology was also affected by increasing herbage masses in autumn. Light transmitted to the base of the sward was reduced,

which resulted in increased internode elongation. Very high THM had the greatest number of tillers with internode elongation and the longest length of internode elongation.

Autumn CD was found to affect herbage production, herbage quality, leaf, stem and dead proportions and tiller density over winter and in spring. Autumn CD is responsible for 50% of the herbage available in spring, with each day delay in closing resulting in an extra 16 kg DM^{-1}. Swards closed earlier had a higher herbage mass in spring and lower sward quality compared to later closed swards; that had reduced herbage and a higher herbage quality. Autumn CD effected subsequent growth rates but not quality in spring (2^{nd} rotation); swards closed early had a lower growth rate compared to swards closed later following the initial spring defoliation. Sward structure was negatively affected by early autumn CD. Early CD had greater parent and daughter tiller mortality than later CD. Early CD also resulted in greater leaf extension and leaf senescence rates in daughter tillers compared to late.

The results of this thesis have provided further insight into the grazing management practices in autumn and spring and the impact they have on sward structure, quality and herbage. These results will help improve grazing management practices into the future.

Chapter 1 – Literature review

1.1 Background

There are many significant challenges facing agriculture globally; population increase (United Nations, 2019), rising greenhouse gases (Casey et al., 2005; O'Brien et al., 2012), eutrophication (Briggs and Courtney, 1989; Benoit et al., 1995; Benoit et al., 2004; Basset-Mens et al., 2009) and losses to biodiversity and habitats (Atkinson et al., 2005; McMahon et al., 2010; Nitsch et al., 2012; Taube et al., 2014). Grassland systems offer the opportunity to make use of a human inedible feed source, and convert it to human edible food in the form of milk and meat (Laisse et al., 2018; Hennessy et al., 2021). They offer a competitive and sustainable alternative to higher input systems (Dillon et al., 2008; Peyraud et al., 2010; Ramsbottom et al., 2015). Dairy production systems in Ireland aim to utilise grazed grass as it is a lower feed cost (O'Brien et al., 2018), has a lower environmental impact (O'Brien et al., 2012) and has a better consumer perception (Shortall, 2019), animal welfare (Mee and Boyle, 2020) and a healthier product (Stanton et al., 2021) compared to confinement systems (Elgersma, 2015). Hennessy et al. (2020) identified improving herbage utilisation as a challenge to sustainability in dairy production systems. Any increase in animal production should come as a result of increased utilisation of grazed grass (Dillon et al., 2005). In recent years in Ireland, there has been an increased demand on feed on farm (2008–2017) due to an increase in the whole farm stocking (Hanrahan et al., 2018).

Perennial ryegrass growth rates are highly dependent on temperature (Peacock, 1975) and therefore are reduced in autumn, over-winter and in spring (Dillon et al., 1995; Parsons and Chapman, 2000; Hennessy et al., 2008). This can lead to inadequate amounts of grazed herbage available on farm in autumn and in spring (Ryan et al., 2010; Lawrence et al., 2017) to meet herd demands from grazed grass. To overcome the inadequate amount of herbage and match feed demand with grazed grass, management guidelines have been created for both autumn and spring. Both management guidelines focus on accumulating herbage. Previous research has identified autumn closing date as a key management factor affecting grass availability on farm in spring (Carton et al., 1988; O'Donovan et al., 2002; Hennessy et al., 2006; Lawrence et al., 2017). Any changes in autumn and spring management

guidelines must consider sward structure and should not compromise the sward. This is particularly important in higher herbage masses (>2,000 kg DM ha^{-1}; approximately).

1.2 Pasture-based dairy systems in Ireland

Pasture-based systems aim to utilise the dairy cows' capability to convert the perennial ryegrass (PRG) plant cell walls and cellular material into milk (Leaver, 1985). Perennial ryegrass (either grazed in situ or as grass silage) currently makes up 82% of the diet of a cow in Irish pasture-based systems on a dry matter basis (O'Brien et al., 2018). Due to Ireland's temperate oceanic climate, with soil temperatures greater than 6˚C for the majority of the season and little chance of a soil moisture deficit, there is a huge potential to produce large quantities of herbage. High herbage utilisation is achievable with research targets aiming for 13 tonnes dry matter (DM) per ha utilised (French et al., 2019; Table 1.1).

Table 1.1: Physical performance required to achieve the national average and target performance at a farm level as adopted from French et al. (2019).

Parameter	National average	Research Target
Milk yield (kg MS* cow^{-1})	405	475
Milk yield (kg cow^{-1})	5409	5800
Milk protein (%)	3.45	3.7
Milk fat (%)	4.06	4.5
Milk yield (kg ha^{-1})	11090	16820
Milk solids (kg ha^{-1})	825	1380
Calving interval (days)	394	365
Mean calving date	06-Mar	14-Feb
Six-week calving rate (%)	58	90
Replacement rate (%)	23	19
Labour (h cow^{-1})	30	16
Stocking rate (LU** ha^{-1})	2.05	2.9
Concentrate feeding (kg cow^{-1})	933	450
Pasture utilised (t ha^{-1})	8	13.1

*MS = Milk solids

**LU = Livestock units

There have been a number of key changes in the dairy sector in Ireland in recent years: Between 2008 and 2017 Irish dairy farmers made considerable herd fertility improvements by reducing mean calving interval, increasing 6-week calving rate from 61% to 72%, while mean calving dates have reduced by 8 days (Dillon et al., 2018). The proportion of cows calving in the months of January to April has increased from 74% in 2008 to 84% in 2018 (ICBF, 2018). This coupled with an increase in average herd size from 48 cows in 2008 to 76 cows in 2016 (Kelly et al., 2020) was associated with an increase in whole-farm stocking rate from 1.71 LU ha^{-1} to 1.93 LU ha^{-1} (Hanrahan et al., 2018). All these factors have increased the feed demand on Irish dairy farms. Any increased farm output must come from feeding grazed grass, it is the cheapest form of feed available and there is an increase cost associated with concentrates and silage (Dillon et al., 1995; Shalloo et al., 2011). This is in line with

research which found focusing on a pasture-based systems would reduce the costs per litre of milk produced as grazed grass it is the cheapest feed source available (Finneran et al., 2010). Several lines of study suggest that pasture-based production systems offer a competitive and sustainable alternative to other intensive higher input systems (Dillon et al., 2008). Previous studies have found increasing the amount of grazed grass in the diet of a dairy cow will increase efficiencies on farm (Kelly et al., 2013) and there is major potential for improvement (Creighton et al., 2011). The Teagasc Grass 10 programme has focused on knowledge transfer from research findings as one way to improve competitiveness. Increasing the proportion of grazed grass in the diet depends on numerous factors, including pasture utilisation, management and extension of the grazing system.

Other challenges identified for the pasture-based system but not addressed in the current thesis are climate change, maintenance of water quality, remaining competitive, shortage of skilled labour and keeping reputation (Dillon, 2019).

1.3 Irish Climate

Ireland's location brings it within the temperate zones, (roughly between 30˚ and 60˚ north and south of the equator). Ireland has a humid temperate climate and is influenced by the Gulf Stream and a prevailing westerly wind. Average annual rainfall in Ireland varies from 750 mm year^{-1} in the east and north-east to 1200 mm year^{-1} in the south and south-west and 1600-1700 in the west, with even greater rainfall, > 2000 mm year^{-1}, experienced in mountain ranges. The average air temperatures across Ireland fluctuate between 18°C to 20°C during the summer and 8°C during the winter (Met Éireann, 2021). Experiments carried out in Ireland within this thesis were carried out in the Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland which has had a Met Éireann meteorological station since 2008. The average annual rainfall at this station between 2008 and 2016 was 788 mm and the average daily temperature was 10˚C (Met Éireann, 2021). The monthly averages are shown in Figure 1.1.

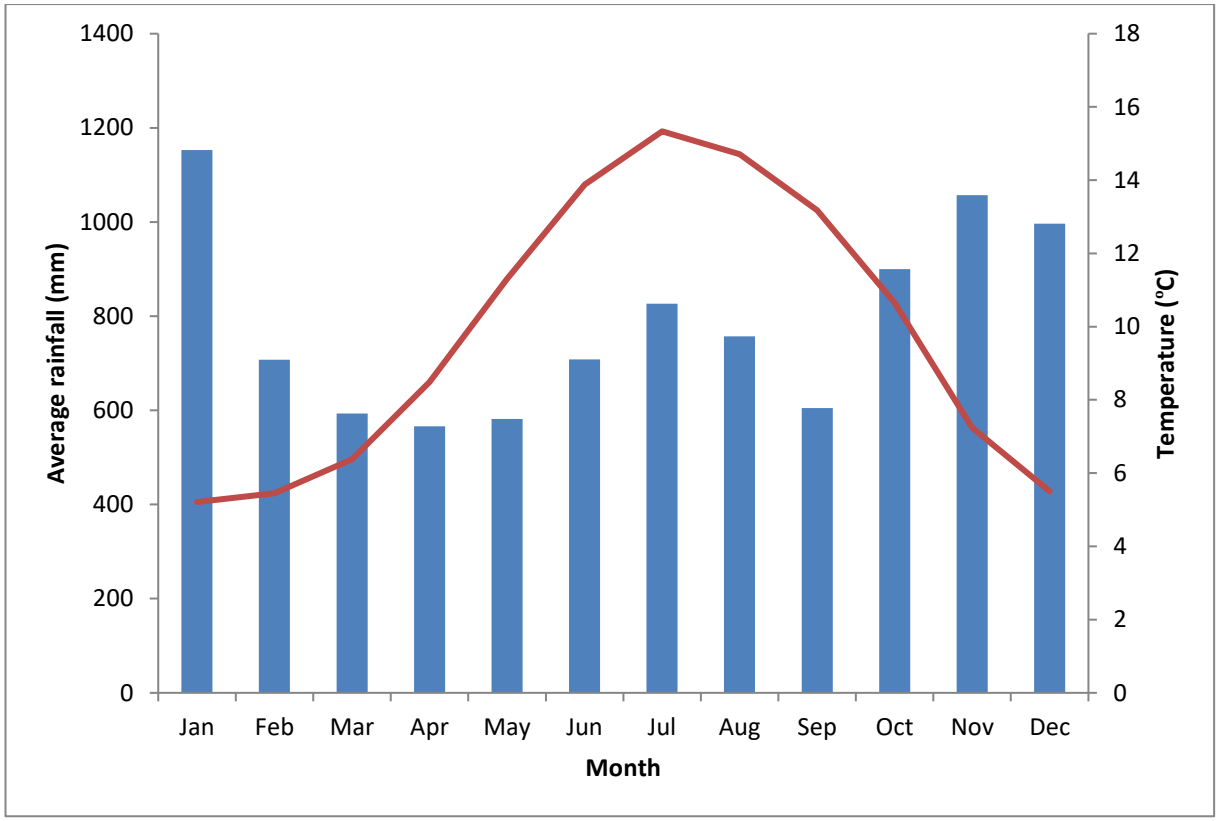


Figure 1.1: The average total rainfall (bar chart) and average daily air temperature (line chart) between 2008 and 2016 at the Moorepark meteorological station (Met Éireann, 2021).

1.4 Herbage production in Ireland

The Irish temperate climate is very conducive to high levels of grass growth which, if utilised, can support intensive pasture-based systems. There is the potential in Irish pastures to produce between 12 and 17 tonnes DM ha^{-1} (O'Donovan and Egan, 2019) over a long growing season (up to 340 days). PastureBase Ireland is a web-based grassland database developed for the dual function of real-time decision making for farmers and compiling a national database to capture information to benchmark Ireland's growth rates, and it can be used for research purposes (Hanrahan et al., 2018). This has allowed the quantification of the grass growth and herbage production (total and seasonal) across a variety of enterprises, systems, regions and soil types. Approximately 4,000 farmers, 96% of whom are dairy farmers in 2020, used PastureBase Ireland (*Personal communication*: O' Leary, 2020). In 2019 dairy farmers using PastureBase grew an average of 13.6 tonnes DM ha^{-1} with 55% of the

production achieved between April and October. The average grass grown in Ireland, between the 2013 (establishment of Pasturebase) and 2017 was 13.7 tonnes DM ha^{-1}, in 2018 there was an unusual drought and growth was reduced to 11 tonnes DM ha^{-1}.

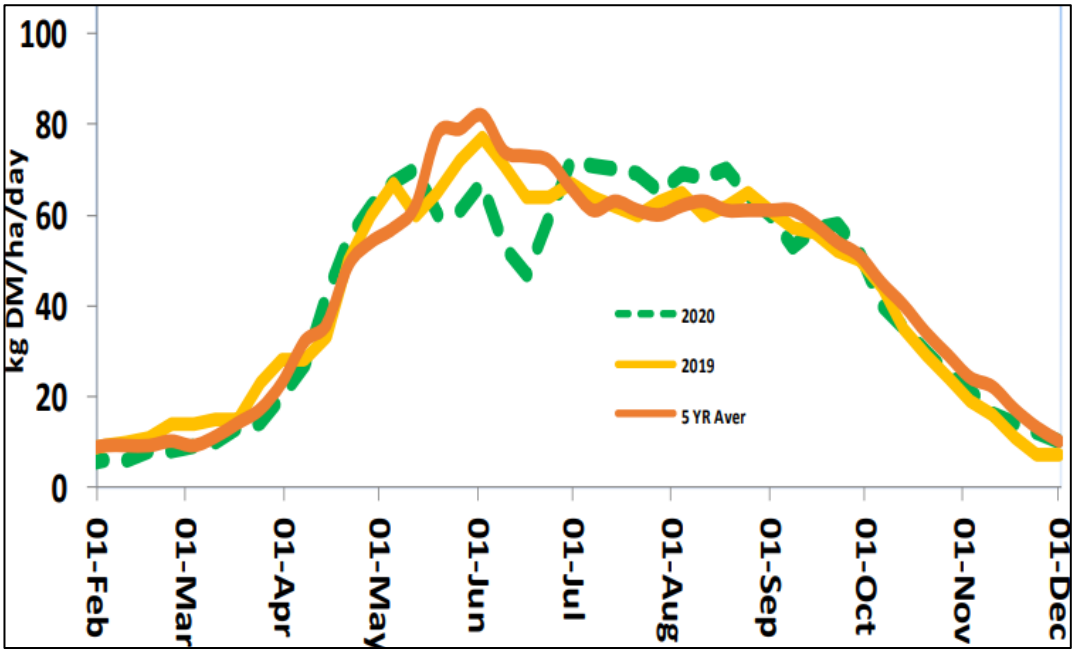


Figure 1.2: The annual herbage growth of dairy farms throughout Ireland (kg DM/ha/day), 5-year average (2011-2016), 2019 and 2020 (Teagasc, 2020).

Figure 1.2 shows grass growth increases from early spring, leading to a peak in May and June, a plateau from July to September and a steady decrease from autumn through winter (Teagasc, 2020).

Data collected by PastureBase has shown that there can be high levels of herbage production achieved despite the influence of geographical location through following recommended grazing management practices, soil fertility and grazing infrastructure (O'Donovan and Maher, 2015). The research targets in Ireland aim to utilise 13 tonnes of DM ha^{-1} (French et al., 2019). Current Grass10 targets aim to grow 14 tonnes DM ha^{-1} with a 75% utilisation (Teagasc, 2020). These targets can be achieved by increasing the number of days at grass to 300 days (Kennedy et al., 2009), increasing utilisation through improved infrastructure and improving production through correct soil fertility (pH > 6.3; Index 3 or 4 in Phosphorous (P) and Potassium

(K)) and altering grazing management practices in spring and autumn (O'Donovan and Egan, 2019).

From the National Grass Growth Curve (Figure 1.2) and PastureBase Ireland data it is evident that there is lower growth from October to April. This reduction in growth can lead to shortages in herbage available in autumn and early spring. In spring calving systems, that are predominant in Ireland (Dillon et al., 1995), there are high feed requirements post calving. To ensure that adequate herbage is available at spring turnout, it is critical to meet animal feed requirements with grazed grass to increase milk production and reduce feed supplementation (Claffey et al., 2019). Teagasc reported that each extra day at grass in spring is worth €3 $cow^{-1}day^{-1}$ (Bogue, 2018) when supplementary feed such as silage and concentrates are removed from the diet and replaced with grazed grass.

1.5 Perennial Ryegrass

Perennial ryegrass is the most dominant and preferred species (Grogan and Gilliland, 2011) used in temperate pasture-based systems, such as Ireland, the UK, North West Europe, New Zealand and certain parts of North America and Australia (Hannaway et al., 1999). Perennial ryegrass is suitable for use in pasture-based systems as it has the ability to produce large amounts of high-quality herbage (Finneran et al., 2012). Due to the location of its basal meristem at ground level, PRG can withstand intensive grazing (Jones, 2013). There are a number of factors which make PRG such a valuable crop in livestock production systems in regions with temperate climates including its digestibility (Garry, 2015), grazing efficiency (Byrne, 2018), ability to respond to nitrogen fertiliser, palatability, yield potential and suitability to the cool, moist climate (Hannaway et al., 1999).

The PRG plant begins life as a seed and grows up to 5 leaves before settling in to a stable state of approximately three live leaves (Jones, 2013). The PRG plant has three stages of production 1) vegetative phase which begins in autumn and lasts until late spring (August to March in Ireland), 2) the elongation phase in late spring (April) which is stimulated by vernalisation over winter and 3) the reproductive phase from

May to July. This literature review will focus on the vegetative stage of the PRG as autumn and spring grazing management practices are investigated.

1.5.1 Vegetative stage

In the vegetative stage, the shoot apex in a tiller consists of a meristematic apical dome that continuously lays down primordia from which leaves develop in alternating order along its opposing flanks (Jewiss, 1993). The development of new leaves is restricted to the basal meristem. New leaves grow linearly and the tip/end of the leaf is always older than the base (Jones, 2013). Each new leaf grows up within the older leave sheath (the pseudo stem) with oldest sheath on the outside. The 'true stem' is located at the base of the pseudo stem and is made up of accumulating nodes and internodes (Jones, 2013). The 'true stem' is concealed entirely by encircling sheaths and should remain under 1 cm at ground level in the vegetative phase (Parsons and Chapman, 2000). As each new leaf is produced an axillary meristem is also produced from the opposite side of the internode (axil of the previous leaf).

An axillary meristem, present at every node, is the potential site for a new tiller and is capable of exponential growth theoretically (Jewiss, 1993). In production there are allometric constraints that limit the number of tillers that can be sustained per unit ground area (Matthew et al., 1995, 1996) and therefore exponential growth of tillers is not achieved. Brock and Thomas (1991) found that under realistic field conditions the mean number of tillers per plant is typically four or five.

At a cellular level, leaf growth involves cell expansion with the aid of turgor pressure (Kirkham et al., 1972). Cell walls first expand and then become rigid through synthesis of cellulose and other cell wall materials (Kirkham et al., 1972). The processes involved in leaf growth are all directly affected by factors such as temperature, light, water, nutrients and management practices linked to defoliation (Humphries and Wheeler, 1963).

1.5.2 Reproductive stage

Although PRG depend on asexual reproduction to persist in swards (Hunt and Field, 1978) flowering is induced by vernalisation. Approximately 6 weeks of cold are

required to fully vernalize the PRG plant (Thomas and Evans, 1990). This stimulates floral induction and the tillers move into the reproductive stage. Stem elongation occurs, providing day length is above the threshold level of 8 hours per day (Robson et al., 1988). The shoot apex moves upwards as rapid cell division and expansion occurs, which lifts the developing inflorescence (seed head) above the surrounding herbage; reproductive tillers cannot initiate leaf or tiller production due to floral parts at the apex (Hunt and Field, 1978). When environmental conditions are the same in spring, tillers in the reproductive stage grow considerably faster compared to tillers in the vegetative stage (Hunt and Field, 1978). The difference occurs due to more efficient utilisation of light for growth by reproductive swards (Leafe et al., 1974). Tillers produced the previous autumn compared to those produced in winter are more likely to flower (Korte, 1984). In some cases tillers turn reproductive in months considered outside of the suitable phase of floral induction and it is suggested that these tillers were tiller buds in this phase indicating tiller buds are susceptible to vernalisation (Kleinendorst, 1974; Laidlaw, 2004).

1.5.3 Leaf stage

Perennial ryegrass is a 'three-leaf' stage plant; each tiller maintains about three live leaves (Davies, 1960 & 1971; Hunt, 1965). When the fourth (youngest leaf) begins to emerge the first (oldest leaf) begins to senesce (Alberda and Sibma, 1968; Davies, 1971). When a sward is defoliated to approximately 4 cm, the regrowth of the PRG plant follows the stages shown in Figure 1.3. Leaf stage has been used as a grazing management decision tool on the optimum grazing time of PRG swards (Fulkerson and Donaghy, 2001). Grazing at the two and a half to three-leaf stage is the recommended stage for defoliation (Fulkerson and Donaghy, 2001). Grazing at the three-leaf stage has been shown to allow sufficient replenishment of water soluble carbohydrate (WSC) reserves in the stubble of the plant which in turn maximises leaf re-growth, root growth and tillering (Fulkerson and Donaghy, 2001). As well as optimising sward utilisation at grazing, as once the PRG plant passes the three leaf stage, the oldest leaf senesces, leading to a reduction in sward quality and utilisation (Fulkerson and Donaghy 2001). Defoliating plants that have not reached the three-leaf stage was found to suppress regrowth of swards and increase the levels of

potassium and N (in the form of nitrate and other non-protein N compounds), possibly causing metabolic problems in grazing stock (Fulkerson and Donaghy, 2001).

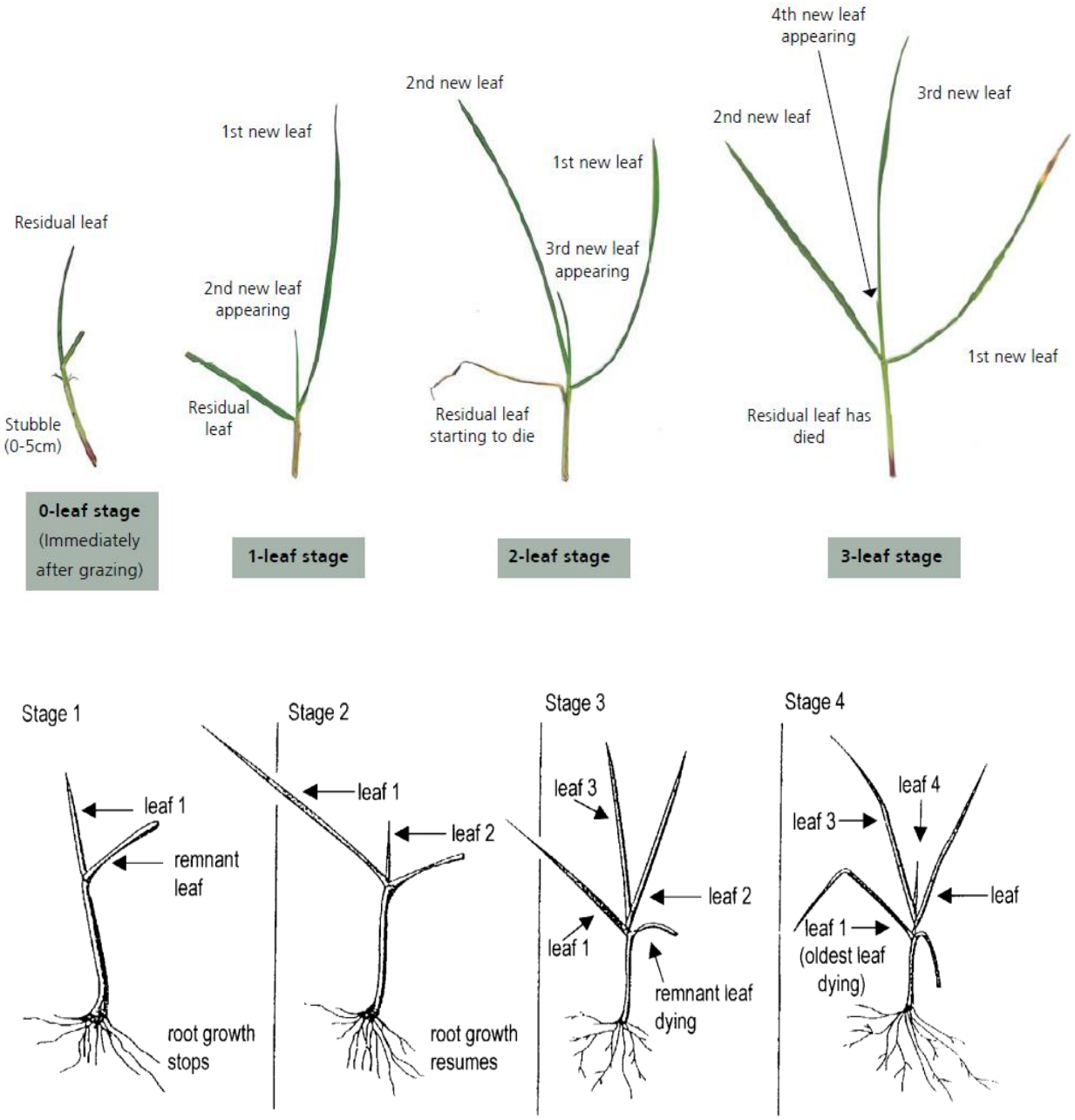


Figure 1.2: Perennial ryegrass leaf stage development from the 0 leaf stage to the 3 leaf stage, as presented in the Dairy NZ 'Perennial ryegrass grazing management in spring' as adopted from Figure 1B (Donaghy, 1998).

1.5.4 Tissue Turnover

Tissue turnover is the continued production of material within a sward; new material appears and old material senesces (Brereton et al., 1985). After defoliation, sward turnover is rapid (Davies, 1977) and any leaf material remaining senesces and new leaves begin to appear. Leaf appearance rate (LAR) is the rate at which new leaves

appear per tiller per day (Culleton, 1987). When conditions are optimum new leaves appear every 7-10 days (Alberda and Sibma, 1968), and the entire leaf canopy is replaced. There is variation in leaf appearance across the growing season, December is the longest at 32.7 days, September took 9.2 days, in January it took 33.6 days and declined to 7.9 days in May (Peacock, 1975). Due to the variation in LAR across the growing season, defoliation interval must adapt in line with LAR to allow swards reach the three-leaf stage for optimum utilisation (Fulkerson and Donaghy, 2001).

Both environmental conditions and management Peacock (1975) can affect LAR. Leaf appearance rate it is closely correlated to air temperature and as temperatures increase (up until 25°C) LAR increases linearly (Thomas and Norris, 1977; Davies and Simons, 1979). However, this response to temperature is also influenced by vernalisation and LAR responds better to temperature in spring compared to in autumn (Davies, 1971), if temperatures are the same in autumn and spring LAR will be greater in spring. Davies and Thomas (1983) reported that LAR was very low in winter (0.015 leaves tiller^{-1} day^{-1}) and very high in the summer (0.14 tiller^{-1} day^{-1}) reflecting the differences in LAR due to temperatures. Light intensity and the length of photoperiod can also affect LAR; very low light intensity as a result of seasonal fluctuations and shading severely limit LAR (Langer, 1979). This also leads to the reduction in LAR reported in winter (Davies and Thomas, 1983). Management practices, particularly defoliation, have been reported to initially lower LAR (Davies, 1977). However, there is a consequent increase in LAR after the initial lower LAR post defoliation when compared to LAR of undefoliated plants.

Leaf extension rate (LER) is the increase in leaf length for each tiller divided by the number of days between measurements (mm tiller^{-1} day^{-1}; Culleton, 1987), and is intrinsically linked to the productivity of a sward. Peacock (1975) reported that LER is affected by the air temperature at the apex of the PRG plant. In a controlled environment, with a temperature average of 15^{o}C, the average LER has been reported to be 31.4 mm tiller^{-1} day^{-1} (Peacock, 1975). When the PRG is exposed to a normal yearly cycle it was found that the LER was highest in April and May (30 mm tiller^{-1} day^{-1}; Peacock, 1975) and lowest over winter (2 mm tiller^{-1} day^{-1} or lower;

Brereton, 1985). Despite the low temperatures over winter, LER is continuously occurring (Parsons and Robson, 1980; Brereton et al., 1985; Culleton, 1987; Carton et al., 1988; Hennessy et al., 2008). Similar to LAR, LER is affected by the vernalisation response in spring, and at the same temperature it will show a greater response in spring compared to autumn (Peacock, 1975; Thomas and Norris, 1977; Parsons and Robson, 1980; Brereton et al., 1985; Hennessy et al., 2008; Table 1.2).

Table 1.2: The percentage response of leaf extension rate (mm tiller^{-1} day^{-1}; LER) in spring compared to autumn at three different temperatures (5 ^{o}C, 10 ^{o}C, 14 ^{o}C) as adopted from Peacock (1975).

Percentage response of LER in spring compared to Autumn	Temperature
20%	5^{o}C
50%	10 ^{o}C
100%	14 ^{o}C

Leaf extension rate can also be affected by the length of the sheath tube, after a severe defoliation in autumn, when the sheath tube is shortened, regrowth is reduced (Grant et al., 1981). As the sheath tube is shorter after defoliation, it reduces the LER of the leaves expanding through the sheath tube (Grant et al., 1981) which is exacerbated by reduced growth rates in autumn.

Leaf senescence is characterised by a loss of chlorophyll, yellowing of the lamina, degradation of proteins, membranes, lipids and RNA which are then recycled to young plant tissue (Nooden, 2012). Leaf senescence in plants can be an age related internal process, or due to stress inducing environmental factors such as shading, drought, pathogen attacks or oxidative stresses (Hensel et al., 1993; Quirino et al., 2000). Leaf senescence rate (LSR) is the quantity of leaf senescing for each individual tiller divided by the number of days between measurements (mm tiller^{-1} day^{-1}; Culleton, 1987). Additionally, LSR partitions available carbon to aid leaf tissue turnover (Carton et al., 1988) which can be beneficial to herbage production. Similar to LAR and LER, LSR is affected by temperature (Hennessy et al., 2006), as

temperatures increase LSR also increases and responds faster to temperature post vernalisation (Thomas and Norris, 1981; Carton et al., 1988). As LAR and LER increase so too does LSR, as the amount of leaf material to senesce increases (Hennessy et al., 2006). The LSR is also affected by the time between defoliations; as the time between defoliations increases so too does the LSR resulting in an increase in the overall proportion of senescent material in the sward (Davies and Simons, 1979).

1.5.5 Extended sheath and tiller height

Free leaf lamina (FLL) is a sward structural characteristic measured by taking the extended sheath height (ESH) from the extended tiller height (ETH; Figure 1.4). The FLL reflects the proportion of green leaf on a plant and is reported to be a good indicator of intake potential (Gilliland et al., 2002) in PRG and improved grazing efficiency in swards (Byrne et al., 2018).

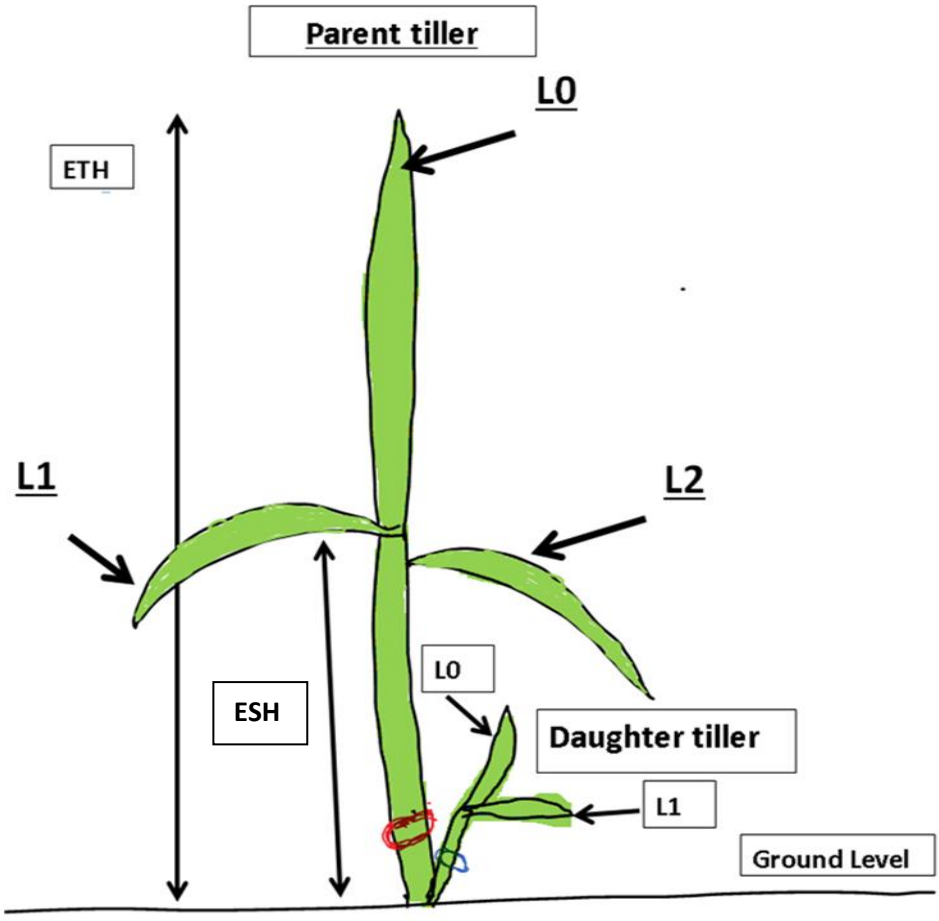


Figure 1.4: A perennial ryegrass parent tiller, marked with red wire, shows the extended sheath height (ESH) and extended tiller height (ETH) measurement area and the leaves presented as L0-the youngest leaf, L1- the second youngest leaf and L2- the oldest leaf as investigated in the current thesis.

1.6 Light transmitted to the base of the sward

Plants utilise photosynthetically active radiation (PAR) which is light in the 400 – 700 nanometres wave length range, for conversion to chemical energy (McCree, 1981). Studies on light availability in forage grasses have looked at how it applies to optimising herbage production and quality (Woledge et al., 1992; Kephart and Buxton, 1993). When there is low light availability in grasses, common adaptive morphological responses such as increased leaf area index (leaf area per unit of ground; LAI; Robson and Sheehy, 1981); increased shoot/root ratio, decreased leaf thickness, reductions in mesophyll cell number and stomatal density and a decreased

photosynthetic capacity are all frequently observed (Woledge, 1978; Prioul et al., 1980; Allard et al., 1991; Kephart et al., 1992).

Optimum LAI is the point at which nearly all of the available light is intercepted and the photosynthetic rate is at the maximum (Jaindl and Sharrow, 1991). As leaves age and are shaded during development the photosynthetic capacity reduces (Woledge, 1978).

1.7 Water soluble carbohydrates

Water soluble carbohydrates and starch are the non-structural carbohydrates which are the first formed products of photosynthesis and used for the processes associated with growth (Danckwerts and Gordan, 1987). Water soluble carbohydrates are made up of sucrose and fructosans (Mc Donald and Henderson, 1964). Weinman (1948) reported the importance of WSC concentration on plant regrowth potential and persistence; lower concentrations result in reduced regrowth potential and persistence. The balance between source (photosynthesis) and sinks (growth and respiration) determines concentrations of starch and WSC. The absolute levels of WSC and starch are determined by plant growth and environmental conditions (White, 1973). Perennial ryegrass WSC reserves are lowest once the first leaf has appeared post defoliation and highest once the plant has reached the three-leaf stage (Fulkerson and Donaghy, 2001). Water soluble carbohydrates are generally highest in winter when temperature is low and skies are clear (Fulkerson et al., 1998) as factors that reduce growth rates (low temperature) and a low rate of respiration (Auda et al., 1966) allow WSC to accumulate. Once energy requirements for growth and respiration have been met the remaining WSC and starch are stored in the tiller base (stubble; < 5cm) of the PRG plant (Fulkerson and Slack, 1994).

The production of new leaves, the primary component of sward growth, requires energy from the stubble input before the first leaf emerges and begins to photosynthesise (Davies and Simons, 1979). After defoliation, WSC is used for regrowth and then increases as PRG goes through its regrowth cycle (Fulkerson and Slack, 1994). Water soluble carbohydrates in the stubble are used post-grazing, to stimulate regrowth of the remnant leaf and the emergence of the first leaf (Davies

and Simons, 1979). As the plant begins to photosynthesise again, WSC are accumulated and stored until the plant reaches the third-leaf stage (Davies and Simons, 1979, Fulkerson and Donaghy, 2001). A limiting factor of regrowth is the carbohydrate store in the base of the tiller (Lee et al., 2005). If the plant was not given the required regrowth interval to replenish WSC reserves, subsequent regrowth may be suppressed and persistency reduced (Fulkerson and Donaghy, 2001). When three new leaves have fully emerged post-defoliation, WSC levels are completely restored (Fulkerson and Donaghy, 2001). It is important that WSC levels in the stem are allowed to adequately replenish in order to stimulate regrowth as there is a positive correlation between regrowth capacity and WSC concentration (Fulkerson and Donaghy, 2001; Figure 1.2).

It should also be noted WSC can be found outside of the stubble in the plant, particularly in the lamina (White, 1973). A high WSC content in the lamina results in the lamina being the most digestible part of the plant and increases palatability (Garry et al., 2020). A high PRG leaf percentage in the grazing sward maximizes the nutritive quality in the sward (Beecher et al., 2015) and grazing efficiency (Byrne et al., 2018).

1.8 Vernalisation

Vernalisation is the physiological process in which prolonged cold exposure provides plants, such as PRG, with the competency to produce seed heads (Xu and Chong, 2018). The critical day light length required at the apex of the PRG plant to achieve vernalisation is between 8 – 13 hours (Cooper, 1951). It has been reported in Ireland, that vernalisation occurs in the first two weeks of January (Cooper, 1960; Parsons and Robson 1980). Plants have the ability to have a greater response to temperature changes post-vernalisation (Peacock, 1976; Thomas & Norris, 1977; Wingler & Hennessy, 2016). The threshold temperature for positive net herbage production in vernalised plants is 5˚C, and for unvernalised plants it is 8˚C (Brereton et al., 1985).

1.9 Tiller density

The rates of tiller production and growth of individual tillers are integral to the overall production of the sward (Kays and Harper, 1974). Perennial ryegrass tillers are

relatively short lived, with the majority of tillers surviving for 12 months, while few persist into a second year (Langer, 1956; Robson, 1968; Davies, 1977). There can be various reasons for PRG tiller mortality, including the removal of growing points during stem elongation, flowering, shading, pests and uprooting during grazing (Ong et al., 1978; Woodward, 1998). Previous studies on tillering of PRG swards indicated that tiller numbers peak in spring and autumn (Garwood, 1969; Laidlaw, 2005). Peacock (1975) found that the number of PRG tillers remained remarkably constant during the autumn at around 8000 m^{-2} and tillers were almost entirely vegetative. Further studies showed that allowing solar radiation to reach developing tiller buds at the base of the sward in existing tillers results in rapid tiller production from late February to mid-April (Thomas and Norris, 1981).

Davies and Simons (1979) found that tiller survival at low temperatures was poorer in swards not defoliated after the end of August. This could be due to the increased level of shading affecting tiller production (Langer, 1979) and mortality (Laidlaw and Mayne, 2000). It would also have been exacerbated by the decreased grass growth rates due to lower temperatures which would inhibit the growth of tillers in the sward (Peacock, 1975). Davies and Simons (1979) reported that the number of tillers in spring increased on swards that had been defoliated later and/or more frequently, during the autumn and winter period, as a result of lower levels of herbage on swards over winter. Thom (1991) found that reproductive development of tillers increases the vulnerability of tillers to seasonal and management stresses; reproductive tillers have a higher probability of dying as they have already reproduced by putting out a seed head. However, the interaction of physiological status, defoliation stress and climate are all likely to be the most important factors when determining tiller and ultimately overall sward persistence (Thom, 1991). Accumulation of large herbage mass is a major cause of tiller death (Ong et al., 1978; Carton et al 1989) due to increased levels of shading at the base of the sward and reduced light penetration. Thus a short interval between grazing is favoured for the maintenance of tiller density (L'Huillier, 1987). Stress factors such as severe defoliation (stubble height <2.5cm) and physical damage (dung, urine scorch) can also lead to tiller and plant death and

sward defoliation (Wade, 1979; Thom et al., 1986, Bahmani et al., 2003); these stress factors should be avoided as they can result in an overall reduction in tiller density.

1.10 Sward Quality

Nutritive value of grass is determined by its chemical composition (Rattray and Joyce, 1974). Chemical composition in PRG is highly variable (Beever et al., 2000; Figure 1.4), with stage of maturity having a significant impact; increasing cell wall and cell contents and decreasing crude protein concentration (Beever et al., 2000; Figure 1.4). Sward morphological features can have a significant impact on nutrient availability. During the reproductive stage, the lignin content increases, resulting in a decline in nutritive value (Browse et al 1984; Tallowin et al 1989). Frame et al. (1992) reported that different growth stages (reproductive stage has lower quality than the vegetative due to increased lignin; Beecher et al., 2015), soil fertility (soil pH and soil nutrient; P and K index), grazing and cutting management (defoliation interval and post-grazing sward height) and proportion of leaf, stem and dead material all impact sward quality. The chemical composition of green leaf material has a higher nutritive value that steam or dead material, and as such is more suited to grazing (Frame, 1992). Therefore, pre-grazing herbage mass can play a significant role in sward nutritive value (McEvoy et al., 2009; Beecher et al., 2018) having more green leaf material gives a better sward quality. As pre grazing herbage mass increases, there is a greater percentage of stem and senescent material which reduces sward quality (Binnie et al., 2001). Sward quality can also be affected by the amount of N fertiliser applied as is impacts chemical composition (Delegarde et al., 1997). Chemical composition can also be altered by the PRG cultivar (Wims et al., 2013) resulting in a change in sward quality through breeding, an example of this is a higher WSC in the leaves. Finally, Incorporating different sward species (Johanson et al., 2017; Grace et al., 2019) can also alter the swards chemical composition and in the case of addition of white clover quality is improved (Schills et al., 1999).

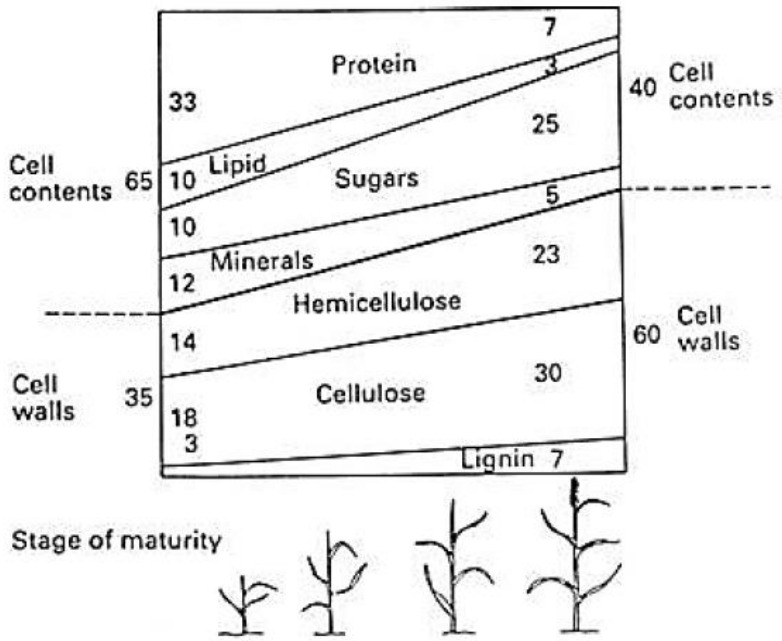


Figure 1.4: The effect of grass plant maturity on the chemical composition of the sward (Beever et al., 2000).

Digestible energy content of a forage is reported in the organic matter digestibility (OMD) (Jones, 2013). Organic matter digestibility is probably the best individual parameter to estimate herbage nutritional value (Van Soest 1994; Wilkins & Humphreys 2003). The OMD concentration of PRG changes throughout the year, McEvoy et al. (2009) and Beecher et al. (2015) reported that grass OMD is greatest in spring (as high as 850 g kg DM^{-1}) when in the vegetative state, and continually declines as PRG moves from the vegetative stage to the reproductive stage (McEvoy et al., 2009). Herbage has a lower OMD (450 g kg DM^{-1}) in autumn and winter and has a lower feed value compared to spring. The decline in OMD can be attributed to increasing fibre content (Coleman et al., 2010), as a result of increasing the true stem proportion and cell wall fraction (Beecher et al., 2015). Perennial ryegrass OMD can have a significant impact on animal performance (Lippke, 1980), as the OMD of herbage increases, animal dry matter intake and subsequent production increases (McEvoy et al., 2008; Johansen et al., 2017). Both parameters, CP and NDF contents, are usually correlated with organic matter digestibility is usually correlated with

neutral detergent fibre (NDF) and crude protein (CP; Wilson & Kennedy 1996; Wilkins & Humphreys, 2003).

The fibre within a PRG sward is measured using NDF (Wilkins and Humphreys, 2003). Herbage digestibility is largely influenced by cell wall concentration (Van Soest, 1994). Neutral detergent fibre contains cellulose, hemicelluloses and lignin and acid detergent fibre (ADF) contains cellulose and lignin fractions (Minson, 1990, Van Soest, 1994). Neutral detergent fibre is an estimate of the cell wall concentration and is negatively related to dry matter intake for the animal performance, while ADF is negatively related to the digestibility of forages (Van Soest, 1994, Bruxton, 1996). The total insoluble matrix fibre, represented by NDF, relates to rumination, gut fill and dry matter intake (Van Soest, 1994). Digestibility of NDF therefore influences animal performance (Oba & Allen 1999). If a PRG sward is well managed and fertilised it will have a crude protein (CP) concentration greater than 20% throughout the grazing season (Kennedy et al., 2005; Wims et al., 2010). Therefore a well-managed sward generally exceeds the CP requirements of a dairy cow (15 -18% CP; NRC, 2001). The CP content in a sward is affected by many factors; a sward in the vegetative stage has a higher CP concentration compared to the reproductive stage (Steinshamn et al., 2016; Elgersma and Soegaard, 2018). Nitrogen fertiliser increases the CP concentration of the sward (Van Soest 1994). Givens et al. (1993) found summer regrowth to be lower in CP concentration compared to spring regrowth in PRG swards due to the decrease in leaf proportion and an increase in stem proportion in PRG swards.

1.11 Factors affecting herbage production

Perennial ryegrass herbage production is dependent multiple factors at farm level (O'Donovan et al., 2011). Soil type, region, altitude, aspect and meteorological conditions, all factors that cannot be controllable by farmers, have a major impact on herbage production (Frame et al., 1992, O'Donovan et al., 2011). However, management factors controlled by the farmer, can play a significant role in herbage production, such as N fertiliser application, soil pH, and soil indexes for P and K,

grazing or cutting intensity, rotation length and spring and autumn grazing management (O'Donovan et al., 2011).

Nitrogen fertiliser is the most important nutrient influencing grass and forage production as PRG has a strong capability to respond to N fertiliser (Whitehead, 1995, Hannaway et al., 1999) and its supply is largely under the farmer's control (Whitehead, 1995). In agricultural grassland, N is required for increased grass growth for the production of meat, milk and wool (Whitehead, 1995). For grass growth, N is derived from the soil through different processes including the mineralisation of soil organic N, animal excreta and N fixed from the atmosphere by legume plants and chemical fertiliser (Whitehead, 1995). The N in the soil available for plant uptake varies from 6 to 250 kg N ha^{-1} $annum^{-1}$ (Whitehead, 1995). The capacity of grass swards to take up N is high, compared to other crops; in favourable conditions can exceed 500 kg N ha^{-1} (Whitehead, 1995). Daily rate of N uptake varies and depends on factors such as stage of growth of the sward, time interval since the application of N fertiliser and/or defoliation, time of year, and weather conditions such as temperature and rainfall (Whitehead, 1995). The response herbage growth to N applied is greatest when grass is actively growing and when conditions of light, temperature and water supply are favourable such as in late spring/early summer (Murphy, 1982). The use of N can extend the grazing season at three weeks extra production at either end of the growing season (Armitage and Templeman, 1964; McCarthy, 1982). Spring N application is considered important to increasing herbage availability in spring (Murphy, 1977; Carton et al., 1989; O Donovan et al., 2004). The response to N fertiliser in spring has shown to be > 10 kg DM kg^{-1} N (Murphy, 1977; O Donovan et al., 2004). However, this response can vary depending on soil type, soil fertility, soil temperature and rainfall (Sun et al., 2008) which makes the prediction of application date difficult due to year to year variations (Stevens et al., 1989). Previous research concluded that the optimum date for N application over winter and into spring was mid to late January in the south of Ireland (O'Donovan et al., 2004) and early to mid-February in the midlands and north of Ireland (Stevens et al., 1989). During the main growing season the DM yield increases linearly in response to N application rates up to 250-350 kg N ha^{-1} as grass is growing (Frame, 1992). After

350 kg N ha^{-1} the response declines until the maximum DM yield is attained, and there may be no further response, between 450 and 600 kg N ha^{-1}. The response to applied N in late August/early September reduces, compared to mid-season (van Burg et al., 1981), due to a decrease in grass growth potential as light intensity decreases (Prins and van Burg, 1977), and due to higher soil N mineralisation than in summer (Jordon and Smith, 1985).

Grazing or cutting intensity is the height at which the sward is defoliated to (post-grazing sward height; post-GSH). The target post-GSH, as outlined in the current grazing recommendations (Teagasc, 2011) is ≤ 4 cm in the first grazing rotation (McEvoy et al., 2008), between 4 – 4.5 cm in subsequent rotations and 4 cm in the final rotation (McEvoy et al., 2009). Optimal grazing intensity balances sward utilisation, with no negative impact on herbage or animal production (Ganche et al., 2015). Swards grazed severely (a very low post-grazing residual < 2.7 cm) experienced conflicting effects on regrowth potential (Frame and Hunt, 1971; Carton et al., 1988; Ganche et al., 2015). Kennedy et al., (2007) and Ganche at al., (2013) reported that increasing grazing severity in spring lead to an increase in herbage utilisation, particularly at a time when herbage available is limited (McEvoy et al., 2008; Ganche et al., 2013). McEvoy et al., (2008) reported that where a post-grazing sward height was not restricted (5 cm) and a low grass allowance was offered in early spring, there was a greater sward utilisation. When swards are grazed laxly (> 5 cm), it can lead to the accumulation of stem and senescent material (Mayne et al., 1987), in subsequent rotations reducing over sward quality and utilisation. Dillon et al., (1998) reported that to increase herbage accumulation in autumn, grazing severity can also be reduced (> 5 cm). Mayne et al., (1987) showed this can result in an increase in the proportion of stem and senescent material, resulting in a reduction in sward quality.

Rotational grazing systems, common in Ireland (Roche et al., 2017), are defined as systems in which paddocks are grazed in sequence with animals spending a short period of time (from hours to days) in each paddock. The length of time between grazings on individual paddocks in a rotational grazing system is known as the rotation length. Coleno and Duru (1999) described rotation length as the period of time which elapses between grazing a paddock and the date at which the cows return

to the paddock as part of the grazing rotation. The main advantages of rotational grazing, as suggested by Matthew et al. (1999), are controlled intake by animals, rationing of pastures and increased net herbage accumulation. Rotation length is recommended, in New Zealand, to match the PRG plant reaching the three-leaf stage (Fulkerson and Donaghy, 2001), and rotation length should follow this throughout the season. On average it takes 7 days for one leaf to appear when all growth factors are optimal (Fulkerson and Donaghy, 2001), similar to grazing recommendation in Ireland, that rotation length mid-season of 21 days (Tunon, 2013), to achieve maximum utilisation and production. Any rotation length shorter than 21 days increases PRG tiller density due to increased light interception but can lead to a reduction in herbage mass due to a shorter regrowth interval and smaller tillers. Wims et al. (2014) also found that a shorter rotation length can have a negative effect on the WSC reserves supporting the DM production. Rotation length is continually changing across the growing season, to match growth and ensure the PRG matches the 3-leaf stage (Fulkerson and Donaghy, 2001). When the temperatures are lower, particularly in autumn, rotation lengths are extended to increase the herbage produced (Lawrence et al., 2017). In spring temperatures are also lower and a set rotation length can be used to ensure grass is maintained in the diet of a cow until growth rates equal the herd feed demand (Bryant and L'Huillier, 1986).

1.12 Extension of the grazing season

Rotational grazing systems were found to be particularly useful in winter, with paddocks gradually closed to build a 'bank of grass' i.e. accumulating herbage masses (Matthew et al., 1999). This building herbage mass facilitates the extension of the grazing season in autumn and spring. The extension of the grazing season is positively correlated with increased on-farm profitability (Hanrahan et al., 2018), a reduction in the carbon footprint of milk (O' Brien et al., 2015). The main grazing season takes place between April and August and there is a surplus of grass compared to herd requirements. Outside of the main grazing season, management factors heavily influence the amount of grass available and two specific management practices have been developed (Figure 1.6) to accumulate herbage (Teagasc, 2011). For extended grazing in autumn, herbage masses are accumulated from August to allow for

increased herbage to grazed throughout the final grazing rotation. For extension of the grazing season in spring, the closing date of paddock in autumn influences the herbage available for spring as these herbage masses are carried over winter while cows are housed (Hennessy et al., 2006; Ryan et al., 2010; Lawrence et al., 2017).

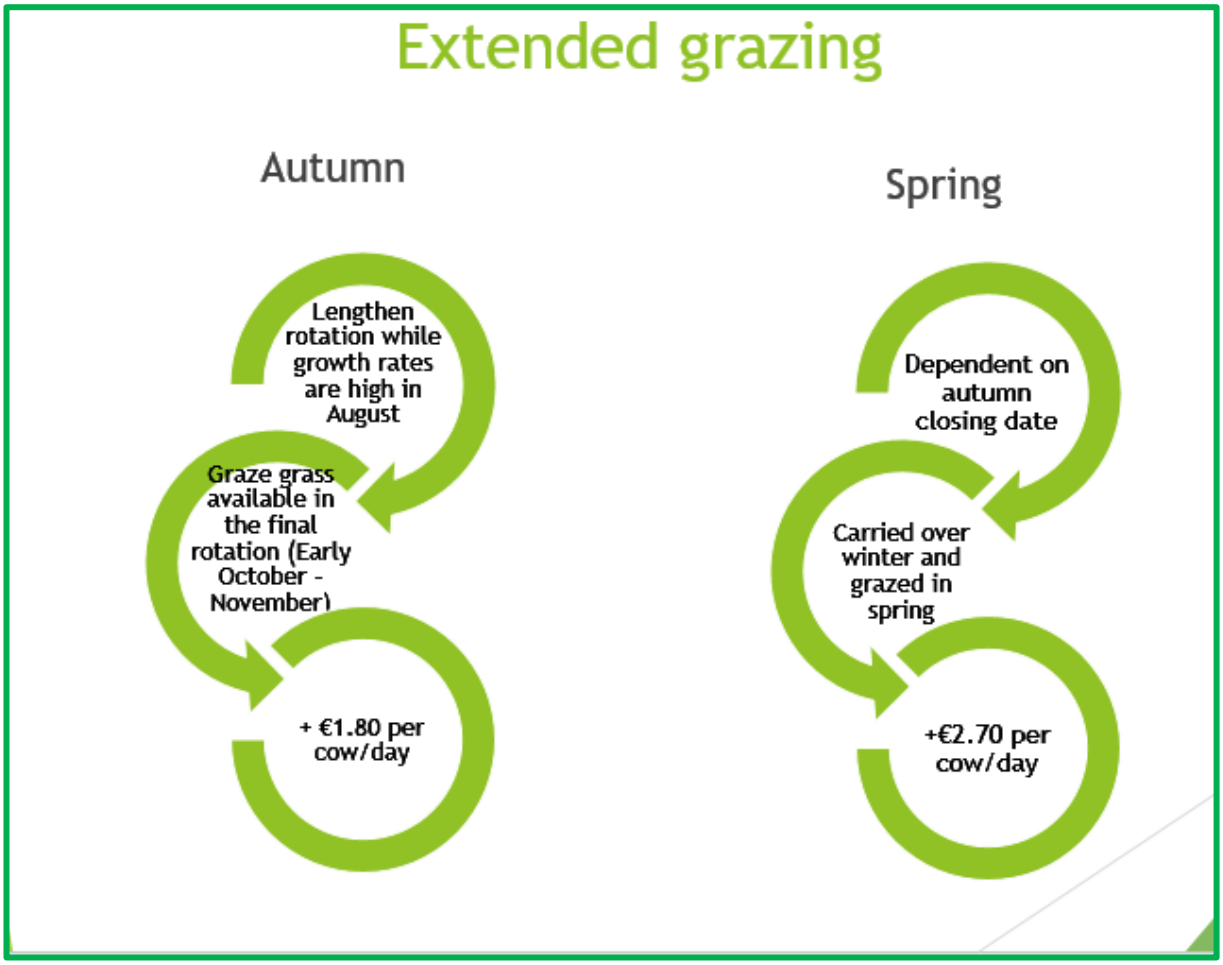


Figure 1.6: Management practices implemented for the extension of the grazing season in autumn and spring.

1.13 Autumn grazing management

Improving management practices to extend the grazing season in autumn before cows are housed and balance this with the amount of grass that will be available in spring when cows are turned post-calving is important to improve efficiency and sustainability on farm. Autumn closing date refers to the date a paddock receives its final defoliation in autumn, this paddock will then remain closed and un-defoliated until spring (Claffey, 2019).

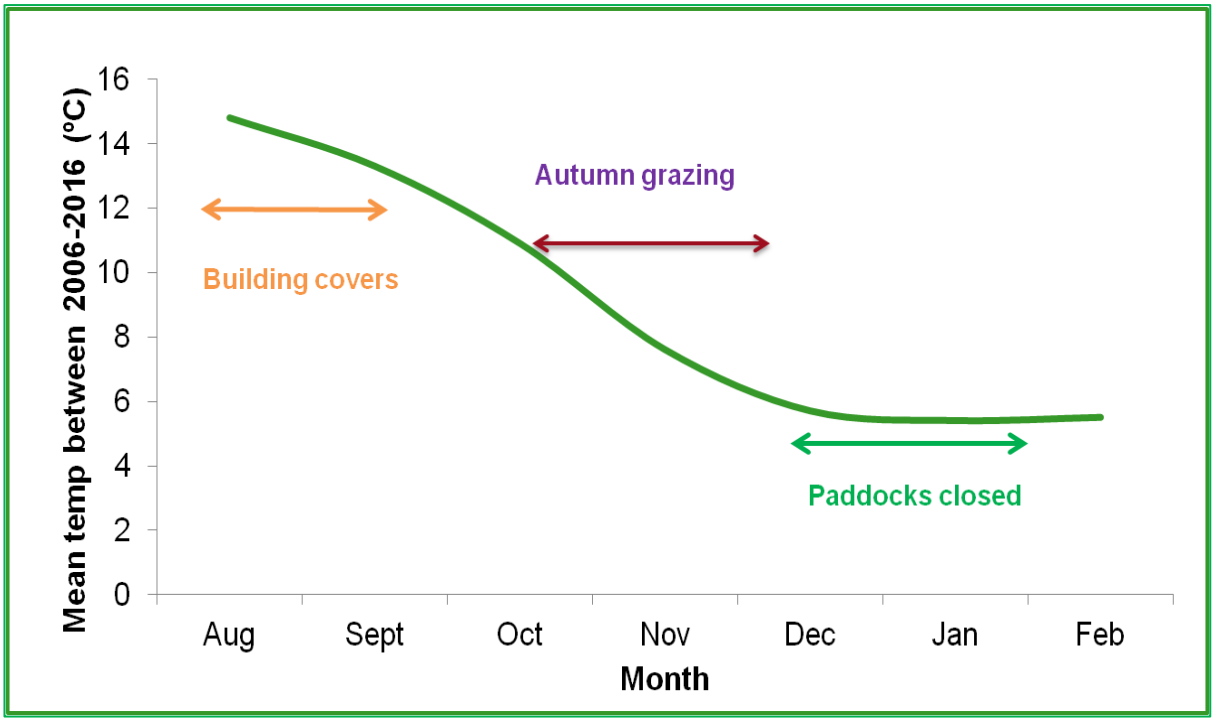


Figure 1.7: Irish grazing management practices from August to February (Teagasc, 2011) compared to decreasing mean temperature (°C; Pasture base, 2017); covers are built from August for the extension of the final rotation from the 15th October where autumn grazing takes place until the 21st November when paddocks are closed for winter until turnout in spring.

Every additional day at grass in autumn worth an extra €1.80 $cow^{-1}day^{-1}$ (Teagasc, 2011). Extending the autumn grazing season requires specific grazing management targets, as growth rates begin to decline in autumn (Hennessy et al., 2006; Figure 1.7). As a result quantities of herbage are built up from August, prior to the grass growth decline in autumn, to facilitate the extension of the grazing season (Teagasc, 2011; Claffey et al., 2019). Herbage is accumulated by extending rotation length by 2.5 days a week from the 10th of August (Teagasc, 2011). Previous management recommendations aimed to begin the final grazing rotation on the 15th of October, to have 60% of the farm grazed by the 7th of November and the last grazing to take place on the 21st of November (Teagasc, 2011). However, work by Claffey et al., (2019) has recommended to move away from this date centred grazing management to focusing on having an average farm cover between 650 -750 kg DM ha^{-1} on the 1st of December. Previous animal studies on the extension of the grazing season in

autumn, report that increasing the proportion of grazed grass in the diet was beneficial as the milk protein concentration decreases as grazed grass is replaced by silage (Dillon et al., 1998; Claffey et al., 2019). Extending the grazing season in autumn also leads to a reduction in costs due to the lower supplementation requirement (Läpple et al., 2012).

However, extending the length of the grazing season in autumn could potentially have a negative impact on spring grass availability (Claffey et al., 2019), as autumn closing date impacts the herbage available in spring (Roche et al., 1996, Hennessy et al., 2006; Ryan et al. 2010). A summary of previous Irish research on autumn grazing management has been described in Table 1.3. This research has been carried out on plot studies (Carton et al., 1998; Hennessy et al., 2006; Lawrence et al., 2017), within grazing studies (Roche et al., 1996; Ryan et al., 2010) or on commercial farms (O' Donovan et al., 2002).

Earlier mechanical studies show that lengthening defoliation interval over winter increased the amount of harvestable herbage in spring (Murphy et al., 1977; Davies and Simons, 1979; Carton et al., 1988). This was then applied to autumn grazing management and closing date was studied as key factor to accumulate herbage over winter in an Irish pasture-based production system (Lawrence et al., 2017, Ryan et al., 2010, Hennessy et al., 2006, O'Donovan et al., 2002, Roche et al., 1996; Table 1.3). Autumn closing date has a direct correlation with the amount of available grass the following spring (O'Donovan et al., 2002, Lawrence et al., 2017). It was reported that every one day extra a paddock is closed from October 1st resulted in between 10 and 15 kg DM ha^{-1} more herbage in spring (Lawrence et al., 2017, O'Donovan et al., 2002; respectively). Closing paddocks earlier in autumn can lead to an earlier turnout in spring; this is beneficial as the proportion of grass in the diet can be increased and this will improve production (Claffey et al., 2019)

Table 1.3: Overview of previous research on autumn and spring grazing management practices in Ireland.

Authors	Management	Experimental design	Duration of experiment	Autumn Closing Date	Defoliation Date	Grazing residual	Measurements	Measurement Dates
Carton et al. (1988)	Rotational paddock grazing and silage cuts prior to autumn closing treatment	24 plots (10 x 10 m)	1 year	Mid-Sept Mid-Oct Mid-Nov Mid-Dec	22-Apr	Lax and severe grazing treatments	Herbage mass Dry matter Leaf, stem and dead proportion	8 times from closing until 22-April
Roche et al. (1996)	Rotational paddock grazing and silage cuts prior to autumn closing treatment	32 paddocks	1 year	20-Oct 2-Dec	4-Mar 25-Mar	4 cm	Herbage mass Dry matter Quality: Digestibility, NDF and crude protein Height (sward stick) Leaf area index Tiller density Milk yield Grass intake	20-Oct 11-Nov 1-Dec 13-Jan 13-Feb 14-Mar
O'Donovan et al. (2002)	Rotational paddock grazing on farm	9 farms within 170 km of Cork City	2 years	Decided on farm and recorded	-	4 cm	Visual assessment of herbage mass	Once per month between Oct – Feb Twice per month Mar and Apr
Hennessy et al. (2006)	Sward (previously rotationally	64 plots (9 x 10 m)	Moorepark – 2 years	10-Aug 1-Sept 20-Sept	20-Nov 20-Dec 20-Jan	4 cm	Herbage mass Dry matter	Each defoliation date

	grazed and cut for silage) divided into plots (number) and grazed Two sites: Moorepark and Grange	4 x 4 factorial design	Grange – 3 years	10-Oct	20-Feb		Leaf, stem and dead proportion Sward composition Tiller density Quality: DMD and crude protein	Late Mar/ early Apr Every grazing hereafter
Ryan et al. (2010)	Rotational paddock grazing as part of a larger experiment	36 paddocks (15 x 15 m)	1 year	23 Sept – 1 Dec Mean CD: 29-Sept 13-Oct 27-Oct 10-Nov 24-Nov	10 Feb – 19 April Mean defoliation dates: 16-Feb 2-Mar 15-Mar 29-Mar 12-Apr	4 cm	Herbage mass Dry matter Leaf, stem and dead proportion Leaf area index Tiller density Leaf mass	28-Nov 19-Dec 9-Jan 20-Jan 20-Feb
Lawrence et al. (2017)	Sward (previously rotationally grazed and cut for silage) divided into 48 plots and defoliated mechanically	48 plots (1.5 x 5 m) 2 x 4 factorial design	2 years	1-Oct 15-Oct 1-Nov 14-Nov	1-Feb 1-Mar	4 cm	Herbage mass Quality: DMD and crude protein Leaf, stem and dead proportion Tiller density	Each CD 15-Dec 15-Jan Each defoliation date

1.14 Spring grazing management

Spring grazing management aims to incorporate the highest percentage of grazed grass into the diet as possible to replace grass silage with grazed grass (Finneran et al., 2010) and improving the subsequent herbage quality (Kennedy et al., 2006). One study suggested a negative impact on early spring turnout on herbage production, where herbage was reduced from turnout in mid-March compared to mid-April (Carton et al., 1989). However, other studies have reported no significant difference in herbage produced after an early turnout, which would increase herbage availability in spring (McFeely and McCarthy, 1981; O Donovan et al., 2002). Claffey et al. (2020) reported that having increased herbage availability in spring, increased daily herbage allowance, and resulted in an increase in animal production by 1.4 kg milk $cow^{-1}day^{-1}$. Current spring management recommendations propose earlier turnout; they aim to begin grazing in early February, have approx. 30% grazed by March 1st, with 60% of the area grazed by 17th of March and begin the second rotation in early April (Teagasc, 2011). There have been significant advances in grassland management practices since these studies were conducted (Kennedy et al., 2006; McCarthy et al., 2013; Claffey et al., 2020) and in PRG variety and on spring herbage production potential (McDonagh et al., 2016). PastureBase data showed some benefit of early turnout (February grazing) on commercial farms, with a significant increase in spring herbage production shown: Egan et al. (2017) reported that for every additional 1% in area grazed in February, there was an additional 14 kg DM ha^{-1} grown by the 10th of April, highlighting the importance of early spring grazing.

1.15 Mid-season grazing management

Summer grazing management differs from autumn and spring as the growth rates surpass herbage demand and as a result herd feed demand can be met with grazed grass (O Donovan et al., 2002). The PRG sward is in the reproductive stage, which can result in a decreases in sward quality due to the increase in mature stem material (Beecher et al., 2015). The chemical composition of mature stem increases the fibre content in the

sward (NDF 350 – 400 g kg^{-1} DM; ADF 180 – 250 g kg^{-1} DM) which decreases digestibility (Beecher et al., 2015). In recent years there has been a move to later heading varieties to overcome this quality decline (O' Donovan et al., 2011; Tubritt et al., 2021). The average farm cover per cow during the summer should be maintained at 160 to 190 kg DM day^{-1} (Teagasc, 2011). Any excess herbage is conserved as grass silage (McEniry et al., 2011) and the target post grazing sward height is 4 – 4.5 cm (O Donovan et al., 2011) and the target pre-grazing yields are between 1,300 -1,600kg DM ha^{-1} with high leaf content (Wims et al., 2013) in order to maximise herbage production and utilisation. During mid-season the suggested a rotation length of 18–21 days will optimise both herbage production and utilisation during the April to mid-August period (Kennedy et al. 2007).

1.16 Incorporating perennial ryegrass morphology and physiology with spring and autumn grazing management

A review by Langensiepen et al. (2020) identified the need for plant physiology to be integrated with agricultural practices to achieve sustainable production. Within the pasture-based production systems there is room for management practices to be adapted and improved (Hennessy and Wingler, 2016). This literature review has looked at PRG morphology, physiology and pasture-based systems separately. In particular autumn and spring grazing management recommendations need to be improved to increase the length of the grazing season; grassland productivity is limited by low temperatures and seasonality of herbage growth (Hennessy and Wingler, 2016).

Previous research has reported that autumn grazing management strategies can impact LAR, with defoliation of swards in autumn generally followed by the initial suppression of LAR (Davies, 1977). Although LAR is supressed by autumn defoliation there is then a benefit on spring LAR, as the LAR is greater than autumn rested swards (Davies and Simons, 1979). This can be accounted for by the increased light transmitted to the base of the sward once defoliated (Langer, 1979), and less senescent material at the base of the sward which is less photosynthetically efficient (Woledge, 1978). Thomas and Norris

(1977) also found that LAR was only reduced for the first month after defoliation in October, which would indicate the sward has enough time to recover after the defoliation before the spring. High levels of herbage mass being accumulated and carried over winter can depress LAR as a result of increased defoliation interval and/or delayed winter grazing (Hennessy et al. 2008). Hennessy et al. (2008) reported that LER over winter decreases, due to decreased temperature, and an increase in LSR due to increased herbage available for senescence. This coincides with an overall decline in herbage mass and quality over winter from early autumn closing swards (Hennessy et al., 2006; 2008). Autumn grazing management has also been found to affect leaf length with Davies and Simons (1979) finding the length of leaves produced subsequently was dramatically reduced by more frequent and later cutting in autumn, while the number of tillers and leaves were much less affected. Severe autumn defoliation can result in the removal of the sheath as well as lamina material (Grant et al., 1981) which slows the regrowth of the sward, shortening the sheath tube, reducing the LER of leaves expanding through the tube (Casey et al*,* 1999), and is compounded by the lower growth rates at the time of the year.

Despite low over-winter growth rates, herbage is continuously accumulating throughout the winter (Brereton et al., 1985; Carton et al., 1988) albeit at a slower rate compared to spring, summer and autumn. Closing swards early in autumn, can result in high herbage masses (>2000 kg DM ha^{-1}; approximately) that can then be carried over winter (Roche et al., 1996; O'Donovan et al., 2002; Hennessy et al., 2006; Ryan et al., 2010; Lawrence et al., 2017). This can result in a reduction in sward quality, reducing the amount of green leaf material in the sward and increasing the level of senescent material (Laidlaw and Mayne, 2000). Herbage was lower in plots cut frequently in autumn and winter and in plots that had delayed cutting in autumn (Davies and Simons, 1979). Davies and Simons also found that swards left undefoliated had a greater herbage mass compared to those defoliated however, they had an increased number of senesced leaves and reduced sward quality.

As the length of time between defoliations increases due to earlier autumn closing, so too does the proportion of senescent material, which was demonstrated by many studies (Davies and Simons, 1979; Jaindl et al., 1991; Hennessy et al., 2008). This was linked to the LSR surpassing the LER during the experiment and a result of senescence experienced by relatively young leaves. The length of leaf lamina produced during winter is shorter than during other times of the year (Davies, 1977; Davies and Simons, 1979). Potentially this can result in a reduction in net grass growth if the leaf length of new leaves produced over winter are not longer than older leaves. Net grass growth can also be reduced when LSR surpasses LER (Davies, 1977). Alberda and Sibma (1968), Robson et al. (1988) and Ryan et al. (2010) all reported that the senescence of younger leaves leads to a decrease in herbage yield in spring. Carton et al. (1988) reported that the length of the regrowth interval is directly related to the length of leaf senescing. Early closing of swards in autumn was found to increase the herbage mass available which had a high proportion of senescent material (Davies and Simons, 1979; Binnie et al., 2001; Hennessy et al., 2006). When herbage mass reaches a ceiling yield (> 2000 kg DM ha^{-1}) it is likely that the herbage mass continues to decrease, unless the sward is defoliated (O'Riordan et al., 1995; Hennessy et al., 2006; Ryan et al., 2010). Beyond this point of the ceiling yield the level of LSR increases (Parsons and Chapman, 2000) reducing over sward quality and yield.

Grazing management factors in autumn can affect tiller density (Woodward, 1998) of swards. As a result of the increased amount of senescent material in the sward, shading of PRG tillers over a prolonged period of time can occur; this can happen in both autumn and spring when new daughter tillers are produced in the vegetative phase (Laidlaw and Mayne, 2000; Hennessy et al., 2006). Pastures with a high herbage mass during the winter can have fewer growing points and photosynthetically less active residual leaves following a late winter/early spring grazing (Parmenter and Boswell, 1983). A study by Thom (1991) found that tiller density might be altered by early spring defoliation; however, these results were transient and were not found to last into the following grazing defoliation. The timing of spring grazing did not affect reproductive

development, but frequent grazing resulted in tillers that were more prostrate than when grazing was less frequent (Thom, 1991). A fast spring rotation increased ryegrass tiller densities in summer (Thom, 1991), however, Garay et al. (1999) reported that severe grazing of reproductive tillers may increase summer-autumn pasture productivity. Bryant and L'Hullier (1986) reported that fast spring rotation results in a lower pre-grazing herbage mass and reduced shading of tillers, which is often the cause of death in less frequency grazed swards (Ong, 1978).

Fulkerson and Donaghy (2001) have studied the effect of management practices incorporating leaf stage. However, the effect of autumn management specifically on WSC in the stubble has not been widely studied. Only assumptions can be made from previous studies, for example an earlier study by Alberda (1957) showed that defoliation interval can influence the WSC content in PRG swards at any point in the season. However, there was no evidence to support that autumn management affects spring growth because of its effect of the WSC reserves in the plant (Davies and Simons, 1979). Ong and Marshall (1979) observed that, in partially shaded swards, unshaded tillers supplied shaded tillers with WSC, but when the whole plant was shaded, provision of WSC from larger tillers to smaller tillers ceased and smaller tillers die. This could lead to reduced tiller density in swards with high herbage masses due to the death of smaller tillers. Ong (1978) reported that the smallest tillers were the first to die when subject to shading or nutrient stress.

The work completed in the current thesis aimed to examine the effect of current management practices for the extension of the grazing season and their impact the perennial ryegrass plant and the following grazing.

1.17 Conclusion

This literature review confirms the importance of grazing management practices for the extension of the grazing season; and the possible impact of accumulating high herbage masses in order to extend the grazing season in autumn, over winter and into spring. This literature review identified areas within the grassland management practices that

can be improved and require further investigation. For instance, previous research on autumn grazing management was carried out prior to 2010. Since then, management practices have been updated to match increased demand from the beginning of February. Specifically, previous research at a sward structure level has not focused on autumn management and the impact of this over winter and into spring. The original investigation for the thesis looked at accumulating herbage masses for autumn grazing (Chapter 2) or spring grazing (Chapter 4). Monitoring the swards for herbage production in year 1 of chapter 4 led to discussion on potential sward structural changes that were occurring and the development of the experiments carried out in chapter 3 and 5. More literature was reviewed, as outlined above, and this led to a research visit to Massey University, New Zealand. Measurements of in depth sward characteristics were done alongside experienced researchers such as Prof. Danny Donaghy and Prof. Corey Matthews. These results then provided the basis for measurements in chapter 3 and 5. These in depth measurements translated into greater management improvements alongside chapter 2 and 4.

1.18 Research objectives

The objectives of this thesis were to examine:

1. How accumulating high herbage masses for the extension of the grazing season in autumn affects herbage production and sward structure in autumn and in spring (Chapter 2 and 3).
2. The impact of autumn closing date on herbage availability in spring for up to date management practices (Chapter 4).
3. The impact of accumulating herbage masses in autumn and spring on tiller density, tissue turnover, sward morphology and water soluble carbohydrates in the stubble (Chapter 3 and 5).

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Chapter 2 - The impact of herbage mass on perennial ryegrass swards in autumn on autumn and over winter production and characteristics

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2.1 Abstract:

Accumulating herbage mass to facilitate the extension of the grazing season in autumn is commonly practised. The objective of the current study was to investigate the effect of accumulating varying target herbage masses (THM) in autumn and imposing different defoliation dates (DD), on herbage mass, sward quality and water soluble carbohydrates in autumn and the subsequent spring. A 4 x 3 factorial split plot design was assigned with four THM (Low ≈ 500 kg DM ha^{-1}, Medium ≈ 1500 kg DM ha^{-1}, High ≈ 2000 kg DM ha^{-1} and Very high ≈ 3000 kg DM ha^{-1}) and three DD (DD1 – 15 October, DD2 – 7 November and DD3 – 21 November), across two years. Measurements were carried out at each DD and in spring. Differences in sward quality were found between each THM on different DD. Sward quality reduced from DD2 to DD3 in the high THM (- 13 g kg^{-1} DM CP, $P < 0.001$). The very high THM had the lowest sward quality from DD1 (206 g kg^{-1} DM CP, $P < 0.001$ and 787 g kg^{-1} DM DMD, $P < 0.05$). This study has identified defoliation date of THM in autumn as key to improving autumn management strategies for increased utilisation and sward quality.

Keywords: perennial ryegrass; herbage mass; autumn grazing; sward quality; defoliation date

2.2 Introduction

Temperate oceanic climatic zones have the potential to support a competitive and sustainable pasture-based production system (Hennessy et al., 2020). Perennial ryegrass (*Lolium perenne* L.; PRG) is the central species in temperate pasture-based systems (Grogan and Gilliland, 2011), as it can produce large quantities of high-quality herbage (Finneran et al., 2012) and can persist under intensive grazing (Robson et al., 1988). To improve environmental (Donnellan et al., 2018) and economic (MacDonald et al., 2010; Hanrahan et al., 2018) sustainability within a pasture-based system, the production and utilisation of grazed grass must be maximised. Grazed grass has been identified as the cheapest feed source available within ruminant production systems (Finneran et al., 2010), and as such, increasing the proportion of grazed grass in the diet of animals

(Kennedy et al., 2005) is a key objective of pasture-based dairy production systems. The efficient utilisation of swards was defined as the proportion of green leaf tissue that is removed by grazing animals before entering the senescent state (Lemaire and Chapman, 1996).

Extending the autumn grazing season has been recognised as one of the key objectives for reducing agricultural greenhouse gas emissions in the Marginal Abatement Cost Curve for Irish agriculture (Schulte et al., 2012; Lanigan et al., 2018) as it has been positively correlated with the reduced carbon footprint of milk (O'Brien et al., 2015) and increased on-farm profitability (Hanrahan et al., 2018). A 300-day grazing season length has been identified as a key strategy in improving utilisation in temperate climates (O'Donovan et al., 2011); however, in Ireland, the current average length of the grazing season in Ireland is only 223 days (Läpple et al., 2012; Teagasc, 2019). It has previously been reported in animal studies that maintaining grazed grass in the diet of animals in late autumn can help to maintain or increase milk protein output (Dillon et al., 1998; Claffey et al., 2020) and reduce costs due to the lower supplementation requirement (Läpple et al., 2012). Specific grazing management targets are required in autumn to achieve an extension in the grazing season, as growth rates decline during this period (Hennessy et al., 2006). Typically, the grazing rotation length is extended to allow for large quantities of herbage to be built up from August, prior to the decline of grass growth, to facilitate the extension of the grazing season for the final rotation (approximately 15 October – 21 November) (Hennessy et al., 2006; Teagasc, 2011; Claffey et al., 2020).

Increasing the level of herbage mass in swards at any point during the vegetative phase can have negative implications on the PRG plant. Herbage mass continues to accumulate when temperatures are low, albeit at a slower rate, and continues to increase yield until swards have reached a ceiling yield (Brereton et al., 1985). The ceiling yield is when no further increase of herbage occurs, as green leaf production is matched or surpassed by leaf senescence and the high herbage mass results in limited light entering to the base

of the sward (Parsons and Chapman, 2000). Lawrence et al. (2017) reported that swards with high herbage masses did not increase herbage mass, from early November, as they had reached ceiling yield. The longer a sward remains undefoliated for, once ceiling yield is reached, the more senescence progresses (Davies and Simons, 1979), particularly if there are relatively high temperatures (> 5°C) over winter (Hennessy et al., 2006) and if the sward is post-vernalisation (Brereton et al., 1985; Wingler and Hennessey, 2016). Previous studies, investigating the impact of carrying high herbage masses over winter, reported that the level of senescent material in the sward increases resulting in a lower sward quality in spring (Hennessy et al., 2008; Looney et al., 2021). High herbage masses (> 2000 kg DM ha^{-1}) can result in shading at the base of the sward which can reduce tiller production and hinder tiller establishment and survival (Laidlaw & Mayne, 2000). Reduced tiller production can impact herbage production by decreasing the number of growing points in the sward (Garay, 1999). However, to date there has been little research on the impact of different lengths of defoliation interval, over the autumn period, on varying herbage masses.

It has widely been acknowledged that autumn closing date is one of the main controllable factors contributing to the accumulation of herbage over winter months (Hennessy et al., 2006; Looney et al., 2021). Earlier closing of swards in autumn, results in greater herbage mass available the following spring (Hennessy et al., 2006; Ryan et al., 2010; Lawrence et al., 2017; Looney et al., 2021). However, the research has been limited on the management prior to defoliation in autumn, identifying the optimal herbage masses to defoliate at different stages of the final rotation, could be beneficial to improved autumn grazing management, as has previously been identified for mid-season management (Teagasc, 2011). It is important that autumn grazing management practices to facilitate the extension of the grazing season, should not compromise herbage availability the following spring. Previous research has been limited mainly to autumn closing date and further research is warranted on the management practices recommended to achieve the extension of the grazing season in autumn and how they influence PRG swards both in the autumn, over winter and into the spring. The current

gaps in research on extending the grazing season in autumn, by accumulating high levels of herbage mass, warrant further investigating on the impacts on sward production and finding the optimal dates for defoliation of different herbage masses to improve decision making on farm to allow for efficient utilisation of swards and the extension of the grazing season without compromising over winter herbage production.

The objective of this study was to investigate the effect of accumulating herbage mass in autumn and imposing different defoliation dates in the final grazing rotation to determine the impact on herbage mass, sward quality and water soluble carbohydrates (WSC) in the stubble in autumn and the subsequent carryover to spring.

Table 2.1: Average daily air temperature (˚C), monthly rainfall (mm), solar radiation, and mean soil temperature to a depth of 100 mm (˚C) between August and April for Year 1 (2018/2019), Year 2 (2019/2020) and the 10-year average (2006 – 2016) at the experimental site.

	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	April
Average daily air temp (˚C)									
Year 1 - 2018/2019	15.6	12.4	9.9	8.1	8.5	6.5	7.7	7.5	9.1
Year 2 - 2019/2020	15.6	13.6	9.7	7.1	6	6.1	6.5	6.3	9.8
10-year average	14.8	13.3	10.9	7.6	5.7	5.4	5.5	6.4	8.7
Monthly rainfall (mm)									
Year 1 - 2018/2019	43.3	60.0	72.4	167.1	168.2	65.9	56.7	117.9	108.9
Year 2 - 2019/2020	106.8	71.5	155.0	141.0	115.2	89.7	113.3	47.9	64.8
10-year average	81.7	67.5	105.5	116.8	113.2	122.5	82.6	68.7	58.8
Solar radiation									
Year 1 - 2018/2019	1329	1074	691	267	176	247	484	937	1316
Year 2 - 2019/2020	1376.5	1101	654	270	203	297	447	891	1391
10-year average*	1347	964	560	320	192	249	408	825	1314
Mean soil temp to a depth of 100 mm (˚C)									
Year 1 - 2018/2019	18.0	14.6	10.8	7.8	8.0	6.8	7.3	8.3	10.6
Year 2 - 2019/2020	17.5	15.2	10.9	7.4	5.9	5.7	5.9	6.7	11.0
10-year average	17.0	15.0	11.9	7.9	5.4	5.0	5.4	6.9	10.2

***Data presented from 2008 – 2016**

2.3 Materials and Methods

2.3.1. Experimental site

A plot trial was conducted at the Teagasc, Animal and Grassland Research and Innovation Centre, Moorepark, Fermoy, Ireland (Latitude 50°07'N, Longitude 08°16'W) from 15 October 2018 to 1 April 2019 (Year 1) and 15 October 2019 to 1 April 2020 (Year 2). The soil type was a free-draining acid brown earth of sandy to loam texture. Soils had a pH of 6.4, phosphorus (P) Index of 4 (8.5 mg/l) and potassium (K) Index of 3 (125 mg l^{-1}) (± 0.8; scale 1 to 4; 1 = deficient, 4 = no response to application of nutrient) (Alexander et al., 2008). The experimental site was of south-facing aspect and located approximately 40 m above sea level. Swards were made up of PRG (> 90%) predominantly, with the remaining 10% made of mainly annual weed grass (*Poa annua* L.) and broadleaved plants. Meteorological data were recorded at the experimental site over the experimental period (October to April). Average daily air temperature (°C), soil temperature to a depth of 100 mm (°C), total monthly rainfall (mm) and average solar radiation are shown for the measurement periods in each experimental year (Table 2.1).

2.3.2 Experimental design

The experimental design was a 4 x 3 factorial split plot design with four replicates, resulting in a total of 48 plots of 1.5 m x 6 m. Four target herbage masses (THM; Low ≈ 500 kg DM ha^{-1}, Medium ≈ 1500 kg DM ha^{-1}, High ≈ 2000 kg DM ha^{-1} and Very high ≈ 3000 kg DM ha^{-1}) were targeted to be achieved by 15 October; these were achieved through different defoliation strategies from early August. Three defoliation dates (DD; DD1 – 15 October, DD2 – 7 November and DD3 – 21 November), chosen to reflect Irish autumn grazing management practices (Teagasc, 2011), were examined on each of the four THM. Measurements were carried out on each autumn DD1, DD2 and DD3 and on all plots in spring for the 1st defoliation (21 February), and on the 2nd defoliation in spring (1 April), where only herbage mass (kg DM ha^{-1}; > 3.5 cm) was measured. Outside

of the experimental period, plots were defoliated using an Etesia mower (Etesia UK Ltd., Warwick, UK) to a residual of 4 cm when they reached a pre-grazing herbage mass of 1500 kg DM ha^{-1} between April and July. In August plot defoliation interval was tailored to allow each THM to be achieved by 15 October. In year 1 and year 2 over the experimental period nitrogen (N) was applied in early August at a rate of 35 kg N ha^{-1} in the form of calcium ammonium nitrate (CAN; 27% N). Phosphorus and potassium were applied in February as 30 kg ha^{-1} of 0-7-30 fertiliser (5.67 kg ha^{-1} P; 24.33 kg ha^{-1} K). At the end of January, N was applied at a rate of 28 kg N ha^{-1} in the form of urea (46% N). For the remainder of the year, N was applied, post-defoliation, as 20 kg N ha^{-1} as CAN, with a total of 200 kg N ha^{-1} applied each year.

2.3.3 Sward Measurements

Sward height

Ten sward height measurements were recorded in each plot pre- and post-defoliation using a Grasshopper (Grasshopper, True North Technologies, Shannon, Co. Clare, Ireland; McSweeney et al., 2015).

Herbage Mass

The entire plot was harvested using the Etesia mower (Etesia UK Ltd., Warwick, UK) > 3.5 cm (targeted residual). The mown herbage from the plot was collected and weighed. A sample of approximately 300 g was collected from each cut strip. A subsample of 100 g was weighed and dried for 16 hours at 60°C to determine dry matter (DM) content and milled through a 1 mm sieve and stored for analysis.

Tiller density

Two turves (0.1 m x 0.1 m) were cut to a depth of 0.05 m and removed from each sward in February (1st defoliation). Turves were removed randomly within the plot to take into

account the heterogeneity of the swards (Jewiss, 1993). The grass tillers in each turf were separated into PRG and other grass species (mainly meadow grass, *Poa annua* L.) and counted. From these turves an overall average tiller density per m^2 was calculated.

2.3.4 Chemical analysis

Herbage quality analysis

The milled samples were analysed for dry-matter digestibility (DMD) and crude protein (CP) concentration using the near-infrared spectrometry machine (NIRS, Model 6500, FOSS-NIR System, 3400 Hillerød, Denmark) and the equation derived by Burns et al., (2013).

Water soluble carbohydrates

Water soluble carbohydrates in the stubble were measured on all plots prior to their respective defoliation dates in autumn and on the first defoliation in spring. Forty-five mature tillers with no visible daughter tiller were cut to ground level, using a scalpel, from each plot within three hours of sunrise (approximately 7 am for the experimental period), in order to avoid any diurnal changes that occur from sunrise to mid-afternoon. Tillers were washed to remove excess soil and each tiller was cut from ground level to 3.5 cm (targeted post-grazing residual stubble). The stubble (< 3.5 cm) was weighed and dried at 60˚C in a pre-heated oven for 48 hours and the dried samples were weighed to determine DM content and milled using a 1 mm sieve. Samples were stored in a dry, dark location until analysis.

Water soluble carbohydrates (mg g^{-1} Dry Weight (DW)) present in 45 tillers from each treatment were determined using the anthrone method (Thomas, 1977). Soluble carbohydrates were extracted from samples by adding 9.9 ml of cold water to 0.1 g of dried and milled herbage. The samples were then shaken mechanically for one hour and filtered. Samples were prepared for the auto analyser by diluting the filtrate to one in

ten using a pre-set Hamilton diluter. The auto analyser was prepared by pumping water through for 20 minutes, then 76% sulphuric acid for 10 minutes and finally anthrone reagent for 15 minutes. Once the bubble pattern and baseline reading (<5%) were satisfactory, prepared samples were placed into the auto analyser and heated with anthrone in sulphuric acid under standard conditions in an auto analyser forming a blue complex. This complex was then used to determine the concentration of carbohydrates spectrophotometrically at 630 nm.

2.2.5. Statistical analysis

Statistical analyses were carried out using SAS 9.4 (SAS Institute Inc., Cary, NC, USA, 2002). The effect of THM and DD on sward height, herbage mass, herbage quality (DMD and CP), tiller density and WSC (> 3.5 cm) were determined using the PROC MIXED procedure in SAS, with DD, and THM used in the model. Plot was the experimental unit, with year the random factor and measurement date (MD) was the repeated measure. Data are presented as least square means ± standard error. Variables were analysed using the following model:

Y_jkl " = μ + " 〖target herbage mass〗_j " + " 〖defoliation date〗_k " +" 〖year〗_l " " +

(〖target herbage mass〗_j × 〖defoliation date〗_k)" + " (〖year〗_l × 〖target herbage mass〗_j)" + " (〖year〗_l × 〖defoliation date〗_k)" × " e_jklm

Where:

μ = mean value for the variable

ejkl = residual error term

Yjkl = herbage yield (kg DM ha^{-1}), sward height (cm), DMD (g kg DM^{-1}) and CP (g kg DM^{-1}), tiller density (m^2) and WSC (> 3.5 cm; mg g^{-1} DW)

2.4 Results

2.4.1 Autumn period

Herbage mass

There was a significant (P < 0.001) interaction between DD and year on herbage mass. In year 1, DD2 and DD3 (2366 ± 108.1 kg DM ha^{-1}) had a greater herbage mass than DD2 (1800 ± 108.6 kg DM ha^{-1}) and DD3 (1547 ± 108.6 kg DM ha^{-1}) in year 2. In year 1 (1601 ± 108.6 kg DM ha^{-1}) and year 2 (1554 ± 108.6 kg DM ha^{-1}), DD1 did not have a significantly different herbage mass. The very high THM treatment resulted in a greater herbage mass (P<0.001) than all other THM (Table 2.2). The medium and high THM treatments both resulted in greater herbage mass than the low THM. Defoliating swards earlier (DD1) in the autumn resulted in a significantly (P < 0.001) lower herbage mass compared to DD2 and DD3. Herbage mass was significantly (P < 0.001) greater in year 1 (2172 ± 62.7 kg DM ha^{-1}) compared to year 2 (1634 ± 62.7 kg DM ha^{-1}).

Pre-defoliation height

There was a significant (P < 0.001) effect of THM and DD on pre-defoliation height in autumn (Table 2.2); defoliating earlier (DD1) in the low and medium THM had a lower pre-defoliation height than defoliating later (DD2 & DD3). There was a significant (P < 0.001) effect of THM and year on pre-defoliation height; the low and medium THM were greater in year 1 (8.5 and 10.3 ± 0.26 cm, respectively) compared to year 2 (4.4 and 8.5 ± 0.26 cm, respectively). The very high THM had the greatest pre-defoliation height, followed by the high, then medium and the low THM had the lowest pre-defoliation height (P < 0.001; Table 2.2). Earlier (DD1) defoliation in the autumn had a significantly (P < 0.001) lower pre-defoliation height than DD2 and DD3 (Table 2.2). Year 1 (10.9 ±

0.13 cm) had a significantly ($P < 0.001$) greater pre-defoliation height than year 2 (9.1 ± 0.13 cm). There was a correlation of $R^2 = 0.71$ between pre defoliation height and herbage mass in autumn (Figure 2.1). As herbage mass increased pre defoliation height increased until herbage mass surpassed 2000kg DM ha^{-1}, when pre defoliation height no longer increases in line with herbage mass.

Table 2.2: Effect of the interaction of target herbage mass (Low - 500 kg DM ha^{-1}, Medium - 1500 kg DM ha^{-1}, High - 2000 kg DM ha^{-1} and Very high - 3000 kg DM ha^{-1}) and defoliation dates (DD; DD1 – 15 October, DD2 – 7 November and DD3 – 21 November) at defoliation in autumn on the herbage mass (kg DM ha^{-1}) and the pre- grazing sward height (cm) across year 1 and year 2.

Target herbage mass	Low	Medium	High	Very high	Defoliation date average	S.E.	Significance		
Herbage mass (kg DM ha^{-1})							THM	DD	THM x DD
Defoliation date 1	650	1210	1695	2758	1578^{a}	153.6	***	***	NS
Defoliation date 2	962	2172	2187	3077	2100^{b}				
Defoliation date 3	1088	1823	1932	2917	1940^{b}				
Target herbage mass average	900^{1}	1735^{2}	1938^{2}	2917^{3}					
Pre-defoliation height (cm)					Defoliation date average				
Defoliation date 1	4.6	8.2	11.0	13.6	9.4^{a}	0.32	***	***	**
Defoliation date 2	7.0	10.1	11.3	12.9	10.3^{b}				
Defoliation date 3	7.7	10.0	10.9	12.9	10.4^{b}				
Target herbage mass average	6.4^{1}	9.4^{2}	11.1^{3}	13.2^{4}					

P > 0.05 NS, P < 0.05 *, P < 0.01 **, P < 0.001 ***.
Alphabetic superscripts within columns denote different superscripts differ significantly for defoliation date.
Numeric superscripts within row denote different superscripts differ significantly for target herbage mass.

Sward Quality

Crude protein

There was a significant ($P < 0.001$) effect of THM and DD on sward CP concentration (Table 2.3). When the low, medium and high THM, were defoliated earlier (DD1) in the autumn they had a higher CP concentration compared to later (DD2 & DD3). The very high THM CP concentration increased when defoliated later (DD 2 & DD3) compared to early (DD1) rotation. The low THM had the greatest CP concentration, followed by the medium and high THM, with the very high THM the lowest ($P < 0.001$; Table 2.3). Defoliating earlier (DD1) in the autumn resulted in a significantly ($P < 0.01$) higher CP concentration than later (DD2 & DD3; Table 2.3). In year 2 CP concentration (225 ± 2.1 g kg^{-1} DM) was significantly ($P < 0.01$) greater than in year 1 (214 ± 2.1 g kg^{-1} DM).

Dry matter digestibility

The very high THM led to a significantly ($P < 0.05$) lower DMD concentration than the low and medium THM, with the high THM intermediate (Table 2.3). There was no significant ($P > 0.05$) effect of DD (798 ± 3.4 g kg^{-1} DM; Table 2.3) or year (801 ± 3.4 g kg^{-1} DM) on DMD concentration.

Table 2.3: Effect of the interaction of target herbage mass (Low - 500 kg DM ha^{-1}, Medium - 1500 kg DM ha^{-1}, High - 2000 kg DM ha^{-1} and Very high - 3000 kg DM ha^{-1}) and defoliation dates (DD; DD1 – 15 October, DD2 – 7 November and DD3 – 21 November) for year 1 and year 2 at defoliation in autumn on the crude protein (g kg^{-1} DM) and dry matter digestibility (DMD; g kg^{-1} DM).

Target herbage mass	Low	Medium	High	Very high	Defoliation date average	S.E.	Significance		
Crude Protein (g kg^{-1} DM)							THM	DD	THM x DD
Defoliation date 1	255	224	225	199	226^{a}	2.9	***	**	***
Defoliation date 2	232	215	212	209	217^{b}				
Defoliation date 3	229	225	213	209	219^{b}				
Target herbage mass average	238^{1}	221^{2}	217^{2}	206^{3}					
Dry Matter Digestibility (g kg^{-1} DM)					Defoliation date average				
Defoliation date 1	800	795	800	783	794	3.4	*	NS	NS
Defoliation date 2	812	813	791	794	803				
Defoliation date 3	802	802	794	784	796				
Target herbage mass average	805^{1}	805^{1}	794^{12}	787^{2}					

P > 0.05 NS, P < 0.05 *, P < 0.01 **, P < 0.001 ***.

Alphabetic superscripts within columns denote different superscripts that differ significantly for defoliation date.

Numeric superscripts within row denote different superscripts that differ significantly for target herbage mass.

Water soluble carbohydrates in the stubble

There was a significant ($P < 0.05$) effect of THM and DD on WSC. The low THM had a lower WSC in DD1 compared to all other DDs and THM (Table 2.4). There was a significant ($P < 0.001$) effect of DD and year on WSC concentration in autumn; year 2 had a greater WSC compared to year 1 when defoliated in DD2 (37.8 and 29.6 ± 0.92 mg g^{-1} DW) compared to DD3 (44.5 and 29.9 ± 0.92 mg g^{-1} DW). The high THM had a significantly ($P < 0.01$) greater WSC concentration than the low, with the medium and very high THM intermediate to both (Table 2.4). Defoliating swards earlier (DD1) in the autumn resulted in a significantly ($P < 0.01$) greater WSC concentration than later defoliation (DD2 and DD3; Table 2.4). Year 2 (38.3 ± 0.76 mg g^{-1} DW) had a significantly ($P < 0.001$) greater WSC than year 1 (269 ± 7.6 mg g^{-1} DW).

Table 2.4: Effect of the interaction of target herbage mass (Low - 500 kg DM ha^{-1}, Medium - 1500 kg DM ha^{-1}, High - 2000 kg DM ha^{-1} and Very high - 3000 kg DM ha^{-1}) and defoliation dates (DD; DD1 – 15 October, DD2 – 7 November and DD3 – 21 November) at defoliation in autumn on the water soluble carbohydrates (WSC; mg g^{-1} DW) in the stubble (< 3.5 cm) for year 1 and year 2.

Target herbage mass	Low	Medium	High	Very high	Defoliation date average	S.E.	Significance		
Water Soluble Carbohydrate in stubble (mg g^{-1} DW)							THM	DD	THM x DD
Defoliation date 1	27.6	35.8	39.8	33.1	34.0^{a}	1.30	**	***	*
Defoliation date 2	33.1	30.6	31.4	35.5	32.6^{b}				
Defoliation date 3	31.1	31.4	35.0	34.6	33.0^{b}				
Target herbage mass average	30.6^{1}	32.6^{1,2}	35.4^{2}	34.4^{2}					

P > 0.05 NS, P < 0.05 *, P < 0.01 **, P < 0.001 ***.

Alphabetic superscripts within columns denote different superscripts that differ significantly for defoliation date.

Numeric superscripts within row denote different superscripts that differ significantly for target herbage mass.

2.4.2 First Defoliation of spring period (21 Feb)

Herbage mass

There was no effect (P > 0.05) of autumn THM on spring herbage mass (769 ± 27.5 kg DM ha^{-1}). Defoliating earlier (DD1) in autumn resulted in a significantly (P < 0.001) greater herbage mass in spring than later defoliations (DD2 and DD3; Table 2.5). Spring herbage mass was significantly (P < 0.001) greater in year 1 (993 ± 19.5 kg DM ha^{-1}) than year 2 (541 ± 19.5 kg DM ha^{-1}).

Pre-defoliation height

There was a significant (P < 0.05) effect of autumn THM and DD on pre-defoliation height in spring; the medium, high and very high THM had a greater pre-defoliation height in spring when defoliated earlier (DD1; 7.4, 7.7 and 7.6 ± 0.22 cm, respectively) in the autumn than later defoliations (DD2; 6.9, 6.0 and 6.1 ± 0.22 cm, respectively) and (DD3; 5.8, 5.7 and 5.8 ± 0.22 cm, respectively), with the low THM similar in all DD (6.2 ± 0.22 cm). There was no significant (P > 0.05) effect of autumn THM on pre-defoliation height in spring (6.3 ± 0.12 cm). Defoliating earlier in autumn (DD1) led to a significantly (P < 0.001) greater pre-defoliation height in spring compared to the later defoliation (DD2 and DD3; Table 2.5). Pre-defoliation height in spring was significantly (P < 0.001) greater in year 1 (7.7 ± 0.09 cm) compared to year 2 (5.0 ± 0.09 cm).

Sward Quality

Crude protein

There was no effect (P > 0.05) of autumn THM on sward CP concentration in spring (255 ± 1.1 g kg^{-1} DM). Defoliating swards earlier (DD1) in the autumn resulted in a significantly (P < 0.001) lower CP concentration in spring, followed by DD2 and the greatest CP concentration on DD3 (Table 2.5). Sward CP concentration in spring was significantly (P < 0.001) greater in year 2 (261 ± 0.8 g kg^{-1} DM) compared to year 1 (250 ± 0.8 g kg^{-1} DM).

Dry matter digestibility

The low and high autumn THM had a significantly ($P < 0.05$) lower spring DMD concentration (807 ± 1.2 g kg^{-1} DM) than the medium and very high THM (811 ± 1.2 g kg^{-1} DM). Defoliating swards earlier in the autumn (DD1) resulted in a significantly ($P < 0.05$) lower DMD concentration in spring than defoliation later (DD3) in autumn (Table 2.5). There was no effect ($P > 0.05$) of year on spring DMD concentration (809 ± 0.8 g kg^{-1} DM).

Water soluble carbohydrate in the stubble

There was no effect ($P > 0.05$) of THM, DD or year on WSC concentration in spring (average 24.5 ± 0.50 mg g^{-1} DW; Table 2.5).

Spring tiller density

There was no significant ($P > 0.05$) effect of THM (3324 ± 285.8 tillers m^{-2}), DD (3325 ± 202.1 tillers m^{-2}) on spring tiller density (Table 2.5).

Table 2.5: Effect of the interaction of target herbage mass (Low - 500 kg DM ha^{-1}, Medium - 1500 kg DM ha^{-1}, High - 2000 kg DM ha^{-1} and Very high - 3000 kg DM ha^{-1}) and defoliation dates (DD; DD1 – 15 October, DD2 – 7 November and DD3 – 21 November) at autumn defoliation on the spring herbage mass (kg DM ha^{-1}), pre-defoliation sward height (cm), tiller density (tillers m^{-2}) water soluble carbohydrates (WSC; mg g^{-1} DW) in the stubble (< 3.5 cm), light interception (%), crude protein (g kg^{-1} DM) and dry matter digestibility (DMD; g kg^{-1} DM) in year 1 and 2.

	Defoliation date				
Variable	DD1	DD2	DD3	S.E.	Significance
Herbage mass (kg DM ha^{-1})	932^{a}	711^{b}	659^{b}	23.8	***
Pre-defoliation height (cm)	7.3^{a}	6.1^{b}	5.8^{c}	0.11	***
Tiller density (tillers m^{-2})	3366	3273	3334	247.5	NS
WSC in the stubble (mg g^{-1} DW)	24.5	25.0	24.2	0.50	NS
Crude Protein (g kg^{-1} DM)	249^{a}	257^{b}	260^{c}	1.0	***
Dry matter digestibility (g kg^{-1} DM)	807^{1}	809^{12}	811^{2}	1.0	*

P > 0.05 NS, P < 0.05 *, P < 0.01 **, P < 0.001 ***.

Numeric superscripts within row denote different superscripts that differ significantly for target herbage mass.

2.4.3 2nd Rotation in spring

Herbage mass

There was no significant (P > 0.05) effect of autumn DD and THM on herbage mass in the 2nd rotation in spring (1629 ± 24.4 kg DM ha^{-1}). Year 1 (1765 ± 18.5 kg DM ha^{-1}) had a significantly (P < 0.001) greater herbage mass compared to year 2 (1494 ± 18.5 kg DM ha^{-1}) for the 2nd defoliation in spring.

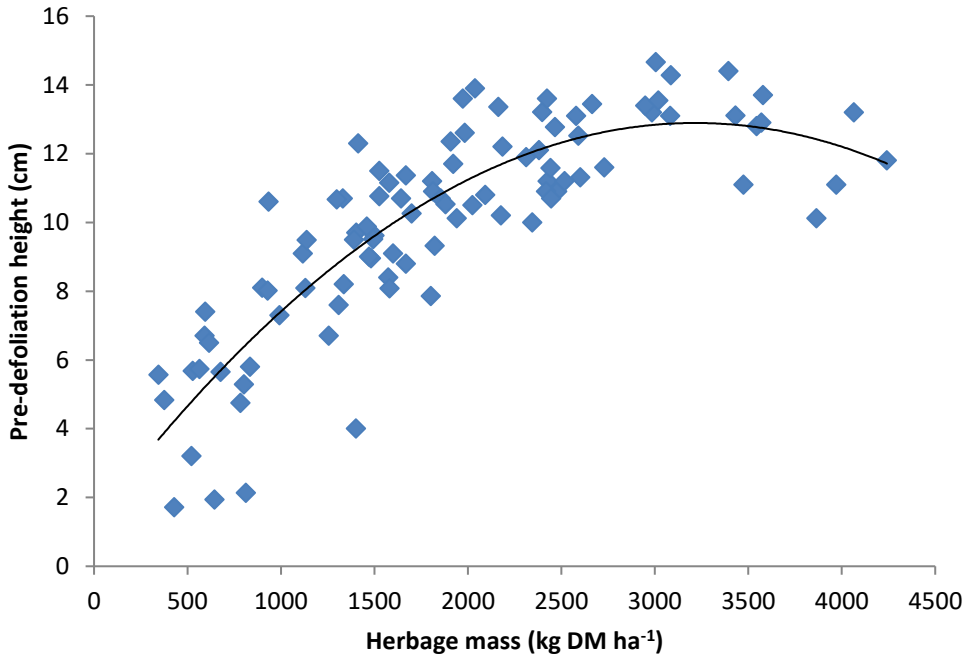


Figure 2.1: The relationship between the herbage mass (kg DM ha^{-1}) and the pre-defoliation height for autumn defoliation. The relationship is described by the equation $y = -1E-06x^2 + 0.072x + 1.34$. $R^2 = 0.74$.

2.5 Discussion

The current study investigated the advantages and disadvantages of defoliating varying herbage masses across different autumn defoliation dates between mid-October and the end of November. Results from the current study highlighted that herbage masses should be accumulated prior to 15 October, to allow for a longer grazing season, as growth rates hereafter are significantly reduced (+ 23 kg DM ha^{-1} day^{-1}, DD1 – DD3), caused by a decline in temperatures (Peacock, 1975) and reduced solar radiation (Hurtado-Uria et al., 2013). In the current study, swards with herbage masses > 2100 kg DM ha^{-1} did not continue to accumulate herbage from early November (DD2) to late November (DD3), with a decline in herbage mass by 11 kg DM ha^{-1} day^{-1} until late November. This can be accounted for in that these herbage masses reached a ceiling yield (Carton et al., 1988a) and the rates of leaf senescence surpassed the green leaf appearance (Hennessy et al., 2006). Additionally, as herbage mass surpasses 2000 kg DM ha^{-1}, the pre-defoliation height (cm) begins to decline (Figure 2.1), indicating that these swards had reached a ceiling yield (Ryan et al., 2010). In this study the loss of herbage did not occur until early November (DD2) and could be a result of greater growth rates between mid October and early November over the two years. A previous study by Hennessy et al., (2006) reported a similar loss of herbage in swards compared to the current study, however, they reported those losses in swards with a greater herbage mass (> 2500 kg DM ha^{-1}) prior to November. Leaf extension and leaf appearance are continuously occurring and accumulating herbage, even in swards with a high herbage masses (Brereton et al., 1985; Carton et al., 1988b). In the current study leaf extension could have been greater or matched the leaf senescence rates resulting in a continued accumulation of herbage mass in the swards.

Selecting a time point at which to defoliate a specific herbage mass in autumn has not previously been defined in grazing management recommendations (Teagasc, 2011). Using the results of the current study the optimal time for defoliation of low, medium,

high and very high THM in autumn rotation are reported based upon herbage mass, WSC and sward quality. Swards with a low THM (500 - 1000 kg DM ha^{-1}) continue to accumulate herbage mass from into late November (DD2 – DD3; + 9 kg DM ha^{-1} day^{-1}) and achieved herbage masses of approximately 1088 kg DM ha^{-1} by the end of November (DD3), a 67% increase in herbage mass from October (DD1). This is probably a result of continuous leaf appearance and extension of swards in response to temperatures above 5°C (Peacock, 1975). However, leaf appearance occurs at a slower rate between October and November (average 25 days; Peacock, 1975). The number of days of growth between DD1 and DD2 (approximately 37 days) indicates that the plants would not have reached the three-leaf stage, at the time of defoliation. As a result the plant material would not have begun senescing, as new green leaf material would be continuously appearing (Peacock, 1975). This continued growth seen throughout the final rotation in low THM, can allow for later defoliation in autumn which can help accommodate an extension of the grazing season. In the medium THM average growth rates between mid October and early November were greater (DD1 - DD2; + 42 kg DM ha^{-1} day^{-1}) than the average growth rates overall in the experimental period (+ 23 kg DM ha^{-1} day^{-1}). The medium THM possibly had a greater leaf extension rate and a low level of leaf senescence (Carton et al., 1988a; 1988b). This allows some flexibility with defoliation in autumn. However, the medium THM swards reached their ceiling yield (> 2000 kg DM ha^{-1}) from the beginning of November (DD2) and from then approximately 18 kg DM ha^{-1} day^{-1} was lost as senescent material (Hennessy et al., 2006) by DD3. Higher herbage masses tend to have increased leaf senescence (Carton et al., 1988a; 1988b) and, as a result, have a greater proportion of dead material below the grazing horizon (Lawrence et al., 2017), leading to lower herbage accumulation (Peacock, 1975; Brereton et al., 1985). This was reported in the high and very high herbage masses within the current study; the high and very herbage masses had reduced growth rates (+ 22 and + 14 kg DM ha^{-1} day^{-1}, respectively) between mid October and early November (DD1 & DD2) compared to the low and medium and began to lose herbage from early November to late November (DD2 & DD3; -18.2 and - 11 kg DM ha^{-1} day^{-1}, respectively). As a result,

swards with very high THM should be grazed earlier in autumn, to avoid any significant losses in herbage mass on these swards.

Overall the WSC in the stubble was an average of 34.1 ± 3.69 mg g^{-1} DW across all THM and DD. However, a significantly lower WSC (27.6 mg g^{-1} DW) was reported in the low herbage mass (650 kg DM ha^{-1}) when they were defoliated in October (DD1); these swards had not reached the 'three-leaf stage' and defoliating at this stage could potentially have impacted the regrowth potential (Fulkerson and Donaghy, 2001). Positively, the current study showed if defoliation of a sward with a low herbage mass did happen in mid-October (DD1), the regrowth potential for the following spring was not impacted, as long as there was a long regrowth interval (minimum 92 days in this experiment) to recover. This could be result of the high WSC levels experienced over winter compared to the rest of the grazing season (Fulkerson, 1998) and the long regrowth interval length between autumn and spring defoliations which allowed swards to accumulate WSC (Fulkerson and Donaghy, 2001). Similar to the experiment by Fulkerson and Donaghy (2001), the WSC increased as herbage mass increased until the end of November (DD3).

Quality of the grazing sward, when facilitating the extension of the grazing season in autumn, needs to meet the majority of the energy requirements of late lactation dairy cow (Kavanagh, 2016). Grazed grass is of a superior nutritional quality when compared to grass silage (696 g kg^{-1} DMD; Kennedy et al., 2005), and as a result will lead an improvement in animal performance (Claffey et al., 2020). In the current study, the low and medium THM swards maintained a high sward quality (805 g kg^{-1} DMD), across all DD, due to the presence of green material (Tunon et al., 2014). The medium herbage mass swards maintained sward quality (DMD & CP), from DD2 to DD3, which can allow for grazing later in November. High and very high THM continued to accumulate herbage from DD1 to DD2 (+ 23 kg DM ha^{-1} day^{-1}; + 13 kg DM ha^{-1} day^{-1}) however, herbage mass reduced from DD2 to DD3 (-18.2 kg DM ha^{-1} day^{-1}; -11.4 kg DM ha^{-1} day^{-1}) and this reduction was probably due to a reduction in green leaf material (Hennessy et al., 2008).

These high and very high THM can have an increased level of senescent material leading to reduced quality (Binnie et al., 2001). This was shown in the study where very high herbage mass swards had the lowest sward quality (CP 206 g kg^{-1} DM; DMD 787 g kg^{-1} DM) from the middle of October. Sward quality of the high herbage mass swards began to reduce from the beginning of November (CP – 13 g kg^{-1} DM; DMD – 9 g kg^{-1} DM). Because of this high and very high herbage masses should be defoliated by early November (DD1 & DD2) to maintain a greater quality of feed for grazing animals. However, despite the lower sward quality in the high and very high THM, the quality of feed was still far superior to that of grass silage (696 g kg^{-1} DM; Kennedy et al., 2005), and as such is still beneficial in the diet of late lactation animals (Claffey et al., 2020).

There was a greater herbage mass in year 1 (+ 538 kg DM ha^{-1}) of the current study, despite the fact that soil and air temperatures experienced were similar between both years (Table 2.1). This could be accounted from compensatory growth experienced after an extended period of drought in the summer of 2018 (Egan et al., 2019), prior to the experimental period (Korte and Chu, 1983; Barker et al., 1985). In an experiment by Korte and Chu (1983), they reported 60% higher compensatory growth rates in swards that had experienced drought stress (24 kg DM ha^{-1} and 15 kg DM ha^{-1}, respectively). In the current experiment the compensatory growth rates were 38% greater after the drought in year 1 (+ 16 kg DM ha-1 day^{-1}; Year 1 – 58 kg DM ha^{-1}; Year 2 – 42 kg DM ha^{-1}) after the period of drought.

Target herbage masses in autumn did not affect the growth rates of swards over winter or spring grass availability, despite the lower WSC concentration on the medium and low THM swards. This is extremely beneficial in terms of autumn grazing management practices as it allows for the accumulating of herbage masses to facilitate extension of the grazing season with no negative implications on over winter growth or spring grass availability. Autumn DD, however, had a much greater impact on over winter growth rate and spring grass availability, similar to Hennessy et al. (2006), Ryan et al. (2010), Lawrence et al. (2017) and Looney et al. (2021). Spring grass availability reduced by 24%

between DD1 and DD2 and 6% between DD2 and DD3. This has a much greater impact on spring grass, and therefore a greater emphasis should be placed on the closing date of swards in autumn to better match spring grass requirements.

It has previously been reported that closing swards earlier in autumn can have a negative effect on tiller density in spring (Hennessy et al., 2006; Looney et al., 2021). However, the current study reported no negative effect of autumn management on tiller density in spring. Adequate light entered the base of the sward to maintain tiller production in all swards (Laidlaw and Mayne, 2000). This is an important factor for the extension of the grazing season in autumn, as prior to the experiment multiple factors associated with carrying high herbage masses were identified as inhibitors of over winter regrowth as the potential to impact the sward's ability to recover after defoliation in autumn to achieve required grass in spring (Hennessy et al., 2006; Hennessy et al., 2008; Looney et al., 2021).

2.6 Conclusion

Accumulating herbage on swards to facilitate the extension of the grazing season in autumn can be done successfully, under mowing conditions, without impacting herbage available and tiller density in spring. However, the date on which swards are defoliated in autumn can have a significant impact on herbage available in spring, with a 24% reduction in swards defoliated in DD2 compared to DD1. In autumn, herbage masses need to be accumulated prior to early October, as growths decline there after (+ 23 kg DM ha^{-1} day^{-1}, average), impacting a swards ability to continue to accumulate herbage. Once a THM is accumulated in autumn, defoliation needs to optimise the swards ability to continue to accumulate herbage and maintain sward quality. In high and very high THM, ceiling yield is reached at the beginning of November resulting in a decline in sward quality and a loss of herbage mass until defoliated. These should be defoliated by early November to minimise any potential losses in herbage. Swards with a low THM can be defoliated later in autumn, as these swards continue to accumulate herbage to the end of November, while still maintaining a high sward quality. The medium THM reduced in

herbage from November but continued to maintain sward quality, and as such these swards can be grazed later in November, while prioritising high and very THM for grazing earlier in autumn. Results from the current study provide information to improve autumn grazing management guidelines and optimise utilisation of herbage masses accumulated for the extension of the grazing season through a more appropriate defoliation strategy in autumn.

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Chapter 3: The impact of accumulating herbage masses in autumn on perennial ryegrass sward characteristics

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3.1 Abstract

Autumn grazing management aims to accumulate herbage prior to a decrease in growth rates for the extension of the grazing season. The current study investigated the impact of building different target herbage masses (THM) in autumn and imposing different defoliation dates (DD) between mid-October and late November on; light transmitted to the base of the sward, free leaf lamina (FLL), leaf stage and internode elongation. Four THM (Low, Medium, High and Very high) and three DD (DD1- 15 October, DD2 - 7 November and DD3 - 21 November) were assigned to a 4 x 3 factorial split plot design over two years. Light transmitted to the base of the sward was greatest in the low THM and decreased from the medium THM to the very high THM. Internode elongation increased in tillers from the medium to the very high THM. Defoliation of the medium, high and, in particular, the very high THM earlier in autumn reduced the effect of decreased light transmission on internode elongation. This study highlights that, as light transmitted to the base of the sward reduces, internode elongation increases and this can negatively impact sward structure.

3.2 Introduction

Perennial ryegrass (*Lolium perenne* L.; PRG) is the preferred species in temperate pasture-based systems (Grogan and Gilliland, 2011), common in Ireland and New Zealand, as it has the ability to produce large quantities of high quality herbage (Finneran et al., 2012), as well as being able to withstand intensive grazing (Robson et al., 1988). Kennedy et al. (2005) identified increasing the proportion of grazed grass in the diet of animals as an important objective of pasture-based systems, in addition to improving the environmental and economic sustainability within the farm system (Donnellan et al., 2018; Hanrahan et al., 2018; MacDonald et al., 2010). One way to increase the proportion of grazed grass in the diet is the extension of the grazing season, which has been reported to increase overall farm profitability by reducing feed and labour costs (Hanrahan et al., 2018) and has been shown to be correlated with the reduction of the carbon footprint of milk (O'Brien et al., 2015). Currently the average length of the grazing season in Ireland is 223 days (Läpple et al., 2012) with the aim to increase this to 300 days (O'Donovan et al., 2010).

Grassland productivity is limited by low temperatures and seasonality (Hennessy and Wingler, 2016) with lower amounts of herbage accumulating from autumn and over winter due to restrictive environmental conditions (Herrman et al., 2005; Hennessy et al., 2006) compared to the summer period. To facilitate the extension of the grazing season specific grazing management strategies are used; herbage masses are 'built and carried' (Hennessy et al., 2006) from August to the target grazing dates for the final grazing rotation (approximately the 15 October – 21 November; Teagasc, 2011). Herbage mass must be accumulated in autumn when growth rates allow for an extended grazing period (Teagasc, 2011; Claffey et al., 2019). Previous studies on autumn grazing management have focused on animal productivity, with an increase in milk protein concentration (Dillon et al., 1998; Claffey et al., 2020), reduction in supplementation requirement (Läpple et al., 2012; Claffey et al., 2020) and the impact of autumn

defoliation (Lawrence et al., 2017). However, few studies have investigated the impact of autumn grazing management practices on sward morphology.

Previous studies have identified that grazing PRG swards at the 'three-leaf stage' (Fulkerson and Donaghy, 2001) and approximately 1500kg DM ha^{-1} (Wims et al., 2014) of herbage is optimal for the maximum utilisation of high quality herbage and allows sufficient build-up of water soluble carbohydrates for PRG swards. The PRG plant is in the vegetative stage in autumn and has one actively growing leaf at a time, with three green leaves in total (Fulkerson and Donaghy, 2001). Once the plant moves above the three-leaf-stage the oldest leaf (first leaf to appear after defoliation) begins to senesce, which results in an increase in the proportion of senescent material in the sward (Fulkerson and Donaghy, 2001). To accumulate herbage masses the defoliation interval is extended which can result in an increase in the number of leaves senesced (Davies and Simons, 1979). This means that leaves are continuously being produced and senescing, even after the ceiling yield is achieved (Brereton et al., 1985), which results in no further accumulation of herbage, just an increase in senescent material at the base of the sward, which reduces light availability to the base of the sward (Parsons and Chapman, 2000). This increase in leaf number (past the three-leaf-stage) and shading can reduce the photosynthetic activity of the PRG leaves (Woledge, 1978). Previous studies on carrying high herbage masses over winter have found that the level of senescent material in the sward increases, resulting in a lower sward quality (Hennessy et al., 2008; Looney et al., 2021a). However, limited research has been carried out on the implications of herbage accumulation in autumn on sward characteristics. The longer a sward remains undefoliated, the greater the chance of increased shading at the base of the sward, which can reduce tiller production and hinder tiller establishment and survival (Laidlaw & Mayne, 2000). A reduction in tiller production can reduce herbage production through decreasing the number of growing points in the sward (Garay, 1999). An increase in shading at the base of the sward, can lead to internode elongation, where the distance between nodes increases (Minderhoud, 1978); the growing point is now no longer at

ground level which may have negative impacts on sward morphology such as increased tiller mortality.

The objective of this study was to investigate the effect of accumulating varying herbage masses in autumn and imposing different defoliation dates in the final grazing rotation on sward morphology, particularly leaf stage, lamina length and the presence of internode elongation.

Table 3.1: Average daily air temperature (˚C), total rainfall (mm), solar radiation, and mean soil temperature to a depth of 100 mm (˚C) between August and April for Year 1 (2018/2019), Year 2 (2019/2020) and the 10 year average (2006 – 2016) at the experimental site.

	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	April
Average daily air temp (˚C)									
Year 1 - 2018/2019	15.6	12.4	9.9	8.1	8.5	6.5	7.7	7.5	9.1
Year 2 - 2019/2020	15.6	13.6	9.7	7.1	6	6.1	6.5	6.3	9.8
10-year average	14.8	13.3	10.9	7.6	5.7	5.4	5.5	6.4	8.7
Total rainfall (mm)									
Year 1 - 2018/2019	43.3	60.0	72.4	167.1	168.2	65.9	56.7	117.9	108.9
Year 2 - 2019/2020	106.8	71.5	155.0	141.0	115.2	89.7	113.3	47.9	64.8
10-year average	81.7	67.5	105.5	116.8	113.2	122.5	82.6	68.7	58.8
Solar radiation									
Year 1 - 2018/2019	1329	1074	691	267	176	247	484	937	1316
Year 2 - 2019/2020	1376.5	1101	654	270	203	297	447	891	1391
10-year average*	1347	964	560	320	192	249	408	825	1314
Mean soil temp to a depth of 100 mm (˚C)									
Year 1 - 2018/2019	18.0	14.6	10.8	7.8	8.0	6.8	7.3	8.3	10.6
Year 2 - 2019/2020	17.5	15.2	10.9	7.4	5.9	5.7	5.9	6.7	11.0
10-year average	17.0	15.0	11.9	7.9	5.4	5.0	5.4	6.9	10.2

*Data presented from 2008 – 2016

3.3 Materials and methods

3.3.1 Site

A plot trial was conducted at the Teagasc, Animal and Grassland Research and Innovation Centre, Moorepark, Fermoy, Ireland (Latitude 50°07'N, Longitude 08°16'W) from 1 August 2018 to 1 April 2019 (Year 1) and 1 August 2019 to 1 April 2020 (Year 2; Looney et al., 2021 b) The soil type was a free-draining acid brown earth of sandy to loam texture. Soils had a pH of 6.4, phosphorus (P) Index of 4 and potassium (K) Index of 3 (± 0.8; scale 1 to 4; 1 = deficient, 4 = no response to application of nutrient) (Alexander et al., 2008). The experimental site was of south facing aspect and located approximately 40 m above sea level. Swards were made up of PRG (*Lolium perenne* L; > 85%) predominantly, with the remaining 15% made of mainly annual weed grass (*Poa annua* L.) and broadleaf plants. Meteorological data were recorded at the experimental site over the experimental period (October to February). Average daily air temperature (°C), soil temp to a depth of 100 mm (°C), total daily rainfall (mm) and average solar radiation are shown for the measurement periods in each experimental year (Table 3.1).

3.3.2 Experimental design

The experimental design was 4 x 3 factorial split plot design with four replicates, resulting in 48 plots (1.5 m x 6 m). Four target herbage masses (THM; Low - 500 kg DM ha^{-1}, Medium - 1500 kg DM ha^{-1}, High - 2000 kg DM ha^{-1} and Very high - 3000 kg DM ha^{-1}; see Table 2 for achieved herbage masses) were targeted for 15 October. Growth rates achieved were higher (Table 3.2), particularly in the low THM, due to the compensatory growth experienced post drought in 2018. Three defoliation dates (DD; DD1 – 15 October, DD2 – 7 November and DD3 – 21 November), chosen to reflect Irish autumn grazing management practices (Teagasc, 2011), were examined on the four THM. Measurements of sward characteristics, (see below) were carried out on each autumn DD (DD1, DD2 and DD3), in addition to measurement of herbage mass and light at the base of the sward for the 1st defoliation in spring (21 February). Outside of the experimental period plots were defoliated, using an Etesia mower (Etesia UK Ltd.,

Warwick, UK), to a residual of 4 cm when they reached a pre-grazing herbage mass of 1500 kg DM ha^{-1} between February and July. In August plot defoliation was tailored, using defoliation management and back-calculation from previous daily growth rates, to accumulate each THM for the 15 October. Over the experimental period nitrogen was applied in early August at a rate of 35 kg N ha^{-1} in the form of calcium ammonium nitrate (CAN; 27% N). Phosphorus and potassium were applied in January as 30 kg ha^{-1} of 0-7-30. At the end of January, nitrogen was applied at a rate of 28 kg N ha^{-1} in the form of urea (46% N). Outside of the experimental period nitrogen was applied, post-defoliation, as 20 kg N/ha as CAN. In year 2, 30 kg ha^{-1} of 0-7-30 was applied to all plots in August.

3.3.3 Herbage mass

The entire plot was harvested using the Etesia mower (Etesia UK Ltd., Warwick, UK) > 3.5 cm (targeted residual). The mown herbage from the plot was collected and weighed. A sample of approximately 300 g was collected from each cut strip. A subsample of 100 g was weighed and dried for 16 hours at 60°C to determine dry matter (DM) content. .

3.3.4 Light at base of sward

The photosynthetically active radiation (PAR; 400-700 nm), was measured on all plots pre and post each defoliation, using a line quantum sensor (1 m with 10 interval sensor points; LI-COR Inc), attached to a data logger. The above canopy PAR was recorded for each plot first by placing the line quantum sensor at canopy level beside the plot, with nothing interfering with its light interception, and a ten-second average from across the ten points of the line quantum sensor was recorded. The below canopy PAR was taken, twice in each plot, by inserting the line quantum sensor at the base of the canopy, making sure not to disrupt the sward. For each plot an average of both below canopy PARs was used. The percentage of light transmitted to base of the sward was calculated using the below equation;

$$\frac{\text{below canopy measurement}}{\text{above canopy measurement}} \text{ x } 100 = \% \text{ light at base of sward}$$

3.3.5 Leaf stage

Perennial ryegrass leaf stage was measured by taking ten vegetative PRG tillers randomly selected from each plot prior to defoliation in at each DD in autumn and again in spring as outlined by Dairy NZ (2021). On each tiller, the remnant leaf was identified (if more than one remnant leaf was present, only the uppermost remnant leaf was included). The length of this remnant leaf was compared with the leaf above it (first new leaf), and if less than half the size of the new leaf, it was not included in the measurement; if greater than half the size, it was counted as half, three quarters or a whole leaf in its own right. Each fully grown leaf, un-defoliated and with a pointed tip, was counted. If the uppermost leaf was not fully grown it was compared in size to the leaf below it, and counted to the nearest ¼ of a leaf. The leaf stage of each of the individual tillers was recorded and averaged to give the leaf stage for each plot.

3.3.6 Free leaf lamina, total green leaf lamina length and internode elongation

From each plot prior to defoliation 45 mature PRG tillers with no visible daughter tillers were manually harvested at the ground level using a scalpel blade at random areas within each plot. On each harvested tiller the extended tiller height (ETH) was measured using a graduated ruler from ground level to the tip of the longest green leaf lamina. The extended sheath height (ESH) was measured from ground level to the newest sheath. The free leaf lamina (FLL) was then calculated by subtracting the ESH from the ETH (Gilliland et al., 2002). The total green leaf lamina length was also recorded. After the ESH and ETH were recorded the sheath was carefully removed and examined for internode elongation. If internode elongation was visible the length of elongation was measured to the nearest mm and the location of apical meristem.

3.3.7 Statistical analysis

Statistical analyses were carried out using SAS 9.4 (SAS Institute Inc., Cary, NC, USA, 2002). The effect of THM and DD on herbage mass, light at base of sward, leaf stage, free leaf lamina, total green leaf lamina length, internode elongation and the no. of nodes was determined using the PROC MIXED procedure in SAS, with THM, DD, year, plot being used in the model. Plot was the experimental unit and year was the random factor. Data are presented as least square means ± standard error. Variables were analysed using the following model:

$$Y_{jkl} = \mu + target\ herbage\ mass_j + defoliation\ date_k + year_l + \left(target\ herbage\ mass_j \times defoliation\ date_k\right) + \left(year_l \times defoliation\ date_j\right) + \left(defoliation\ date_j \times target\ herbage\ mass_k\right) \times e_{jkl}$$

Where:

μ = mean value for the variable

e_{jkl} = residual error term

Y_{jkl} = herbage mass (kg DM ha^{-1}), light at base of sward (%), leaf stage (leaves), free leaf lamina (cm), total green leaf lamina length (cm), percentage of tillers with visible internode elongation (%), length of internode elongation (cm) and percentage of tillers with an apical meristem > 4 cm.

3.4 Results

3.4.1 Autumn Period

Herbage mass

The interaction between DD and year was significant (P < 0.001). In year 1, DD2 and DD3 (2366 ± 108.1 kg DM ha^{-1}) had a greater herbage mass than DD2 (1800 ± 108.6 kg DM ha^{-1}) and DD3 (1547 ± 108.6 kg DM ha^{-1}) in year 2. There was a significant (P < 0.001) effect of THM on herbage mass; the very high THM had a greater herbage mass than all other THM. The medium and high THM were both greater than the low THM (Table 3.2).

Defoliation date significantly ($P < 0.001$) affected herbage mass; defoliation of swards in mid-October (DD1) resulted in a lower herbage mass compared to November (DD2 and DD3; Table 3.3). Herbage mass was significantly ($P < 0.001$) greater in year 1 (2172 ± 62.7 kg DM ha^{-1}) compared to year 2 (1634 ± 62.7 kg DM ha^{-1}).

Table 3.2: Effect of the interaction of target herbage mass (Low - 500 kg DM ha^{-1}, Medium - 1500 kg DM ha^{-}1, High - 2000 kg DM ha^{-1} and Very high - 3000 kg DM ha^{-1}) and defoliation dates (DD; DD1 – 15 October, DD2 – 7 November and DD3 – 21 November) at defoliation in autumn on the herbage mass (kg DM ha^{-1}), light at the base of the sward (%), leaf stage (leaves), free leaf lamina (cm) and the total green leaf lamina (cm).

	Target herbage mass					
Variable	**Low**	**Medium**	**High**	**Very high**	**S.E.M**	**Significance**
Herbage mass (kg DM ha^{-1})	900^{a}	1735^{b}	1938^{b}	2917^{c}	153.6	***
Light at the base of the sward (%)	66^{a}	57^{b}	58^{b}	55^{b}	2.8	***
Leaf stage (leaves)	2.2^{a}	2.8^{b}	3.3^{c}	3.9^{d}	0.06	***
Free leaf lamina (cm)	18.6^{a}	24.9^{b}	27.4^{c}	32.8^{d}	0.41	***
Total green leaf lamina per plant (cm)	36.3^{a}	52.2^{b}	58.7^{c}	68.2^{d}	1.51	***

Table 3.3: The effect of defoliation dates (DD; DD1 – 15 October, DD2 – 7 November and DD3 – 21 November) in autumn on the herbage mass (kg DM ha^{-1}), light at the base of the sward (%), leaf stage (leaves), free leaf lamina (cm) and the total green leaf lamina (cm) are presented.

	Defoliation date				
Variable	**DD1**	**DD2**	**DD3**	**S.E.M**	**Significance**
Herbage mass (kg DM ha^{-1})	1578^{a}	2100^{b}	1940^{b}	153.6	***
Light at the base of the sward (%)	56	61	60	2.6	NS
Leaf stage (number leaves)	2.8^{a}	3.1^{b}	3.3^{b}	0.05	***
Free leaf lamina (cm)	24.6^{a}	26.4^{b}	26.6^{b}	0.35	***
Total green leaf lamina per plant (cm)	47.4^{a}	58.1^{b}	56.0^{c}	1.33	***

Light at base of the sward

Light at base of the sward was greatest ($P < 0.001$) in the low THM compared to the medium, high and very high THM (Table 3.2). There was no significant effect of DD on light at base of the sward (Table 3.3). Year 1 (39 ± 1.9 %) had a significantly ($P < 0.001$) greater light at base of the sward than year 2 (12 ± 1.9 %).

Leaf stage

There was a significant ($P < 0.001$) interaction between THM and year on leaf stage; the high herbage mass had a greater leaf stage in year 1 (3.8 ± 0.09 leaves) compared to year 2 (2.8 ± 0.09 leaves) and all other THM were similar in year 1 and year 2. There was a significant interaction between THM and DD ($P < 0.05$) on leaf stage. The low THM in DD1 (1.9 ± 0.11 leaves) had a lower leaf stage compared to DD3 (2.6 ± 0.11 leaves) with DD2 (2.2 ± 0.11 leaves) intermediate. The medium THM had a greater leaf stage in DD3 (3.3 ± 0.11 leaves) compared to DD1 and DD2 (2.6 ± 0.11 leaves). The leaf stage increased significantly ($P < 0.001$) from the low THM to the very high THM (Table 3.2). Leaf stage was significantly ($P < 0.001$) lower in DD1 compared to DD2 and DD3 (Table 3.3). Year had a significant ($P < 0.001$) effect on leaf stage. Year 1 (3.2 ± 0.04 leaves) had a greater leaf stage than year 2 (2.9 ± 0.04 leaves).

Free leaf lamina

There was a significant interaction ($P < 0.001$) between THM and year on the FLL, the low, medium and high THM had a greater FLL in year 1 (21.8, 26.8 and 29.4 ± 0.57 cm, respectively), compared to year 2 (15.3, 23.2 and 25.3 ± 0.57 cm, respectively). The very high herbage mass had a similar FFL in year 1 and year 2 (32.8 ± 0.57 cm). There was a significant interaction ($P < 0.001$) between DD and year on FLL, in year 1, DD2 and DD3 (28.4 and 30.4 ± 0.49, respectively) had a greater FLL compared to DD2 and DD3 in year 2 (24.5 and 22.9 ± 0.49, respectively). Free leaf lamina was significantly ($P < 0.001$) different for all THM (Table 3.2). Defoliation date had a significant ($P < 0.001$) effect on FLL, DD2 and DD3 (26.5 ± 0.35 cm) had a greater FLL than DD1 (24.7 ± 0.35 cm). Year

significantly (P < 0.001) affected FLL with year 1 (27.8 ± 0.29 cm) having a greater FLL compared to year 2 (24.1 ± 0.29 cm).

Total green leaf lamina length

Target herbage mass had a significant (P < 0.001) effect on total green leaf lamina length, with the very high THM the greatest, followed by the high, then medium and the low THM the lowest (Table 3.2). Defoliation date significantly (P < 0.001) affected the total green leaf lamina length, DD1 was lower than DD2 and DD3 (Table 3.3). Year 1 (59.7 ± 1.08 cm) had a significantly (P < 0.001) greater total green leaf lamina compared to year 2 (47.9 ± 1.08 cm).

Percentage of tillers with internode elongation present

There was a significant (P < 0.001) effect of THM x DD on internode elongation; DD3 had a greater percentage of tillers with internode elongation present in the high and very high THM compared to DD1 and DD2 (Table 3.4A). The percentage of tillers with internode elongation was significantly (P < 0.001) affected by THM (Table 3.4A). The medium THM had the lowest percentage, then the low THM and the high THM. The very high THM had the greatest percentage of tillers with internode elongation. Defoliation date significantly affected the percentage of tillers with internode elongation present (Table 3.4A); DD3 had a greater percentage than DD1 and DD2. The lowest percentage of internode elongation present was found in DD1. Year had a significant (P < 0.001) effect on the percentage of tillers with internode elongation; year 1 (32 ± 1.1%) had a greater percentage of tillers compared to year 2 (21 ± 1.1%).

Length of internode elongation (cm)

There was a significant (P < 0.001) effect of THM x DD on the length of internode elongation (Table 3.4B); within DD3 the low THM had the shortest length of elongation compared to the very high THM with the medium and high intermediate to both. The THM had a significant (P < 0.001) effect on the length of internode of elongation (Table 3.4B). The very high THM had longer internode elongation compared to the low THM

with the medium and high intermediate to both. Defoliation date did not significantly ($P > 0.05$) affect the length of internode elongation. Year had a significant ($P < 0.001$) effect on the length of internode elongation; Year 2 (2.2 ± 0.18 cm) had a greater length of internode elongation compared to year 1 (1.0 ± 0.18 cm).

Percentage of tillers with apical meristem > 4 cm

There was a significant ($P < 0.001$) effect of THM x DD on the percentage of tillers with apical meristem > 4 cm (Table 3.4B); in DD1 and DD2 the low and medium THM had a lower number of tillers with apical meristem > 4 cm compared to the very high THM with high THM intermediate. The THM had a significant ($P < 0.001$) effect on the percentage of tillers with apical meristem > 4 cm (Table 3.4B). The very high THM had a greater number of tillers with apical meristem > 4 cm compared all other THM. Defoliation date or year did not significantly affect the percentage of tillers with apical meristem > 4 cm.

Table 3.4A: The effect of the interaction of target herbage mass (Low - 500 kg DM ha^{-1}, Medium - 1500 kg DM ha^{-1}, High - 2000 kg DM ha^{-1} and Very high - 3000 kg DM ha^{-1}) and defoliation dates (DD; DD1 – 15 October, DD2 – 7 November and DD3 – 21 November) at defoliation in autumn on the percentage of tillers (%) with visible internode elongation are presented.

Target herbage mass	Low	Medium	High	Very high	DD average	S.E.	Significance		
Percentage of tillers with visible internode elongation (%)							**THM**	**DD**	**THM x DD**
DD1	18.8	8.9	21.2	30.9	20.0	2.5	***	***	***
DD2	16.4	9.2	23.8	51.3	25.2				
DD3	17.1	10.2	40.8	78.0	36.5				
Target herbage mass average	17.3	9.4	28.6	53.4					

Table 3.4B: The effect of the interaction of target herbage mass (Low - 500 kg DM ha^{-1}, Medium - 1500 kg DM ha^{-1}, High - 2000 kg DM ha^{-1} and Very high - 3000 kg DM ha^{-1}) and defoliation dates (DD; DD1 – 15 October, DD2 – 7 November and DD3 – 21 November) at defoliation in autumn on the average length of visible internode elongation (cm) and the proportion of tillers > 4cm are presented.

Target herbage mass	Low	Medium	High	Very high	DD average	S.E.	Significance		
Average length of visible internode elongation (cm)*							**THM**	**DD**	**THM x DD**
DD1	0.45	1.84	0.69	1.94	1.23	0.338	***	NS	***
DD2	0.61	1.63	0.87	2.19	1.33				
DD3	0.88	1.38	1.50	2.02	1.45				
THM average	0.65	1.60	1.02	2.05					
Apical meristem > 4 cm (%)									
DD1	0.1	2.0	3.7	7.8	4	2.3	***	NS	***
DD2	2.6	2.1	1.2	9.7	4				
DD3	0.4	0.2	1.4	13.4	4				
THM average	1.0	1.4	2.1	10.3					

*Only including tillers that have internode elongation present

3.5 Discussion

The current study has shown that autumn grazing management strategies, i.e. accumulating varying herbage masses and different defoliation dates, have significant impacts on sward morphology (leaf stage, FLL, presence and length of internode elongation). Previous studies have reported that, to ensure optimal grazing utilisation, swards should be grazed at a three-leaf-stage (Fulkerson and Donaghy, 2001) and a herbage mass of 1500 kg DM ha^{-1} (Wims et al., 2014). In the current study, the low THM did not meet the three leaf stage requirement (DD1 – 1.9 leaves) and herbage mass (900 kg DM ha^{-1}) to ensure optimum utilisation for grazing. However, low THM had the greatest percentage of light transmitted to the base of the sward in autumn and as a result it did not trigger the same extent of internode elongation compared to the high and very high THM. Previous studies have reported that light transmitted to the base of the sward impacts tiller appearance (Laidlaw and Mayne, 2000) and internode elongation (Brock and Fletcher, 1993). The light transmitted to the base of the sward reduced by 9% from the low to the medium THM, which did not increase the % of tillers with visible internode elongation however, it did increase the length of visible internode elongation between the low and medium (+ 0.95; Harris et al., 1979)**.** This indicates that although the light at the base of the sward did decrease between the low and medium THM, the number of tillers with visible internode elongation did not change significantly however, the length of those tillers present did increase. Decreasing light to the base of the sward can result in tiller bud suppression (Hunt, 1978) which can result in the loss of daughter tillers (Korte, 1981) and can inhibit the production of new tillers (Baker, 1956). Internode elongation is an unfavourable morphological trait in PRG swards as the growing point is no longer at ground level (Minderhoud, 1978). If internode elongation is above the grazing/defoliation height (3.5 cm in the current study), it can result in an increased tiller mortality after defoliation. This can then lead to a reduction in growing points (Garay, 1999) for herbage production following defoliation. In the current study, when swards reached a herbage mass of between ~1700 kg DM ha^{-1} to ~2900 kg DM ha^{-1}, the light transmitted to the base of the sward remained constant at 57% similar to

Thomas and Norris (1981). The medium and high THM had increased effects on internode elongation; however, the greatest impact was seen in the very high THM, with 53% of tillers having internode elongation, compared to 29% in the high THM, and a greater percentage of internode elongation above 4 cm. The length of time between defoliation (DD1 – DD2 – DD3) did not impact the amount of light transmitted to the base of the sward. This indicates that prolonging defoliation from 15 October to 21 November does not impact the light transmitted to the base of the sward once the sward has reached its saturation point for light transmission. The light transmitted to the base of the sward in the current study did not decrease when herbage mass increased (1735 kg DM ha^{-1} to 2917 kg DM ha^{-1}). However, increasing the length of time between defoliations in autumn did increase the percentage of tillers with visible internode elongation.

Post-defoliation, all plots were found to return to approximately 79 ± 2.9% light at base of the sward in autumn and there was no effect on tiller density (Looney et al., 2021b). This increased light transmission to the base of the sward (Brougham et al., 1960) would have stimulated the production of tillers (Kays and Harper, 1974; Laidlaw and Mayne, 2000), giving enough growing points for production (Garay, 1999) in spring. The very high THM experienced the greatest morphological changes over the experimental period due to the length and level of shading (Laidlaw and Mayne, 2000). To reduce prolonged shading and impacts on internode elongation the very high THM should be defoliated as early as possible in autumn. Defoliation should ideally happen in swards at ~1700 kg DM ha^{-1} to allow light transmit to the base of the sward to promote new tiller production (Kays & Harper, 1974; Laidlaw & Mayne, 2000).

The leaf stage increased as THM increased from low THM (2.2 leaves) to very high THM (3.9 leaves; Table 3.2) similar to Fulkerson and Donaghy (2001), with any increase in leaf stage past the three-leaf-stage leading to the senescence of the fourth leaf (Fulkerson and Donaghy 2001). This can contribute to the decrease in herbage mass in swards that go past the three-leaf-stage (Looney et al 2021, b) as a result of an increase in senescent

material. As senescent material increases, sward quality reduces (Binnie et al., 2001), due to a lower level of organic matter in dead material (Beecher at al., 2015). Although there was a reduction in herbage and increase in senescent material from early November in the very high THM, the FLL and green leaf lamina available for grazing were greatest on the very high THM. A greater FLL can result in an increased grazing efficiency due to the greater amount of green leaf available for defoliation (Byrne et al., 2018). A maximum FLL appears to have been achieved in the very high THM. However, it was found that the FLL never surpassed approximately 33 cm, and this appears to be the maximum achievable FLL in autumn. After the maximum is reached, the amount of senescent material will continue to increase and this will lead to reduced sward quality (Binnie et al., 2001).

3.6 Conclusions

The current study reported that, the light transmitted to the base of the sward and sward morphology are impacted by autumn grazing management for the extension of the grazing season. Management practices can be altered to achieve grazing targets and improve sward morphology. Swards with a low THM transmit enough light to the base of the sward but have not reached the optimal three-leaf-stage or herbage mass for grazing and should be defoliated from the middle of November. Defoliation can decrease the effect of reduced light transmitted to the base of the sward on internode elongation. Swards from the medium THM to the very high THM experience reduced light transmission to the base of the sward. Defoliating the medium, high and, in particular, the very high THM between mid-October to early November will benefit the sward as internode elongation will be reduced. Earlier defoliation will also reduce the number of tillers with internode elongation > 4 cm in the very high THM.

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Chapter 4: An examination of the effect of autumn closing date on over winter herbage production and on spring yield

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4.1 Abstract

Altering autumn management affects the herbage mass available in spring. An experiment was established to determine the effect of 5 autumn closing dates (CD) on herbage production, herbage quality, leaf, stem and dead proportions and tiller density over winter. In the study, 50% of the herbage available in spring was accounted for by autumn closing date. Each one day extra a sward was closed from 25 September to 9 December increased herbage mass by 16 kg DM ha^{-1} in spring. Swards closed earlier (25 September – 26 October) had consistently higher herbage masses in spring (1301 kg DM ha^{-1}) compared to swards closed later (11 November – 9 December; 703 kg DM ha^{-1}). Later closed swards had a higher herbage quality compared to earlier closed swards (OMD = 852 and 825 g kg^{-1} DM, respectively), due to increased stem and dead material in the grazing horizon of earlier closed swards. There was no effect of autumn closing date on sward quality in the subsequent defoliation in spring. However, there was an effect on subsequent growth rates in spring; swards closed in October had a lower growth rate (33 kg DM ha^{-1} day^{-1}) compared to swards closed in November and early December (49 kg DM ha^{-1} day^{-1}) following the initial spring defoliation. Results indicate that an earlier autumn closing is beneficial to meet high feed demand in spring but can affect sward quality in spring and growth rates in the subsequent defoliation.

Key words: Autumn grazing date, spring grass, herbage mass, sward quality

4.2 Introduction

In temperate regions of the world grass-based dairy production systems offer a competitive and sustainable alternative to intensive, high-output systems (Dillon et al., 2008; Peyraud et al., 2010; Ramsbotton et al., 2015). Grazed grass is the cheapest feed source available for ruminant production systems (Finneran et al., 2010), and increasing the production and utilization of grazed grass is of the utmost importance in improving environmental (Donnellan et al., 2018) and economic (MacDonald et al., 2010; Hanrahan et al., 2018) sustainability. In spring calving systems, which are dominant in Ireland (Dillon et al., 1995; O Donovan et al., 2011), there are high feed requirements to meet animal demands in spring. In temperate climatic zones, such as Ireland and New Zealand, there is a high dependence on environmental conditions such as temperature, for perennial ryegrass (*Lolium perenne* L.; PRG) growth. As a result there is little grass growth during late autumn, winter and early spring (Dillon et al., 1995; Parsons & Chapman, 2000; Hennessy et al., 2008) which can lead to inadequate amounts of grazed herbage available on farm in spring (Ryan et al., 2010; Lawrence et al., 2017). Autumn closing date is one of the main factors contributing to the accumulation of herbage over the winter months (Roche et al., 1996; Hennessy et al., 2006). The date on which a sward is grazed in the previous autumn has a direct impact on the amount of grass available in the following spring (Davies & Simons, 1979; O'Donovan et al., 2002; Lawrence et al., 2017). It has previously been reported that every one day delay in closing, from 1 October, results in a reduction in spring herbage accumulation of between 10 and 15 kg DM ha^{-1} day^{-1} in pre-grazing herbage mass (O'Donovan et al., 2002; Lawrence et al., 2017). Closing swards earlier in autumn (early October) can lead to an increase in herbage available in spring, which can allow for an earlier turnout of animals (Roche et al., 1996; Hennessy et al., 2006).

Despite low over winter growth rates on farms in Ireland (3 to 8 kg DM ha^{-1} day^{-1}; December-January) (Pasturebase Ireland Data - O'Leary, Personal Communication), herbage is continuously accumulating throughout the winter (Brereton et al., 1985)

albeit at a slower rate compared to spring, summer and autumn. When a high herbage mass (>2000 kg DM ha^{1}; approximately) is carried over winter, it can result in a reduction in sward quality, as the amount of green leaf material in the sward declines and the level of senescent material increases (Hennessy et al., 2008). Additionally high herbage mass results in shading which can reduce tiller production and hinder tiller establishment and survival (Laidlaw & Mayne, 2000). To meet the target of matching animal feed requirements with available herbage in spring, autumn grazing management has been identified as the key controllable management practice on farm (Claffey et al., 2019). Over the last 10 years (2008–2017), the 6-week calving rate on Irish dairy farms has increased from 61% to 72%, while mean calving date has reduced by 8 days (Dillon et al., 2018). The proportion of cows calving between January and April has increased from 74% in 2008 to 84% in 2018 (ICBF, 2018). This coupled with an increase in average herd size from 48 cows in 2005 to 76 cows in 2016 (Kelly et al., 2020) and an increase in whole farm stocking rate from 1.7 to 1.9 LU ha^{-1} (Hanrahan et al., 2018) has resulted in an increase in dairy cow feed demand on Irish farms in spring. This increased demand must be met through increased grass growth and utilisation if farms are to remain economically sustainable (Dillon et al., 2005). Current autumn grazing recommendations in Ireland are that the farm begins closing in early October, 60% of the farm is closed from grazing by the 1 November, with a closing average farm cover (AFC; amount of grass available on farm) of between 650 – 750 kg DM ha^{-1} (3.5 cm above ground level) on the 1 December and an opening average farm cover in spring of approximately 1000 kg DM ha^{-1} (Teagasc, 2019; Claffey et al., 2020). One option to increase spring grass availability is to close swards early in autumn and thereby carry a greater quantity of grass over winter into spring (Hennessy et al., 2006).

Previous research in the area of autumn closing date has been carried out on plot studies (Carton et al., 1988; Hennessy et al., 2006; Lawrence et al., 2017), within grazing studies (Roche et al., 1996; Ryan et al., 2010) or on commercial farms (O Donovan et al., 2002). However, much of this work was prior to the rapid expansion within the Irish dairy industry (Kelly et al., 2020). Grazing management practices have not evolved to meet

increased herd demand in spring, in line with increased stocking densities and earlier and more compact calving. Earlier autumn closing has been recommended as a strategy to help meet the herbage demand in spring (Claffey et al., 2019). Some of the previous studies that investigated autumn closing dates over multiple years (Hennessy et al., 2006; Lawrence et al., 2017) had very early autumn closing (10 August – 10 October) and the grazing dates did not represent that of a dairy farm in spring (20 November – 20 February; Hennessy et al., 2006). Closing swards over a period in autumn followed by spring defoliation is more representative of grazing management practices on farm. Additionally, little research has taken place on the impact of autumn closing date on the regrowth of swards in spring following initial defoliation. There is still potential to improve both autumn and spring grazing management recommendations through a multiple year study that is representative of on farm autumn closing dates and spring grazing requirements.

The objective of this experiment was to investigate the effect of closing paddocks between late September and early December on over winter herbage production, herbage quality, leaf, stem and dead proportions, tiller density in spring and the subsequent effects on herbage production.

4.3 Materials and Methods

The experiment was undertaken at the Teagasc, Animal and Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork, Ireland (Latitude 50°07'N, Longitude 08°16'W) from August 2016 to April 2019. The paddocks were approximately 40 m above sea level with a south facing aspect. The soil type was a free-draining acid brown earth of sandy to loam texture (Teagasc, 2017). Swards were predominantly PRG (> 85 %,) plus < 15% broadleaf plants and weed grass including, white clover (*Trifolium repens* L.) and annual meadow grass (*Poa annua* L.). Soils had a pH of 6.8 (± 0.2), phosphorus (P) Index of 3.8 (± 0.4) and potassium (K) Index of 3.3 (±0.8; scale 1 to 4; 1 = deficient, 4 = no response to application of nutrient) (Alexander et al., 2008). This study was undertaken within a larger grazing experiment (Claffey et al., 2019; Claffey et al., 2020), where the

rotation length of the grazing treatments dictated the closing dates and initial spring grazing date. Briefly, the larger farm systems study had three autumn closing management treatments: Early (25 September – 9 November), Normal (10 October – 24 November) and Late (25 October – 9 December). A total of 30.6 ha were randomised into three farmlets, with each farmlet split into paddocks and grazed by equal groups of 30 lactating dairy cows, and based on autumn closing treatment. The target post–grazing sward heights in autumn and spring were 3.5 cm. The actual post–grazing sward height achieved was 4 ± 0.05 cm in autumn and 3.6 ± 0.06 cm in spring. All animals were turned out in spring on ~ 5 February (± 2 days) regardless of autumn closing treatment. Across all farmlets in spring the daily area allocation to each grazing group was similar across the first rotation, concentrate supplementation in spring was similar for each grazing group (3 kg DM cow^{-1} day^{-1}) and silage was only supplemented to each individual group if the post-grazing sward height went below 3.5 cm (Claffey et al., 2019). For the remainder of the year (3rd rotation to July, where rotation length was gradually extended in late July to allow autumn closing managements to be implemented) all swards were grazed in a 21 day rotational grazing system to a target post–grazing sward height of 4 cm in line with Teagasc recommendations (Teagasc, 2011).

From the farmlet study 36 paddocks were chosen in year 1 (2016-2017), 48 in year 2 (2017-2018) and 48 in year 3 (2018-2019). The last defoliation of paddocks (swards hereafter) for the season was between 25 September and the 9 December. Swards were assigned to each of the five closing date (CD) treatments; the number of swards assigned to each treatment is shown in Table 4.1. Sward numbers differed for each CD in each year as the overall farm systems experiment dictated grazing dates; the grazing dates of the individual paddocks then fell independently into the allocated CD treatments (Table 4.1). The mean CD of each of the treatments was; 4 October (CD1), 19 October (CD2), 3 November (CD3), 18 November (CD4) and 3 December (CD5). Following the final grazing, swards remained un-defoliated until the following spring. Herbage mass > 3.5 cm, was measured on three measurement dates (MD) over winter (Table 4.1) - MD1 (12 December; average), MD2 (9 January) and MD3 (2 February). Initial spring grazing took

place independently of closing date, over an 8-week period from 11 February to 8 April. Spring grazing (MD4) followed the current Teagasc recommendations (Teagasc, 2020) to reflect what happens on farm. Grazing in MD5 followed sequentially from grazing in MD4. Immediately prior to the first grazing in spring, herbage mass was measured (MD4) on each individual sward. Final herbage measurement on each sward was taken immediately prior to second defoliation in spring (2nd rotation; MD5).

Table 4.1: Closing date (CD) treatments applied in autumn and the number of paddocks allocated per treatment and measurement dates (MD) over the experimental period.

Treatment[1]	Mean CD[2]	2-week interval	No of days closed[3]
CD1	4 Oct	25 Sept – 11 Oct	121
CD2	19 Oct	12 Oct – 26 Oct	106
CD3	3 Nov	27 Oct – 10 Nov	91
CD4	18 Nov	11 Nov – 25 Nov	76
CD5	3 Dec	26 Nov – 9 Dec	61
		No. of paddocks per CD	
	Year 1	**Year 2**	**Year 3**
CD1	8	9	10
CD2	5	13	12
CD3	16	15	12
CD4	7	5	12
CD5	0	6	2
	Measurement Date		
MD1[4]	12 Dec		
MD2	9 Jan		
MD3	2 Feb		
MD4	1st Defoliation (6 Feb – 5 April)		
MD5	2nd Defoliation (6 – 30 April)		
	Measurement period		
MP1	Paddock closing – 12 Dec		
MP2	13 Dec– 9 Jan		

MP3	10 Jan – 2 Feb
MP4	3 Feb –1st defoliation
MP5	1st defoliation – 2nd defoliation

[1]Treatment is the autumn closing date applied to swards: CD1= closing date 1, CD2= closing date 2, CD3= closing date 3, CD4= closing date 4 and CD5= closing date 5.

[2]Mean date for each 2 week interval per treatment.

[3] Number of days closed for each closing date between the mean CD and measurement date 3 (February 2nd)

[4]Measurement dates on swards: MD1 = measurement date 1 = 12 Dec, MD2= measurement date 2 = 9 Jan, MD3 = measurement date 3 = 2 Feb, MD4 = measurement date 4 = 1st defoliation in spring, MD5 = measurement date 5 = 2nd defoliation in spring.

Nitrogen fertiliser was applied in the form of urea at a rate of 53.6 kg N ha^{-1} between January and mid-March and a rate of 26.4 kg N ha^{-1} in mid-April. In mid-April phosphorus (9.6 kg P ha^{-1}) and potassium (19.2 kg K ha^{-1}) were applied.

4.3.1 Measurements

Meteorological data

Meteorological data were recorded at the experimental site for the duration of the experiment. Average daily air temperature (°C), soil temp to a depth of 100 mm (°C), total daily rainfall (mm) and average solar radiation are shown for the measurement periods in each experimental year (Table 4.2).

Herbage mass

Herbage mass (> 3.5 cm; targeted residual) was determined by cutting two strips 1.2 m wide by a known length (approx. 10 m) in the swards using an Etesia mower (Etesia UK Ltd., Warwick, UK). The mown herbage from each strip was collected and weighed. A sample of approximately 300 g was collected from each cut strip. A subsample of 100 g was weighed and dried for 16 hours at 90°C to determine dry matter (DM) content. Compressed sward height was recorded pre- and post-cutting on each cut strip by taking ten measurements per strip using a rising plate meter (Jenquip Rising Plate Pasture Meters, New Zealand). This was used to calculate the sward density (cut herbage mass (kg DM ha^{-1}) / (pre-cutting height – post cutting height)). Herbage mass was then corrected for post grazing sward height using the following equation (Delaby et al., 1998):

$$\begin{aligned} &Corrected\ Herbage\ mass\ (> 3.5\ cm) \\ &\quad = (pre\ cutting\ compressed\ sward\ Height \\ &\quad - \ targeted\ residual\ (3.5cm)) * \ sward\ density \end{aligned}$$

Grass growth rate was calculated by dividing the corrected herbage mass by the number of days closed.

Herbage Quality Analysis

Selected herbage samples were taken at random from each sward, prior to spring grazing and in the second rotation. The method used was designed to be representative of what cows would consume from the sward based on previous observations. The method used was that described by Ganche et al. (2013); samples were taken using handheld Gardena shears (Accu 90, Gardena International GmbH, Germany) cut to 3.5 cm and stored at -18°C. The frozen herbage was bowl-chopped (Muller, Type MKT 204 Special, Saabrücken, Germany), freeze-dried at -50°C for 120 hrs and milled through a 1 mm screen using a Cyclotech 1093 Sample Mill.

Table 4.2: Average daily air temperature, mean soil temperature, total rainfall and average solar radiation between September and April for year 1 (2016/2017), year 2 (2017/2018) and year 3 (2018/2019) and the 10 year average (2006-2016) at the experimental site.

	Sept	Oct	Nov	Dec	Jan	Feb	Mar	April	Mean
Average daily air temp (˚C)									
Year 1 - 2016/2017	13.9	10.6	5.2	6.7	6.3	6.6	8.3	8.7	8.3
Year 2 - 2017/2018	12.9	11.5	7.2	6.3	6.3	4.0	4.7	9.0	7.7
Year 3 - 2018/2019	12.4	9.9	8.1	8.5	6.5	7.7	7.5	9.1	8.7
10-year average	13.3	10.9	7.6	5.7	5.4	5.5	6.4	8.7	7.9
Mean soil temp to a depth of 100 mm (˚C)									
Year 1 - 2016/2017	15.0	11.0	5.7	6.2	5.8	6.6	8.4	10.9	8.7
Year 2 - 2017/2018	14.7	12.3	8.1	5.6	5.5	4.0	5.4	10.0	8.2
Year 3 - 2018/2019	14.6	10.8	7.8	8.0	6.8	7.3	8.3	10.6	9.3
10-year average	15.0	11.9	7.9	5.4	5.0	5.4	6.9	10.2	8.5
Total rainfall (mm)									
Year 1 - 2016/2017	98.6	27.9	44.5	84.7	85.3	108.4	115.8	35.6	75.1
Year 2 - 2017/2018	115.7	102.2	65.5	110.4	138.4	40.4	88.5	174.8	104.5
Year 3 - 2018/2019	60.0	72.4	167.1	168.2	65.9	56.7	117.9	108.9	102.1
10-year average	67.5	105.5	116.8	113.2	122.5	82.6	68.7	58.8	92.0
Average solar radiation									
Year 1 - 2016/2017	895	623	375	169	262	445	821	1108	587
Year 2 - 2017/2018	1026	477	335	189	264	552	770	1080	587

Year 3 - 2018/2019	1074	691	267	176	247	484	937	1316	649
8-year average[1]	964	560	320	192	249	408	825	1314	604

[1]Data presented from 2008 to 2016

(Foss, DK-3400 Hillerød, Denmark). The chemical composition was analysed by wet chemistry for organic matter digestibility (OMD; g kg^{-1}), crude protein (CP; g kg DM^{-1}), neutral detergent fibre (NDF), acid detergent fibre (ADF) and ash (AOAC, 1995; method 942.05) concentrations. The OMD was estimated using the in-vitro neutral detergent cellulase method as described by Morgan et al., (1989) (FibertecTM Systems; Foss, Ballymount, Dublin). Crude protein concentration was determined using a N analyser (Leco FP-428; Leco Australia Pty Ltd, Baulkham Hills B.C. NSW, Australia) based on the AOAC method 990-03 (AOAC, 1990). The NDF and ADF concentrations were determined using a fibre analyser (AOAC, 1995, method 973.18; Ankom Technology, Macedon, NY, USA) based on the method described by Van Soest et al., (1991). Amylase and a sodium sulphate solution were used in the NDF concentration determination process. Ash concentration was estimated by burning a subsample in a muffle furnace at 500°C for 12 h.

Tiller density

Five turves (0.1 m × 0.1 m) were cut to a depth of 0.05 m and removed from each sward twice during the experimental period (December and February). Turves were removed along a 'W' shape across the paddock at equal distances, beginning at the start of the 'W' at 25 m intervals, to take into account the heterogeneity of the swards (Jewiss, 1993). The grass tillers in each turve were separated into PRG and other grass species (mainly meadow grass, *Poa annua* L.) and counted. From these turves an overall average tiller density per m^2 was calculated.

Perennial ryegrass leaf, stem and dead proportion

Perennial ryegrass leaf, stem and dead proportions > 3.5 cm were measured in each sward prior to grazing in spring (MD4) as described by McCarthy et al. (2013). Briefly, at eight randomly chosen locations within each sward PRG tillers were cut to ground level, the vertical structure maintained, a subsample of 40 g was selected and the lower horizon (< 3.5 cm) was then removed. The remaining herbage (> 3.5 cm) was divided into leaf, stem and dead components. The fresh weight of each component was recorded before drying at 90°C for 16 hours to determine the DM proportions (>

3.5 cm) of the leaf, stem and dead material. From the DM proportions the mass of green leaf, stem and dead in the overall herbage mass harvested were calculated.

Statistical analysis

Statistical analysis was carried out using SAS 9.4 (SAS Institute Inc., Cary, NC, USA, 2002). The effect of CD on herbage mass, growth rate, tiller density, green leaf mass, stem mass, dead leaf mass, OMD, CP, NDF ADF and ash were determined using the PROC MIXED procedure with CD, MD and year included in the model. Measurement date was the repeated measure and sward was the experimental unit. Data are presented as least square means ± standard error. Variables were analysed using the following model:

$$Y_{jkl} = \mu + closing\ date_j + measurement\ date_k + year_l\ (closing\ date_j \times measurement\ date_k \times year_l) + (closing\ date_j \times measurement\ date_k) + (year_l \times closing\ date_j) + (closing\ date_j \times measurement\ date_k) \times e_{jkl}$$

Where:

μ = mean value for the variable

e_{jkl} = residual error term

Y_{jkl} = herbage mass (kg DM ha^{-1}), growth rate (kg DM ha^{-1} per day^{-1}), tiller density (m^2), green leaf mass (kg DM ha^{-1}), stem leaf mass (kg DM ha^{-1}), dead leaf mass (kg DM ha^{-1}), OMD (g kg^{-1} DM), CP (g kg^{-1} DM), NDF (g kg^{-1} DM) ADF (g kg^{-1} DM) and ash (g kg^{-1} DM) with sward the experimental unit.

4.4 Results

Weather data collected during the experimental period (September to April) are summarized in Table 4.2. In year 3 the daily air and soil temperature at 100 mm were greatest overall (8.7 and 9.3˚C, respectively) compared to year 1 (8.3 and 8.7˚C,

respectively) and year 2 (7.7 and 8.2˚C, respectively). Monthly rainfall was similar in year 2 and 3 (104.5 and 102.1 mm, respectively) and was lower in year 1 (75.1 mm). Monthly solar radiation was the same in year 1 and 2 (587 MJ m^2) and was greater in year 3 (649 MJ m^2).

4.4.1 Grass growth rate

Growth rates over winter were significantly ($P < 0.001$) affected by the interaction between CD and MD (Table 4.3). On MD2, CD3 and CD4 had a lower growth rate than CD5 and CD1, with CD2 intermediate (Table 4.3). On MD5, CD5 had a greater growth rate compared to CD2 with CD1, CD3 and CD4 intermediate to both (Table 4.3). Growth rates were significantly ($P < 0.001$) affected by the interaction between MD and year (Table 4.4). In year 3, MD2 (9.6 ± 0.56 kg DM ha^{-1} day^{-1}) had a greater growth rate than in year 1 and year 2 (5.6 ± 0.64 kg DM ha^{-1} day^{-1}, average). In year 3, MD4 (4.4 ± 1.11 kg DM ha^{-1} day^{-1}) had a lower growth rate than MD4 in year 1 and year 2 (12.2 ± 1.35 kg DM ha^{-1} day^{-1}). Closing date and MD significantly ($P < 0.001$) affected the average growth rate (Table 4.3). Average growth rate varied significantly ($P < 0.001$) by year, with the greatest growth rate in year 1 (28.0 ± 1.65 kg DM ha^{-1} day^{-1}), the lowest in year 2 (24.9 ± 1.49 kg DM ha^{-1} day^{-1}) and year 3 (26.9 ± 1.89 kg DM ha^{-1} day^{-1}) was intermediate.

Table 4.3: The effect of five autumn closing dates (CD) on the over winter growth rate (kg DM day^{-1}) and herbage mass (kg DM ha^{-1}) in winter over five consecutive measurement dates (MD1 – MD5) over three years (year 1 (2016/2017), year 2 (2017/2018) and year 3 (2018/2019)).

	CD1[1]	CD2	CD3	CD4	CD5	S.E.	P Value		
							CD	MD	CD × MD
Growth rate (kg DM/ha/day)									
MD1[2]	14.9	12.0	10.2	13.9	.[3]	2.38	***	***	***
MD2	10.5	8.0	5.5	6.2	12.3				
MD3	12.3	9.4	9.7	8.6	8.5				
MD4	12.8	12.9	12.2	8.3	9.3				
MD5	39.9	32.6	38.8	35.8	49.4				
Herbage mass (kg DM ha^{-1})									
MD1	1056	604	372	292	262	93.1	***	***	
MD2	1003	646	368	321	433				
MD3	1210	794	504	468	413				
MD4	1544	1058	809	626	779				
MD5	1823	1545	1693	1429	1501				

[1]Autumn closing date applied to swards: CD1 = 27 Sept-11 Oct, CD2 = 12 Oct- 26 Oct, CD3 = 27 Oct – 10 Nov, CD4 = 11 Nov – 25 Nov and CD5 = 26 Nov – 9 Dec.

[2] Measurement dates on swards: MD1 = measurement date 1 = 12 Dec, MD2= measurement date 2 = 9 Jan, MD3 = measurement date 3 = 2 Feb, MD4 = measurement date 4 = 1st defoliation in spring, MD5 = measurement date 5 = 2nd defoliation in spring.
[3]CD5 on MD1 is excluded due to a short closed period (9 days).

4.4.2 Herbage mass

There was a significant effect ($P < 0.001$) of the MD x year interaction on herbage mass (Table 4.4). Herbage mass on MD2 was lower in year 2 (432 ± 55.8 kg DM ha^{-1}) compared to year 3 (710 ± 56.2 kg DM ha^{-1}). Measurement date 3, had a lower HM in year 2 (611 ± 59.8 kg DM ha^{-1}) compared to MD3 in year 3 (836 ± 58.6 kg DM ha^{-1}). There was a significant effect ($P < 0.001$) of CD on spring grass availability, each one day delay in closing from the 25 September resulted in a reduction of 16 kg DM^{-1} in herbage mass (Figure 4.1) on the 6 February. Measurement date had a significant effect ($P < 0.001$) on herbage mass. Average herbage mass across all treatments was greatest on MD5 (1652 ± 77.5 kg DM ha^{-1}), followed by MD4 (981 ± 45.9 kg DM ha^{-1}) and MD3 (713 ± 37.1 kg DM ha^{-1}) with the lowest herbage mass on MD1 and MD2 (average 547 ± 36.8 kg DM ha^{-1}). Herbage mass was significantly ($P < 0.001$) affected by year being lower in year 2 (837 ± 51.0 kg DM ha^{-1}) than year 1 and 3 (average, 956 ± 46.6 kg DM ha^{-1}).

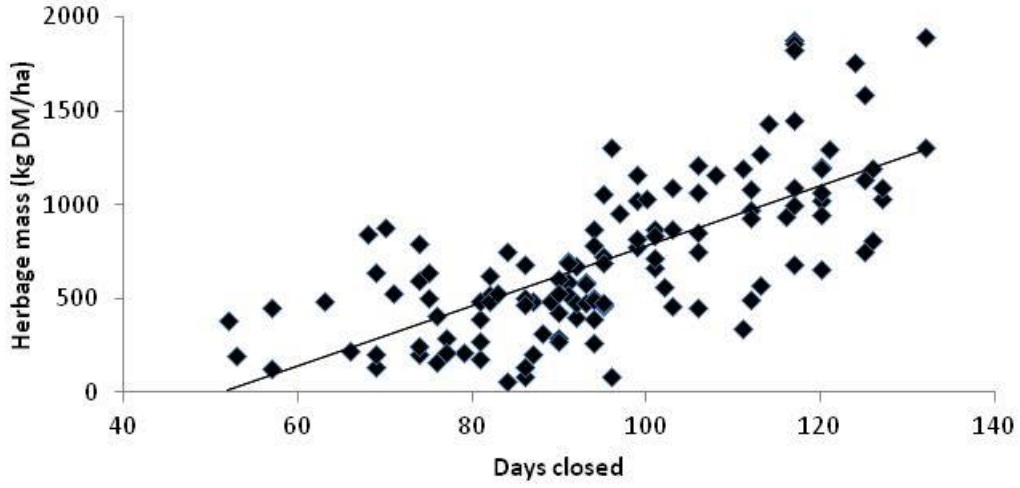


Figure 4.1: The relationship between the number of days a paddock was undefoliated over winter, averaged over three years (2016 – 2019) and the herbage available in MD3 (2nd February). The relationship is described by the equation y = 16.11 x – 826. 33. R^2 = 0.50

Table 4.4: The effect of the interaction of year (year 1 (2016/2017), year 2 (2017/2018) and year 3 (2018/2019)) and measurement date (MD) on growth rate (kg DM ha^{-1} day^{-1}) and herbage mass (kg DM ha^{-1}).

	Year 1	Year 2	Year 3		P - value		
Growth rate (kg DM ha^{-1} day^{-1})				**S.E.**	**MD**	**Year**	**MD x Year**
MD1[1]	**-**[2]	**14.3**	**15.4**	**3.40**	**	**	***
MD2	**5.6**	**6.4**	**9.6**				
MD3	**16.2**	**8.2**	**7.2**				
MD4	**13.4**	**13.1**	**7.4**				
MD5	**46.5**	**37.9**	**31**				
Herbage mass (kg DM ha^{-1})							
MD1	**-**	**485**	**572**	**123.0**	**	**	***
MD2	**426**	**480**	**710**				
MD3	**716**	**574**	**836**				
MD4	**1329**	**864**	**836**				
MD5	**1412**	**1729**	**1768**				

[1] Measurement dates on swards: MD1 = measurement date 1 = 12 Dec, MD2= measurement date 2 = 9 Jan, MD3 = measurement date 3 = 2 Feb, MD4 = measurement date 4 = 1st defoliation in spring, MD5 = measurement date 5 = 2nd defoliation in spring.
[2] In year 1 MD1 excluded due to a low number of recordings.

4.4.3 Herbage quality

The effect of closing date, year and the closing date × year interaction on the OMD, CP, Ash, ADF and NDF on MD4 and MD5 are reported in Table 4.5.

There was no significant effect of CD or MD on ash content. Ash content was significantly ($P < 0.001$) greater in year 3 (88 ± 1.3 g kg DM^{-1}) compared to year 2 (78 ± 1.5 g kg DM^{-1}).

Measurement Date 4:

Organic matter digestibility was significantly ($P < 0.001$) affected by CD; CD1 and CD2 had a lower OMD than CD5. The CD x year interaction significantly affected ($P < 0.05$) OMD; in year 2 CD1 and CD2 (average, 821 ± 7.5 g kg DM^{-1}) were lower compared to CD5 (874 ± 13.1 g kg DM^{-1}), all other CD were intermediate (840 ± 8.1 g kg DM^{-1}). Organic matter digestibility was significantly ($P < 0.05$) affected by CD and was lower on CD2 compared to CD5 (Table 4.5). Year had no effect on OMD.

There was a significant effect ($P < 0.001$) of CD × year on CP concentration; in year 3, CD3 (188 ± 9.3 g kg DM^{-1}) had lower CP concentration compared to CD4 and CD5 (258 ± 11.9 g kg DM^{-1}). Closing date had a significant effect ($P < 0.001$) on CP; CD2 had a lower CP compared to CD1, CD3 and CD4 (Table 4.5). Crude protein was significantly affected ($P < 0.05$) by year. Year 1 (258 ± 5.4 g kg DM^{-1}) had a greater CP than year 2 and year 3 (240 ± 5.4 g kg DM^{-1}).

There was no MD effect on ADF. Acid detergent fibre was significantly ($P < 0.05$) affected by CD. Acid detergent fibre was lower on CD2 (214 ± 5.0 g kg DM^{-1}) compared to CD5 (242 ± 9.2 g kg DM^{-1}), with CD1, CD3 and CD4 (230 ± 5.9 g kg DM^{-1}) intermediate. Year also had an effect ($P < 0.001$) on ADF which was lower in year 2 (216 ± .5 g kg DM^{-1}) than year 3 (242 ± 3.8 g kg DM^{-1}).

Neutral detergent fibre was significantly ($P < 0.05$) affected by CD; CD3 (376 ± 8.5 g kg DM^{-1}) was lower than CD1, CD2 and CD5 (401 ± 8.5 g kg DM^{-1}) with CD4 (382 ± 8.5 g kg DM^{-1}) intermediate to both. Year significantly ($P < 0.01$) affected NDF; NDF was greater in year 3 (402 ± 4.8 g kg DM^{-1}) than year 1 and year 2 (380 ± 4.8 g kg DM^{-1}).

Table 4.5: The effect of five autumn closing dates (CD) on sward quality including organic matter digestibility (OMD), crude protein (CP), ash, acid detergent fibre (ADF) and neutral detergent fibre (NDF) on measurement date (MD) 4 and MD5 between 2016 -2019.

		Closing date						P Value		
MD[1]	Var[2]	CD1[3]	CD2	CD3	CD4	CD5	S.E.	CD	Year	CD x Year
	OMD[4]	825	826	844	843	852	6.3	***		*
4	CP[5]	244	222	250	277	253	1.6	***	*	***
	NDF[6]	398	398	375	381	399	6.1	*	**	
	ADF[7]	277	211	217	219	245	6.1	*	***	
	Ash[8]	86	83	84	84	83	4.2		***	
	OMD	856	860	858	860	864	3.9			
5	CP	245	231	242	230	250	6.7			
	NDF	407	404	397	398	412	9.6		***	
	ADF	228	226	229	218	255	6.6		***	
	Ash	89	87	87	86	90	2. 1		***	

[1] Measurement dates on swards: MD1 = measurement date 1 = 12 Dec, MD2= measurement date 2 = 9 Jan, MD3 = measurement date 3 = 2 Feb, MD4 = measurement date 4 = 1st defoliation in spring, MD5 = measurement date 5 = 2nd defoliation in spring.

[2]Variables measured for quality analysis.

[3]Autumn closing date applied to swards: CD1 = 27 Sept-11 Oct, CD2 = 12 Oct- 26 Oct, CD3 = 27 Oct – 10 Nov, CD4 = 11 Nov – 25 Nov and CD5 = 26 Nov – 9 Dec.

[4]OMD = organic matter digestibility (g kg^{-1} DM).

[5]CP = crude protein (g kg^{-1} DM).

[6]NDF = neutral detergent fibre (g kg^{-1} DM).

[7]ADF = acid detergent fibre (g kg^{-1} DM).

[8]Ash (g kg^{-1} DM).

Measurement Date 5:

Organic matter digestibility and CP were not affected by CD or year; there was no effect of CD on ash content. Ash content was significantly (P<0.001) lower in year 2 (86 ± 1.7 g kg DM^{-1}) compared to year 3 (93 ± 1.74 g kg DM^{-1}). Acid detergent fibre and NDF contents were not affected by CD but were significantly (P < 0.001) affected by year. Both ADF and NDF were greater in year 2 (ADF - 257 ± 5.6 g kg DM^{-1}, NDF - 443 ± 8.3 g kg DM^{-1}) compared to year 3 (ADF - 214 ± 6.9 g kg DM^{-1}, NDF - 398 ± 10.2 g kg DM^{-1}).

4.4.4 Tiller density

There was a significant effect (P < 0.01) of CD on PRG tiller density. Closing date 1, had a lower tiller density compared to CD3 and CD4, with CD2 and CD5 intermediate to both (Figure 4.2). Tiller density was significantly (P < 0.001) greater in Year 3 (4039 ± 126.1 tiller m^{-2}) than year 1 and 2 (average, 2420 ± 153.6 tiller m^{-2}). Tiller density was greater (P < 0.001) in spring (+ 629 plants m^{-2}) than in autumn. There was no effect of CD on weed grass tiller density. Weed grass tiller density was significantly (P < 0.001) lower in Year 1 (1174 ± 190.3 tiller m^{-2}) compared to year 2 and year 3 (average 2173 ± 175.1 tiller m^{-2}).

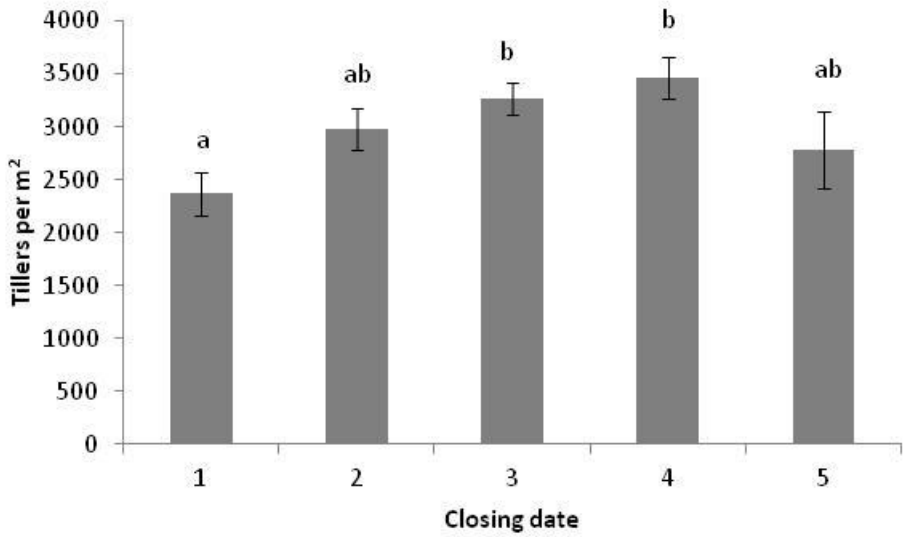


Figure 4.2: The effect of five autumn closing dates (CD; CD1 (27 Sept-11 Oct), CD2 (12 Oct- 26 Oct), CD3 (27 Oct – 10 Nov), CD4 (11 Nov – 25 Nov) and CD5 (26 Nov –

9 Dec) on perennial ryegrass tiller density (tillers per m^2) in February between 2016 - 2019. Error bars show the standard error of the mean.

4.4.5 Leaf, stem and dead proportion

The proportion of green leaf, stem and dead in the sward were significantly ($P < 0.001$) affected by CD (Table 4.6); the green leaf proportion was lowest in CD1 and CD2. Stem and dead proportion were greatest in CD1. Stem proportion in the sward was significantly ($P < 0.001$) higher in year 1 (0.15 ± 0.011) compared to year 2 (0.11 ± 0.009), with year 3 (0.14 ± 0.010) intermediate to both.

Table 4.6: The effect of five autumn closing dates (CD) on the proportion of perennial ryegrass green leaf, stem and dead material on measurement date 4 between 2016 - 2019.

Variable	CD1[1]	CD2	CD3	CD4	CD5	S.E.	P Value
Leaf proportion[2]	0.68^{a}	0.69^{a}	0.74^{ab}	0.80^{b}	0.80^{b}	0.020	***
Stem proportion [3]	0.16^{ab}	0.17^{a}	0.12^{ab}	0.11^{ab}	0.10^{b}	0.071	*
Dead proportion[4]	0.16^{a}	0.14^{ab}	0.14^{ab}	0.09^{c}	0.10^{bc}	0.015	*

[1]Autumn closing date applied to swards: CD1 = 27 Sept-11 Oct, CD2 = 12 Oct- 26 Oct, CD3 = 27 Oct – 10 Nov, CD4 = 11 Nov – 25 Nov and CD5 = 26 Nov – 9 Dec.

[2]Proportion of leaf above 3.5 cm.

[3]Proportion of stem material above 3.5 cm.

[4]Proportion of dead material above 3.5 cm.

4.4.6 Leaf, stem and dead mass

Closing date had a significant (P < 0.001) effect on the green leaf mass available (> 3.5 cm); CD1 had the greatest green leaf mass (1329 ± 72.5 kg DM ha^{-1}) compared to CD2 (933 ± 72.7 kg DM ha^{-1}), and both were greater than CD3 CD4 and CD5 (727 ± 85.9 kg DM ha^{-1}; Figure 4.3). Year 2 had a significantly (P < 0.001) lower green leaf mass (624 ± 53.9 kg DM ha^{-1}) compared to year 1 and year 3 (939 ± 65.1 and 1102 ± 59.9 kg DM ha^{-1}, respectively).

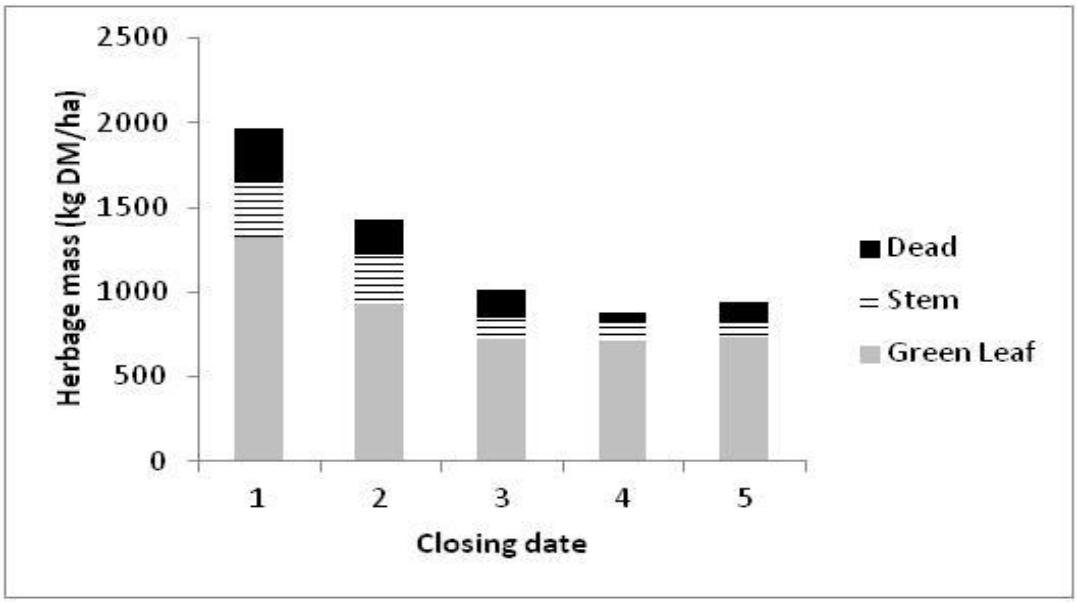


Figure 4.3: Herbage mass (kg DM ha^{-1}), separated into green leaf, stem and dead mass for each autumn closing date (CD; CD1 (27 Sept-11 Oct), CD2 (12 Oct- 26 Oct), CD3 (27 Oct – 10 Nov), CD4 (11 Nov – 25 Nov) and CD5 (26 Nov – 9 Dec) for measurement date 4 (1st defoliation in spring) between 2016 – 2019.

There was significantly (P < 0.001) greater stem mass on CD1 and CD2 (324 ± 23.2 and 288 ± 25.9 kg DM ha^{-1}, respectively) compared to CD3, CD4 and CD5 (105 ± 29.9 kg DM ha^{-1}). Stem mass was significantly (P < 0.001) greater in Year 1 and Year 3 (228 ± 23.6 kg DM ha^{-1}) compared to Year 2 (102 ± 19.0 kg DM ha^{-1}).

Closing date had a significant effect on dead mass which was higher on CD1 (319 ± 25.9 kg DM ha^{-1}) than CD2, CD3, CD4 and CD5 (140 ± 29.2 kg DM ha^{-1}). Dead mass (>3.5 cm) was significantly (P < 0.001) lower in Year 1 and 2 (153 ± 22.9 and 112 ± 21.1 kg DM ha^{-1}, respectively) than in Year 3 (264 ± 21.1 kg DM ha^{-1}).

4.5 Discussion

For each extra day swards were closed from the end of September to the start of December (CD1 to CD5) an additional 16 kg DM ha^{-1} were available in spring. This is similar to O'Donovan et al. (2002) who reported 15 kg DM ha^{-1}, but greater than Lawrence et al. (2017) and Ryan et al. (2010) who reported 10 kg DM ha^{-1} and 12.4 kg DM ha^{-1}, respectively. However, lengthening the period of time a sward is closed for can result in an increase in dead and stem material (Lawrence et al., 2017). In the current experiment each additional day closed from late September to early December increased dead mass by 2.5 kg DM ha^{-1} day^{-1} and stem mass by 2.5 kg DM ha^{-1} day^{-1}. As a result, only 11 kg DM ha^{-1} of the 16 kg DM ha^{-1} was green leaf mass. Swards closed in late September and in October (CD1 and CD2) had greater growth rates over winter (MD1 and MD2) than swards closed in late October and November (CD3 and CD4), similar to Ryan et al. (2010). In the subsequent spring grazing (2^{nd} rotation; MD5) swards closed in late November and early December (CD5) had greater growth rates compared to swards closed in late September and October (CD1 and CD2) in the current study. A possible explanation for this is the reduction in tiller density on the earlier closed swards which decreases the number of growing points (Garay, 1999) in the sward at the initiation of grass growth in spring which might lead to this reduction in growth rate. Although not measured in the current study, in high herbage masses it is also a possibility that there is old leaf or dead material left below the grazing horizon (< 4 cm) (Lawrence et al., 2017). This old leaf material is less photosynthetically efficient than new leaf material (Parmenter & Boswell, 1983). Another reason for reduced growth rates in spring for swards closed in late September and October could be as a result of lower water soluble carbohydrate content in the residual (Looney et al., 2019). Water soluble carbohydrates are required for the supply of energy for growth and function post defoliation (White, 1973). The regrowth is mostly driven by water soluble carbohydrate reserves in the 4 cm above ground level (Donaghy and Fulkerson, 1998), and as such is a fundamental element in the regrowth of swards post defoliation. The increased growth rate in later closed swards once defoliated in spring, in the current study, is contradictory to Lawrence et al. (2017) who reported no effect of CD on subsequent

growth rates following initial spring defoliation. This may be as a result of defoliation method; Lawrence et al. (2017) mechanically harvested swards which may not accurately reflect the impact of animal grazing on herbage growth (Cashman et al., 2016). Targeting high herbage masses, from swards closed in late September and October, for early defoliation may encourage more green herbage and a lower proportion of dead material in subsequent defoliations (Korte et al., 1984) and counteract reduced growth rates in the subsequent defoliation. Early defoliation will also allow for a lengthier regrowth interval prior to the subsequent defoliation and allow utilisation of applied nitrogen (O'Donovan et al., 2004).

In the current study there was a large year to year variation in over winter growth rates and spring grass availability similar to that reported by Brereton et al., (1985), Carton et al., (1989) and Hennessy et al., (2006). Most likely, the year to year variation was a result of climatic conditions. Soil and air temperature are variable and have the greatest influence on over winter growth rates (Peacock, 1975). The range in growth rates lead to a significant variation in pre-grazing herbage mass on the first spring defoliation (MD4) in the three years of the study, similar to Hennessy et al. (2006). In year 2, there was a lower average pre grazing herbage mass compared to year 1 and year 3 which can be attributed to the lower average soil and air temperature (- 0.8 °C). Although, there was large year to year variation in the study, 50% (R^2 = 0.5023) of the variation in spring grass availability was associated with the number of days the sward was closed from grazing. The other 50% of pre-grazing herbage mass in spring was as a result of uncontrollable factors such as meteorological conditions i.e. soil and air temperature, solar radiation and moisture. Controllable factors such as fertiliser application, PRG content in autumn and management were accounted for within the experimental design.

In the current study a higher pre-grazing herbage mass in spring resulted in a reduction in PRG tiller density. Therefore, similar to Laidlaw et al. (2000), Hennessy et al. (2006) and Lawrence et al. (2017) the current study confirms the negative impact of early CD on tiller density. Restricted access to light, due to higher herbage masses, can cause tiller bud suppression (Hunt, 1978) which can result in the loss of daughter tillers (Korte, 1981). Low light interception at the base of the plant in high

pre-grazing herbage mass swards inhibits the production of new tillers (Baker, 1956). Survival of mature tillers at the expense of smaller/younger ones (self-thinning) can occur due to these low light conditions (Laidlaw & Mayne, 2000). When there is a requirement for increased spring pre-grazing herbage mass, swards closed in late September and October should be defoliated as early as possible in spring to allow light interception at the base of the plant (Brougham, 1960) to promote new tiller production (Kays & Harper, 1974; Laidlaw & Mayne, 2000). This might compensate for the reduction in tiller production over winter in earlier closed swards. Earlier defoliation of swards in spring with high herbage masses can also result in an improvement in sward quality in subsequent rotations (Garry et al., 2015).

Sward quality in spring is impacted by autumn closing management (Hennessy et al., 2006; Lawrence et al., 2017). A higher pre-grazing herbage mass in spring results in reduced herbage quality as a result of increased dead material (Binnie et al., 2001) in swards closed in late September and October. However, even if OMD, CP and ADF are lower in swards closed in late September and October (CD1 and CD2), nutritional requirements for a dairy cow in early to peak lactation are still met (Kavanagh, 2016) from grazed grass. The quality of grazed PRG paddocks (average OMD = 826 g kg^{-1} DM), closed in late September and early October (CD1 and CD2) reported in this study are still greater than the medium quality silage (DMD = 696 g kg DM^{-1}) reported by Kennedy et al. (2005). Increasing the proportion of grazed grass in the diet in the place of silage, regardless of autumn CD, will increase animal production (Kennedy et al., 2005; Claffey et al., 2019a). In this study, after the initial spring grazing, no carryover effect of autumn CD was observed in sward quality on the subsequent spring defoliation (MD5), a result similar to Lawrence et al. (2017).

The current study reported that the proportion of green leaf was greater in swards closed in November and early December (CD4 and CD5; + 0.12) compared to swards closed in late September and October (CD1 and CD2) similar to Lawrence et al. (2017) and Hennessy et al. (2006). Likewise, the proportion of dead material in the sward was greatest in swards closed in late September and October, similar to Davies and Simons (1979), Hennessy et al. (2006) and Ryan et al. (2010). Green leaf is of higher nutritional value than stem and dead material (Beecher et al., 2015; Binnie et al.,

2001). Lawrence et al. (2017) reported a correlation of R^2 = 0.7773 between green leaf proportion and DMD in autumn. In spring, the current study found a correlation of R^2 = 0.6127 between green leaf proportion and OMD. The lower correlation reported in the current study, could possibly, be due to the higher quality of grass in spring compared to autumn (McDonald, 2002; Garry, 2020). Swards with a greater green leaf proportion have greater nutritional value but the proportion of green leaf does not reflect the quantity of herbage available. In the current study, although swards closed in November and early December had a greater green leaf proportion, swards closed in September and early October had a greater quantity of green leaf mass available in spring. Reporting the proportion and mass of green leaf, stem and dead should give a more accurate representation of the sward morphology available for grazing. Previous research (Beecher et al., 2015) reported that the available OMD is greatest in the leaf compared to stem and dead material. They reported that OMD in February was greatest in the green leaf component (751 g kg^{-1}) compared to stem and dead material (658 and 541 g kg^{-1}, respectively). Total available kg dry organic matter (kg DOM) in the current study, shows 52% more available digestible material in earlier closed swards (CD1; 1273 kg DOM ha^{-1}) when compared to later closed swards (CD4; 664 kg DOM ha^{-1}). Although earlier closing of swards can result in an increase in stem and dead material and a reduction in overall sward quality, the available material to grazing animals (< 3.5 cm) can have a greater green leaf mass. Which, combined with an increase in consumed herbage quality can increase animal performance. Available green leaf mass combined with DOM should be considered as a means to improving grazing management decisions on farm.

The results of this research have highlighted the success early autumn closing management has on increasing the herbage mass available to meet increased demand for spring grass in an intensive dairy production system. It can now be widely accepted that to meet increased feed demand in spring, farmers must adopt an earlier closing of paddocks in autumn. If implemented, this will be beneficial in terms of industry targets to increase production and utilisation of grazed grass, particularly in spring where a deficit had been identified. It will also contribute to lengthening the grazing season which has been identified as one measure to improving on farm

sustainability through reducing the length of time housed and consequently slurry produced (Lanigan et al., 2018). Successfully managing earlier closed swards on farm should prioritise early defoliation in spring to help maintain quality, and due to lower regrowth potential for the second rotation on early closed swards, a longer regrowth period is required. The year to year variation in over winter growth rates must be considered in grassland management decisions on farm to ensure spring herbage targets are met. A move away from date grazing targets, as is currently recommended (Teagasc, 2011), to target pre grazing herbage masses in autumn may help achieve a consistent target for spring herbage. Future research should investigate the impact of different spring defoliation dates on various herbage masses to determine dates that maximise utilisation of swards and reduce carry over effects of autumn closing management into the second rotation.

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Chapter 5: The effect of autumn closing date on over winter tissue turnover in perennial ryegrass (*Lolium perenne* L.) swards

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5.1 Abstract

Autumn closing date (CD) in intensive pasture-based systems influences spring herbage availability. Little is known about the impact of earlier closing of swards in autumn on sward structure. A two-year experiment was undertaken to investigate the impact of five CD on herbage production, leaf extension rate (LER), leaf senescence rates (LSR), sward free leaf lamina (FLL) content, and the production and survival of tillers overwinter and into spring. The five CD ranges were October 1 – 15 (CD1), October 16 – 30 (CD2), October 31 – November 14 (CD3), November 15 – 29 (CD4), November 30 – December 14 (CD5) and sward measurements were made on four measurement dates (MD): December 11 (MD1), January 6 (MD2), January 27 (MD3) and prior to spring defoliation (MD4). Thirty perennial ryegrass tillers were measured until the first defoliation in spring (average 1 March). Herbage mass was greatest in early CD and tillers had greater LER and LSR (4.6 and 4.5 mm tiller^{-1} day^{-1}, respectively) compared to swards with a later CD (3.2 and 2.3 mm tiller^{-1} day^{-1}, respectively). Early CD had greater parent and daughter tiller mortality than later CD (parent tiller mortality 1.1 and 0.3 ± 0.19 tillers; daughter tiller mortality 1.1 and 0.3 ± 0.27 tillers, respectively). Early CD also had greater LER and LSR in daughter tillers (2.6 and 1.5 mm tiller^{-1} day^{-1}, respectively) compared to late (1.5 and 0.5 mm tiller^{-1} day^{-1}, respectively). Earlier closing of sward increased herbage mass in spring however, there were negative implications, such as increased LSR and tiller mortality.

Keywords *perennial ryegrass*, autumn closing date, tissue turnover, leaf extension rate, leaf senescence rate

5.2 Introduction

Grass currently makes up 82% of the diet of a dairy cow in a pasture-based system in Ireland (either grazed in-situ or grass silage on a dry matter (DM) basis) (O'Brien et al., 2018). In grass-based systems, achieving high herbage DM production (15 tonne DM ha^{-1} $year^{-1}$) and high herbage nutritive value (200 g kg^{-1} crude protein concentration) throughout an extended grazing season is important (O'Donovan et al., 2011). Pasture-based systems are common in temperate climates of the world (Dillon et al., 2008). Perennial ryegrass (*Lolium perenne* L.; PRG) is the predominant sown species used in temperate grass-based ruminant production systems (Wilkins & Humphreys, 2003) due to environmental conditions conducive to PRG pasture growth, with PRG having a seasonal growth curve mirroring yearly temperature fluctuations (Hurtado-Uria et al., 2013). It provides a high nutritive value feed for livestock while maintaining a high regrowth capacity and good grazing persistence (Wilkins & Humphreys, 2003). As a result of lower temperatures and inclement weather conditions over winter, PRG growth rates are low (Hurtado-Uria et al., 2013). This results in low levels of herbage accumulation over winter, which can lead to inadequate quantities of herbage available to meet the feed demands of spring calving dairy cows turned out to grass post-calving (Lawrence et al., 2017). Lewis et al. (2015) reported that the DM intake of cows immediately post-calving in spring was 10 kg DM cow^{-1} and increased to a peak of 18 kg DM cow^{-1} in week 8 of lactation (550 kg mature cow on a grass-only diet); therefore herbage supply should reflect feed demand.

Altering autumn management strategies by closing paddocks earlier in autumn can result in an increase in herbage availability in spring (February – April; Hennessy et al., 2006; Claffey et al., 2020). Over winter, the PRG plant continues growing, albeit at a slower rate compared to spring and summer (3 to 8 kg DM ha^{-1} day^{-1}; December-January and on average 60 kg DM ha^{-1} day^{-1}; May - September) (Pasturebase Ireland Data - O'Leary, Personal Communication). Plant material continues to appear, grow and senesce which, results in tissue turnover (Brereton et al., 1985; Carton et al., 1988). Soil and air temperature at the apex of the plant have a large influence on LER and LSR (Peacock, 1975). Hennessy et al. (2008) found a correlation between

accumulated daily air temperature above 6°C and mean soil temperature with the LER; LER increased as temperature increased. Lower temperatures lead to a reduction in LER (≤ 2 mm tiller^{-1} day^{-1}; Brereton, 1985) which results in low or no grass growth rates over winter.

Despite lower growth rates at low temperature, lengthening the time a paddock remains ungrazed for through earlier autumn closing date can result in the accumulation of large quantities of herbage, above a 3.5 cm residual height, over winter (> 2000 kg DM ha^{-1}; Hennessy et al., 2006; Lawrence et al., 2017). Davies and Simons (1979) reported that the longer a sward remained undefoliated for over winter the more leaves senesced, particularly if temperatures were relatively high resulting in increased leaf extension and appearance rates. An increase in herbage mass can result in increased LSR (up to 34%, Carton et al., 1988) and reduced sward quality (up to 12% reduction, Hennessy et al., 2006; Laidlaw & Mayne, 2000). Additionally, high herbage masses can result in shading at the base of the sward which can reduce tiller production and hinder tiller establishment and survival (Laidlaw & Mayne, 2000; Hennessy et al., 2008) impacting herbage production through reduced numbers of growing points in the sward (Garay, 1999). It was hypothesised that closing swards earlier in autumn results in greater levels of herbage mass, however tiller production and survival are reduced.

The objective of this experiment was to investigate the effect of autumn closing date on herbage production, LER, LSR, free leaf lamina and the production and survival of tillers.

5.3 Materials and Methods

5.3.1 Experimental Site

The study was undertaken at the Teagasc, Animal and Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork, Ireland (Latitude 50°07'N, Longitude 08°16'W) from September 2017 to April 2019. Swards were located 40 m above sea level with a south facing aspect. The soil type at the experimental site was

a free-draining acid brown earth of sandy to loam texture (Teagasc, 2017). Swards were predominantly PRG (> 85%) and sown in a mixture of the cultivars - Tyrella, Astonenergy, Meduno and Oakpark. These cultivars were chosen using the Pasture Profit Index (O'Donovan et al., 2017) and have an average spring yield of 1200 kg DM ha^{-1}, an average total yield of 10200 kg DM ha^{-1} and an average heading date of the 3 June. The remainder of the sward consisted of meadow grasses and clover (*Poa annua* L., *Festuca pratensis* L. and *Trifolium repens* L., cv. Chieftain). Tiller density was recorded for each autumn closing date (CD; the date on which swards received their final grazing before closing for winter) at the beginning of the experiment (Figure 5.1). Soils were sampled to a depth of 10 cm, had a pH of 6.8 (± 0.2), were Index 3 for phosphorus (11 mg l^{-1}) and potassium (132 mg l^{-1}) (scale 1 to 4; 1 = deficient, 4 = no response to application of nutrient; Alexander et al., 2008). Nitrogen fertiliser was applied in the form of urea at a rate of 54 kg N ha^{-1} between January and mid-March and a rate of 26 kg N ha^{-1} in mid-April. In mid-April phosphorus (10 kg P ha^{-1}) and potassium (19 kg K ha^{-1}) were applied.

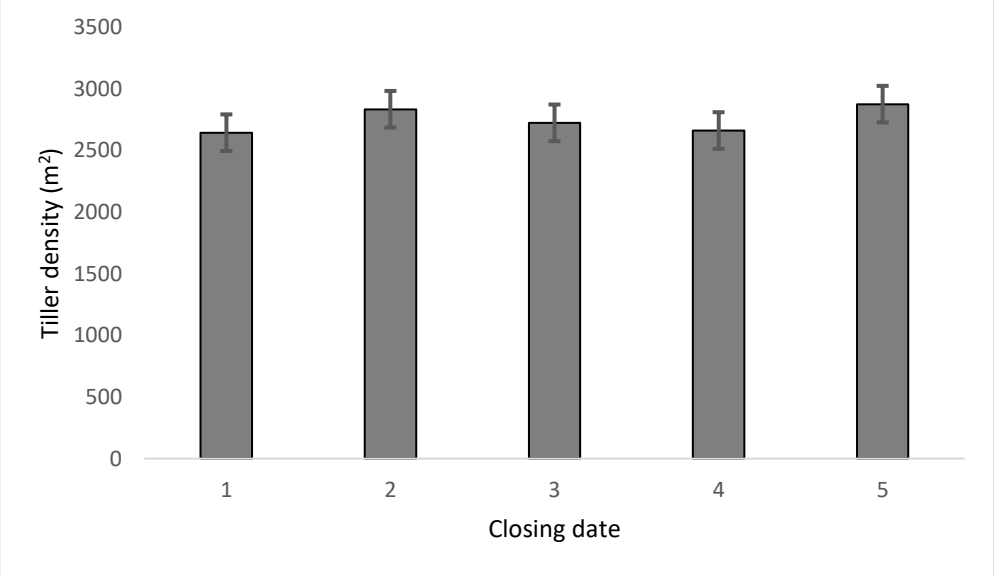


Figure 5.1: Average tiller density (tiller per m^2) for each closing date (CD; CD1: 1 Oct – 15 Oct, CD2: 16 Oct – 30 Oct, CD3: 31 Oct – 14 Nov, CD4: 15 Nov – 29 Nov, CD5: 30 Nov – 9 Dec) across the experiment. Error bars show the standard error of the mean.

5.2.2 Meteorological data

Meteorological data were recorded at the experimental site using an automatic weather station (Met Éireann, 2019). The air temperature (°C), soil temperature to a depth of 100 mm (°C), total rainfall over the measurement period (mm) and average solar radiation (MJ m^{-2}) were recorded throughout the experimental period (Table 5.1).

Table 5.1: Average daily air temperature (mean temp), soil temp to a depth of 100 mm, total daily rainfall and average solar radiation over the experimental period (between September and April) for year 1 (2017/'18) and year 2(2018/'19) for each measurement period (MP) and the 10 year average from 2006 – 2016 at the experimental site.

Year	MP	Mean temp (°C)	Total rainfall (mm)	Solar radiation (MJ m^{-2})	Soil temp to 100 mm (°C)
1	1	8.9	239.0	389.6	11.7
1	2	6.8	82.1	182.6	7.9
1	3	5.9	91.2	266.0	7.1
1	4	4.9	237.3	647.4	6.6
2	1	8.9	344.8	460.1	11.5
2	2	8.6	64.9	164.9	9.3
2	3	6.3	45.6	266.9	9.0
2	4	7.3	202.7	780.3	8.5

10 year average	Sept	Oct	Nov	Dec	Jan	Feb	March	April	Mean
Mean Temp (˚C)	13.3	10.9	7.6	5.7	5.4	5.5	6.4	8.7	7.9
Total Rainfall (mm)	67.5	105.5	116.8	113.2	122.5	82.6	68.7	58.8	92.0
Solar Radiation (MJ m^{-2})	419	264	172	127	149	222	366	487	276
Soil Temp to 100 mm (˚C)	15.0	11.9	7.9	5.4	5.0	5.4	6.9	10.2	8.5

5.3.3 Experimental design

This experiment was undertaken within a larger study (Claffey et al., 2019; Claffey et al., 2020). Briefly, the larger farmlet systems study had three ranges of closing dates: 1) Early – closed over the period of September 25 to November 9, 2) Normal – closed over the period of October 10 to November 24 and 3) Late – closed over the period of October 25 to December 9. Grazing management of the swards within their respective autumn closing managements dictated the closing dates of individual paddocks in autumn and the date of initial grazing in spring. Swards were grazed by lactating dairy cows under their respective autumn closing managements, and remained un-defoliated from autumn grazing until the following spring. Spring defoliation took place independently of autumn defoliation, over an 8-week period from the beginning of February to early-April. From that experiment five paddocks (hereafter referred to as swards) in each experimental year (2017 and 2018) were selected across each of the closing period ranges and measured from the final defoliation in autumn until the first defoliation in spring.

This resulted in five autumn CD treatments, swards were selected from each two week CD range in year 1 and year 2, (Table 5.2); the CD ranges were October 1 – October 15 (CD1), October 16 – October 30 (CD2), October 31 – November 14 (CD3), November 15 – November 29 (CD4), November 30 – December 9 (CD5). Sward measurements, described below, were made on each CD and then on the four measurement dates (MD) during the closed period: December 11 (MD1), January 6 (MD2), January 27 (MD3) and prior to spring defoliation (MD4) (Table 5.2). This resulted in four measurement periods (MP) in each year; MP1 (Paddock Closing – December 11), MP2 (December 12 - January 6), MP3 (January 7 - January 27) and MP4 (28 January - spring defoliation).

Table 5.2: Measurement periods, measurement dates and closing dates in year 1 (2017 - 2018) and year 2 (2018 – 2019).

Measurement Period	Average Measurement Period	Measurement Date
1	Paddock Closing - 11 Dec	11 Dec
2	13 Dec - 6 Jan	6 Jan
3	6 Jan - 27 Jan	27 Jan
4	28 Jan - spring defoliation	Spring Defoliation (average 1 March)

Closing date	Date range
1	1 Oct – 15 Oct
2	16 Oct – 30 Oct
3	31 Oct – 14 Nov
4	15 Nov – 29 Nov
5	30 Nov – 9 Dec

A total of thirty (n = 10) mature individual PRG tillers, with no visible daughter tillers emerging from the basal meristem, were selected and marked post-defoliation at 0.10 m intervals along a 1m transect at three randomly selected locations within each of the five CD swards. Individual parent tillers were labelled using twists of coloured plastic coated wire. At each MD the following parameters were measured on every parent tiller: the length of green laminae on each leaf, extended tiller height (ETH; cm) and extended sheath/pseudo stem height (ESH; cm) were measured using a graduated ruler similar to Gilliland et al. (2002). To record the number of leaves that appeared over each measurement period, leaves were identified in the order in which they appeared and their development stage; i.e. L0 was the expanding leaf at the first marking, L1 was the first/youngest fully expanded leaf, L2 was the second fully expanded leaf and L3 was the third fully expanded leaf. At each marking, L0 (the expanding leaf at marking) was marked, without causing damage to the tiller, using an oil-based water-resistant substance (Tippex®) and the sequence of expansion followed from there similar to Hennessy et al. (2008). New daughter tillers emerging from the basal meristem of the marked parent tiller on each MD were marked in the

same way as the parent tiller but with different coloured plastic-coated wire. The free leaf lamina (FLL; cm) was calculated for each measurement period by subtracting the ESH from the ETH. Average LER (mm tiller^{-1} day^{-1}) and average LSR (mm tiller^{-1} day^{-1}) were calculated for each MP for the original parent tiller and separately for the daughter tillers. Average LER was the daily increase in mean lamina length (mm) on expanding and appearing leaves over the measurement period. Average LSR was calculated from the change in length from the ligule to the end of the green lamina in the two oldest leaves per tiller divided by the number of days in the MP. The total number of daughter tillers produced divided by the total number of marked tillers was the number of daughter tillers produced per parent tiller (DT PT^{-1}). The mortality rate for both parent tillers and daughter tillers were the tillers that visibly died over the experiment.

On MD3, herbage mass to a residual of 3.5 cm was determined by cutting two strips 1.2 m wide and of a known length (approx. 10 m) with an Etesia mower (Etesia UK Ltd., Warwick, UK). The mown herbage from each strip was collected and weighed. A sample from each strip (c. 300 g fresh weight [FW]) was collected. From this a further sub-sample of 100 g FW was collected and dried for 16 h at 90°C (Beecher et al., 2020) to determine DM content. Compressed sward height was recorded pre- and post-cutting on each cut strip by taking ten measurements per strip using a rising plate meter (Jenquip Rising Plate Pasture Metres, New Zealand). The average paddock pre-grazing herbage mass >3.5 cm was then calculated according to the following equation (O'Donovan et al., 2002):

$$\text{Pre-grazing herbage mass (kg DM per ha)} = \frac{\text{weight (kg FW)} \times \text{area (length} \times 1.2\text{ m)} \times 10\,000 \times \text{DM\%}}{100}$$

Sward density was calculated using the following equation (Tuñon et al., 2014):

$$\text{Sward density (kg DM cm}^{-1}\text{ ha}^{-1}\text{)} = \frac{\text{Herbage mass (kg DM ha}^{-1}\text{)}}{\text{Pre-cutting height - post-cutting height}}$$

The average paddock pre-grazing herbage mass was then corrected to 3.5 cm according to the following equation (Delaby et al., 1998):

Pre-grazing herbage mass (kg DM ha^{-1}) = (Pre-cutting height (cm) – 3.5 cm) × sward density (kg DM cm^{-1} ha^{-1})

5.3.4 Statistical analysis

Statistical analyses were carried out using SAS 9.4 (SAS Institute Inc., Cary, NC, USA, 2002). The effect of CD on parent tiller average LER, LSR, FLL, number of leaves to appear, daughter tiller LER, LSR, daughter tiller appearance, daughter tiller mortality, daughter tiller number and herbage mass were determined using the PROC MIXED procedure in SAS, with CD, MD, year, paddock being used in the model. Tiller was the experimental unit, with year the random factor and MD was the repeated measure. Data are presented as least square means ± standard error. Variables were analysed using the following model:

$$Y_{jkl} = \mu + closing\ date_j + measurement\ date_k + year_l\ (closing\ date_j \times measurement\ date_k \times year_l) + (closing\ date_j \times measurement\ date_k) + (year_l \times closing\ date_j) + (closing\ date_j \times measurement\ date_k) \times e_{jkl}$$

Where:

μ = mean value for the variable

e_{jkl} = residual error term

Y_{jkl} = parent tiller average LER (mm tiller^{-1} d^{-1}), parent tiller average LSR (mm tiller^{-1} d^{-1}), FLL (cm) daughter tiller appearance, daughter tiller LER (mm tiller^{-1} d^{-1}), daughter tiller LSR (mm tiller^{-1} d^{-1}), daughter tiller survival and herbage mass (kg DM ha^{-1})

5.4 Results

5.4.1 Parent tillers

Average leaf extension rate

Closing date had a significant ($p < 0.05$) effect on the average parent tiller LER (Table 5.3); closing earlier in autumn (CD1: 5.3 ± 0.51 mm tiller^{-1} day^{-1}) resulted in a greater average parent tiller LER than closing later (CD3, CD4 and CD5: 3.2 ± 0.51 mm tiller^{-1} day^{-1}) with CD2 (4.0 ± 0.51 mm tiller^{-1} day^{-1}) intermediate. There was positive correlation between herbage mass and average parent tiller LER (R^2 = 0.93), as herbage mass increased average LER increased (y = 0.002x + 2.27). Measurement period 1 (2.4 ± 0.46 mm tiller^{-1} day^{-1}) had a significantly ($p < 0.001$; Table 5.4) lower average parent tiller LER than MP2, MP3 and MP4 (4.2 ± 0.46 mm tiller^{-1} day^{-1}). Year 2 (4.2 ± 0.32 mm tiller^{-1} day^{-1}) had a significantly ($p < 0.001$) higher average parent tiller LER than year 1 (3.3 ± 0.32 mm tiller^{-1} day^{-1}). Daily temperature had a negative correlation on average parent tiller LER (R^2 = 0.84); as air temperature decreased average parent tiller LER increased (y = - 0.6828x + 8.54).

Average leaf senescence rate

Closing Date 1 had a significantly ($p < 0.01$; Table 5.3) greater average parent tiller LSR compared to CD5 (5.0 and 1.3 ± 0.60 mm tiller $^{-1}$ day^{-1}, respectively). Leaf senescence rate was significantly ($p < 0.001$; Table 5.4) lower in MP1 (1.1 ± 0.66 mm tiller^{-1} day^{-1}) compared to all other MP (3.8 ± 0.66 mm tiller^{-1} day^{-1}). There was no effect (P > 0.05) of year on average parent tiller LSR (3.2 ± 0.42 mm tiller^{-1} day^{-1}). There was a negative correlation between average daily temperature and average parent tiller LSR (R^2 = 0.90); as temperature decreased average parent tiller LSR increased (y = - 0.1834x + 11.83). There was a positive correlation between herbage mass and average parent tiller LSR (R^2 = 0.69); as herbage mass increased average parent tiller LSR increased (y = 0.0029x + 1.43).

Free leaf lamina

Closing date 1 (11.8 ± 0.86 cm) had significantly ($p < 0.001$) greater FLL than CD3, CD4 and CD5 (8.6 ± 0.86 cm) with CD2 (10.8 ± 0.86 cm) intermediate (Table 5.3). Parent tiller FLL was significantly ($p < 0.001$) greater in MP3 (11.0 ± 0.57 cm) compared to MP1 (7.2 ± 0.57 cm; Table 5.4). Year 1 did not have significantly different parent tiller FLL to year 2 (9.7 ± 0.55 cm).There was a negative correlation between average daily temperature and parent tiller FLL ($R^2 = 0.77$); as temperature decreased parent tiller FLL increased ($y = - 1.1834x + 24.37$). There was a positive correlation between herbage mass and parent tiller FLL ($R^2 = 0.76$); as herbage mass increases over winter, parent tiller FLL increased ($y = 0.0034x + 8.93$).

Tiller mortality

There was a significant ($p < 0.05$) effect of CD on parent tiller mortality (Table 5.3); earlier closed swards had a greater parent tiller mortality (CD1; 1.1 ± 0.20 tillers) than later closed swards (CD4 and CD5; 0.3 ± 0.20 tillers) with CD2 and CD3 (0.7 ± 0.20 tillers) intermediate.

Number of daughter tillers produced

The CD × MD interaction had a significant effect ($p < 0.001$) on the number of daughter tillers produced. In MP1, CD1 (8.1 ± 1.13 tillers) had a greater number of daughter tillers produced compared to MP2 and MP3 (1.2 ± 1.13 tillers) with MP4 (4.0 ± 1.13 tillers) intermediate. Closing date 2 had a greater number of daughter tillers produced in MP1 (5.6 ± 1.13 tillers) than MP3 (0.3 ± 1.13 tillers) with MP2 and MP4 (1.3 ± 0.98 tillers) intermediate. Closing date had a significant ($p < 0.001$) effect on the number of daughter tillers produced with CD1 (1.1 ± 0.27 tillers) greater than CD3, CD4 and CD5 (0.3 ± 0.27 tillers; Table 5.3). The number of daughter tillers produced (Table 5.4) in MP1 (0.1 ± 0.25 tillers) was significantly ($p < 0.001$) greater than in MP4 (1.2 ± 0.25 tillers) with MP2 and MP3 (0.5 ± 0.25 tillers) intermediate.

5.4.2 Daughter tillers

Average leaf extension rate

Measurement period 4 (3.1 ± 0.54 mm tiller^{-1} day^{-1}) had significantly ($p < 0.05$) greater daughter tiller LER compared to MP1 (1.3 ± 0.54 mm tiller^{-1} day^{-1}) with MP2 and MP3 (0.7 ± 0.54 mm tiller^{-1} day^{-1}) intermediate (Table 5.4). Year 2 (0.2 ± 0.47 mm tiller^{-1} day^{-1}) had significantly ($p < 0.01$) lower average daughter tiller LER than year 1 (3.7 ± 0.47 mm tiller^{-1} day^{-1}). There was positive correlation between herbage mass and average daughter tiller LER ($R^2 = 0.76$); as herbage mass increased average daughter tiller LER increased ($y = 0.0167x + 7.05$).

Average leaf senescence rate

There was a significant ($p < 0.01$) interaction between year and CD; earlier closing (CD1 and CD2: 3.4 ± 0. 54 mm tiller^{-1} day^{-1}) had greater average daughter tiller LSR than later (CD3, CD4 and CD5: 0.7 ± 0.54 mm tiller^{-1} day^{-1}) in year 1. In year 1, CD1 and CD2 had greater LSR than in year 2 (0.7 ± 0.54 mm tiller^{-1} day^{-1}). Closing date had a significant effect ($p < 0.01$) on average daughter tiller LSR (Table 5.3); average daughter tiller LSR on CD1 (1.7 ± 0.72 mm tiller^{-1} day^{-1}) was greater than CD5 (0.2 ± 0.54 mm tiller^{-1} day^{-1}). Measurement period 1 (0 ± 0.44 mm tiller^{-1} day^{-1}) had significantly ($p < 0.05$) lower average LSR compared to MP3 and MP4 (1.5 ± 0.44 mm tiller^{-1} day^{-1}; Table 5.4), MP1 had a lower average LSR compared to MP3 and MP4. Year did not affect daughter tiller average LSR. There was a negative correlation between average daily temperature and average daughter tiller LSR ($R^2 = 0.82$); as temperature decreased average daughter tiller LSR increased ($y = - 5.7063x + 50.21$).

Daughter tiller mortality

There was no significant effect of CD or year on daughter tiller mortality (0.9 ± 0.72 and 0.9 ± 0.46 tillers, respectively; Table 5.3). Measurement period however had a significant ($p < 0.05$) effect on daughter tiller mortality, with MP1 (0.1 ± 0.25 tillers) lower than MP4 (1.2 ± 0.25 tillers) and MP2 and MP3 (0.5 ± 0.25 tillers) were intermediate (Table 5.4).

5.4.3 Herbage Mass

Autumn CD had a significant effect on herbage mass in MD3 ($P < 0.001$; Figure 5.2); CD1 (1123 ± 90.2 kg DM ha^{-1}) had a greater herbage mass than CD2 (801± 90.2 kg DM ha^{-1}), and both were greater than CD3, CD4 and CD5 (367 ± 90.2 kg DM ha^{-1}).

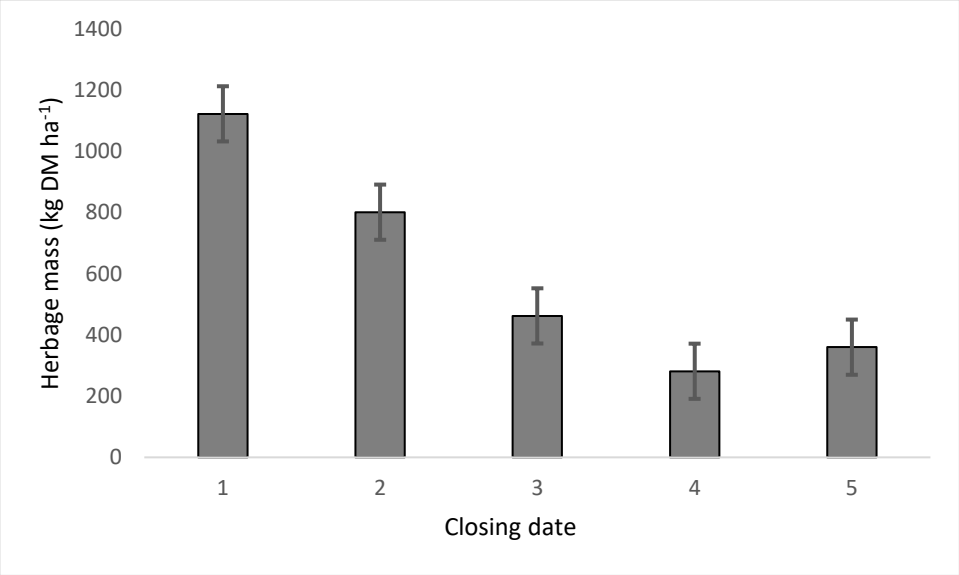


Figure 5.2: Average herbage mass (kg DM ha^{-1}) for each closing date (CD; CD1: 1 Oct – 15 Oct, CD2: 16 Oct – 30 Oct, CD3: 31 Oct – 14 Nov, CD4: 15 Nov – 29 Nov, CD5: 30 Nov – 9 Dec) in MD3. Error bars show the standard error of the mean.

Table 5.3: Average leaf extension rate (mm tiller^{-1} day^{-1}), average leaf senescence rate (mm tiller^{-1} day^{-1}), free leaf lamina (cm) and mortality of parent tillers (PT) and daughter tillers (DT) and the number of daughter tillers produced (DT produced; DT PT^{-1}) for each closing date (CD; CD1: 1 Oct – 15 Oct, CD2: 16 Oct – 30 Oct, CD3: 31 Oct – 14 Nov, CD4: 15 Nov – 29 Nov, CD5: 30 Nov – 9 Dec).

Variable	CD1	CD2	CD3	CD4	CD5	SEM	P-value
Parent tiller (PT)							
Average LER‡	5.3^{a}	4.0^{ab}	3.3^{b}	3.2^{b}	3.1^{b}	0.51	*
Average LSR§	5.0^{a}	4.0^{ab}	3.3^{abc}	2.1^{bc}	1.4^{c}	0.66	**
FLL¶	11.8^{a}	10.8^{ab}	7.7^{b}	8.9^{ab}	9.4^{ab}	0.86	***
PT Mortality	1.1^{a}	0.8^{ab}	0.6^{ab}	0.3^{b}	0.3^{b}	0.19	*
DT produced	3.6^{a}	2.2^{ab}	1.1^{b}	1.0^{b}	0.8^{b}	0.65	*
Daughter tiller (DT)							
DT LER	2.9	2.3	1.7	1.5	1.4	0.75	NS
DT LSR	1.7	1.3	0.5	0.8	0.2	0.72	NS
DT mortality	1.1	0.8	0.1	0.4	0.3	0.27	NS

‡ LER was the average leaf extension rate (mm tiller^{-1} day^{-1})
§LSR was the average leaf senescence rate (mm tiller^{-1} day^{-1})
¶FLL was the free leaf lamina (cm)
NS = > 0.05, * = < 0.05, ** = < 0.01, *** = < 0.001

Table 5.4: Average leaf extension rate (mm tiller^{-1} day^{-1}), average leaf senescence rate (mm tiller^{-1} day^{-1}), free leaf lamina (cm) and mortality of parent tillers (PT) and daughter tillers (DT) and the number of daughter tillers produced (DT produced; DT PT^{-1}) for each MP (MP1: Paddock closing - 11 Dec, MP2: 13 Dec - 6 Jan, MP3: 6 Jan - 27 Jan, MP4: 28 Jan - spring defoliation).

Parent tiller (PT)	MP1	MP2	MP3	MP4	SEM	P-value
Average LER‡	2.4^{a}	4.2^{b}	4.2^{b}	4.3^{b}	0.46	***
Average LSR§	1.1^{a}	3.3^{b}	3.7^{b}	4.6^{b}	0.60	***
FLL¶	7.2^{a}	10.4^{b}	11.0^{b}	10.4^{b}	0.57	***
Mortality	0.6	0.6	0.4	0.8	0.16	NS
DT produced	2.9^{a}	1.2^{ab}	1.0^{b}	1.9^{ab}	0.58	**
Daughter tiller (DT)						
DT LER	1.3^{a}	2.0^{ab}	1.4^{a}	3.1^{b}	0.54	*
DT LSR	0.0^{a}	0.6^{ab}	1.3^{ab}	1.8^{b}	0.45	**
DT mortality	0.1^{a}	0.5^{ab}	0.4^{ab}	1.2^{b}	0.25	*

‡ LER was the average leaf extension rate (mm tiller^{-1} day^{-1})
§LSR was the average leaf senescence rate (mm tiller^{-1} day^{-1})
¶FLL was the free leaf lamina (cm)
NS = > 0.05, * = < 0.05, ** = < 0.01, *** = < 0.001

5.5 Discussion

The current study shows that closing swards earlier in autumn (early October) is associated with greater herbage mass in spring compared to later autumn closing November and December. This is as a result of a longer regrowth period over winter, similar to Hennessy et al. (2006) and Ryan et al., (2010). However, closing swards earlier in autumn for increased herbage availability in spring can have negative implications on sward structure (Hennessy et al., 2006). In the current study soil temperature was higher in autumn (MP1) than in spring; despite this, parent tiller LER was greater in spring (MP2, MP3 and MP4; Figure 5.3) than in autumn, similar to Hennessy et al. (2008). This could be accounted for by a plants ability to have a greater response to temperature changes post-vernalisation (Peacock, 1976; Thomas & Norris, 1977; Wingler & Hennessy, 2016). Plants ability to respond to temperature post vernalisation occurs due to an acceleration of leaf primordia production (Jewiss, 1993). The vernalisation response (due to changes in temperature) in plant growth was reported to occur in January (Cooper, 1960; Parsons & Robson, 1980), similar to the current study. Brereton et al. (1985) reported that LER and LSR were correlated to air temperature but this relationship is affected by vernalisation response and plants responded better to temperature in spring compared to autumn. The threshold temperature for positive net herbage production in vernalised plants is 5°C and for unvernalised plants it is 8°C (Brereton et al., 1985) which would correspond to the temperatures observed in this experiment (MP1 – 8.9ºC, MP2 – 7.7ºC, MP3 – 6.1°C, MP4 – 6.1°C). However, variations in over winter temperatures between years are inevitable and uncontrollable, and as such this will led to variations in tissue turnover over winter, as reported in the current study.

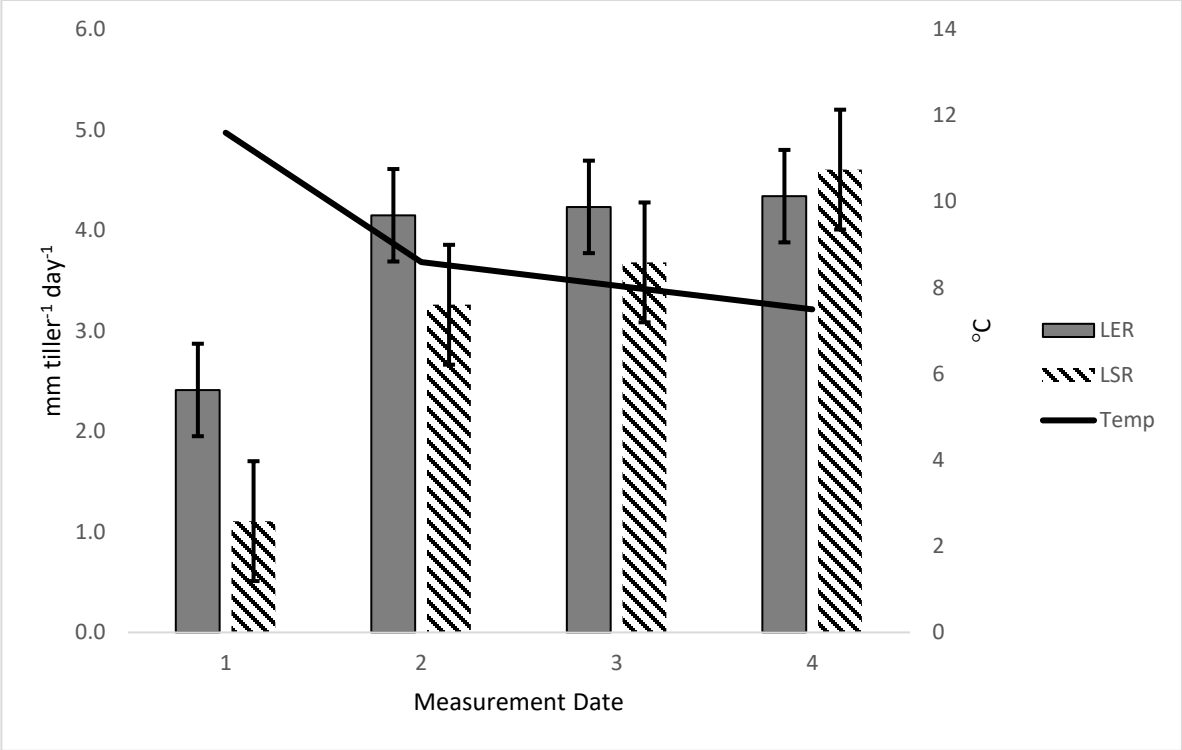


Figure 5.3: Average leaf extension, leaf senescence rates (mm tiller $^{-1}$ day^{-1}) and average soil temperature for each MD (MD1 - 11 Dec, MD2 - 6 Jan, MD3 - 27 Jan, MD4 - spring defoliation). Error bars show the standard error of the mean.

Hennessy et al. (2008) reported that when swards were closed in early September, they experienced higher rates of LER and LSR than later closed swards (October), similar to the current study where the average LER at measurement in December was greater for swards closed earlier than later closed swards. This is because swards that received their final grazing in early October had a greater length of time (70 days) to respond to the warmer temperatures experienced in October post-defoliation resulting in the increased LER compared to later closing. The greater LSR on the parent tillers in the current study was possibly due to a greater quantity of mature leaves (73% in category L2 and L3) on swards closed in October compared to swards closed late in November (53% leaves in category L2 and L3). Casey et al. (1999) reported that a longer sheath (ESH) can led to a reduction in LAR. The longer the sheath height of the PRG plant, the longer it takes for a new leaf to appear, due to the lamina taking a greater length of time to emerge

(Hennessy et al., 2008). In the current study, the greater FLL in earlier closed swards represents a greater ESH in swards, similar to Byrne et al. (2018).

As the time between defoliations increases so too does LSR which results in an increase in the proportion of senescent material in the sward (Davies & Simons, 1979). This can result in a reduction in overall sward quality (Binnie et al., 2001; Hennessy et al., 2006; Claffey et al., 2019). Greater senescence was observed in relatively younger leaves (L2, in the current experiment), similar to other studies (Davies & Simons, 1979; Jaindl et al., 1991; Hennessy et al., 2008), when swards had high herbage mass over winter (CD1 and CD2 swards). This was due to a greater LSR compared to LER which meant the number of leaves was less than the normal three expanded leaves. Senescence of leaves at a younger age can lead to reduced herbage mass as LSR is greater than LER once the 'ceiling yield' is reached (Alberda & Sibma, 1968; Robson et al., 1988; Ryan et al., 2010). When ceiling yield is reached in swards, herbage mass can potentially decline and will continue to decline until the sward is defoliated (Hennessy et al., 2006; Ryan et al., 2010). Defoliating swards that have reached ceiling yield earlier in spring can help mitigate the impact on sward quality (Ryan et al., 2010) and reduce the length of time swards have to senesce material.

The production of daughter tillers is an important factor ensuring the longevity and survival of a sward as these new tillers will be the new growing points in the sward and will replace older tillers at the end of their life cycle, maintaining herbage production (Garay, 1999). In the current experiment, the number of daughter tillers produced was greatest in spring compared to autumn on the later closed swards (CD2 – CD5). This is because daughter tillers are actively produced in autumn, through winter (Davies & Simons, 1979) and in spring to reach peak tiller density in mid-April (Garwood, 1969; Laidlaw, 2005). Early closed swards (CD1), with a herbage mass above 1100 kg DM ha^{-1} on MD3, had greater daughter tiller production in autumn compared to spring. There was also a greater parent tiller mortality observed in earlier closed swards (CD1) in spring, similar to Korte (1981) and Hennessy et al. (2006). The greater parent tiller

mortality occurs due to shading at the base of the sward which can hinder daughter tiller survival due to high herbage masses (Brougham, 1960; Laidlaw & Mayne, 2000). Increased levels of shading can supress tiller bud production and establishment (Hunt, 1978), contributing to reduced tiller density. This supports previous findings that there is a reduction in spring tiller density on swards closed earlier in autumn Hennessy et al. (2006) and Looney et al. (2021). Parent tillers survive increased levels of shading by sacrificing daughter tillers and diverting resources to parent tillers (Laidlaw & Mayne, 2000). From autumn closing date to spring defoliation parent and daughter tiller mortality increased as herbage mass increased. It is possible that early defoliation of these swards in spring could alleviate some of the negative implications experienced in swards with high herbage masses as there is rapid increase in tiller production when shading is removed (Brougham, 1960; Thomas and Norris, 1981).

5.6 Conclusion

This study highlights the impact of autumn management on tiller production and mortality. Closing swards earlier in autumn is essential to increase spring herbage mass through increased LER, however early closing also leads to increased LSR and increased tiller mortality compared to later closing. Closing swards later in autumn, although not beneficial to over winter herbage production, had a positive effect on daughter tiller production. As well as autumn CD, increasing the length of time a sward is closed for between autumn and spring, regardless of herbage mass, leads to greater tiller mortality. This study showed that tiller production is greater post-vernalisation at temperatures greater than 5°C than pre-vernalisation.

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Chapter 6: General Discussion

In grass-based ruminant production systems, like Ireland, there is a competitive advantage, as there is potential to produce large quantities of grass (O' Donovan and Egan, 2019), at a relatively low cost (Finneran et al., 2010), which can be utilised by ruminant animals for production. In recent years, Ireland's dairy sector has gone through rapid expansion (Kelly et al, 2020) with an increase in stocking rates on Irish dairy farms by up to + 12.8% (Hanrahan et al., 2018). Combined with earlier (- 8 days; February 25th in 2018 compared to the March 4th in 2012) and more compact calving (+ 11 % in 6 week calving rate (64 % in 2018 vs. 53 % in 2008; ICBF, 2018)), which has resulted in an increased demand for feed, particularly in spring and autumn. It is particularly challenging in the context of Irish pasture-based farming, as temperatures reduce in late autumn and over the winter, there is a resultant drop in growth rates of PRG, and the feed demand required to meet animal requirements is greater than growth rates and herbage availability. To maintain Ireland's competitive advantage, this increase in feed demand, must come from grazed grass (Dillon et al., 2005) while reducing purchased feed (Finneran et al., 2010). Maintaining Ireland's competitive advantage has become a key challenge alongside improving the environmental sustainability of the dairy sector (Dillon et al., 2019). The extension of the grazing season has been identified in the Teagasc Marginal Abatement Cost Curve as one way to mitigate greenhouse gas emissions as grazed grass replaces concentrate feed and cows do not require full time housing which reduces slurry storage requirements (Lanigan et al., 2018). The extension of the grazing season can be achieved through grazing management strategies in autumn and spring (Teagasc, 2021). Management practices to date have looked at lengthening the grazing rotation in August to carry additional grass on farm for the final rotation before the decline in growth rates, and through autumn closing date to carry grass over winter for spring defoliation (Roche et al., 1996; Hennessy et al., 2008; Ryan et al., 2010; Lawrence et al., 2017). Management guidelines also need to optimise practices to maintain sward structure and quality. This thesis aims to improve management practices for the extension of the grazing season in both autumn and spring through the examination of different management practices in autumn, over winter and into spring.

Grazing management practices in autumn need to consider variability in weather conditions (Ruelle et al., 2018) and its resultant herbage growth rates (Peacock, 1975). This thesis has highlighted the impact of environmental conditions on herbage growth in autumn and over winter. In chapter 2, there was a large range in herbage growth rates due to fluctuations in temperature, between year 1 and year 2. The drought experienced in 2018 showed reduced growth rates however, there was a large compensatory growth after, similar to Korte and Chu (1983) and Barker et al. (1985). However, even if greater growth rates are experienced in autumn, it is still imperative to begin accumulating herbage masses in August for the final grazing rotation. This is due to a slower response of LER to temperatures in autumn compared to spring (Hennessy et al., 2008) which is also demonstrated in chapter 5. As temperatures reduce in autumn, the high (2000 kg DM ha^{-1}) and very high (3000 kg DM ha^{-1}) THM analysed in chapter 2 continued to accumulate herbage until defoliation date 1 (7th November). However, beyond this point, the herbage mass began to reduce due to the reduction in air temperature and plants had reached and surpassed the 'three-leaf' stage (Chapter 2) resulting in an increase in the senescent material (Fulkerson and Donaghy, 2001) as shown in chapter 4. Reaching the 'three-leaf' stage serves as a tipping point where every new leaf appears the oldest leaf begins to senescence (Fulkerson and Donaghy, 2001). This can contribute to the reduction in herbage, as LSR can be greater than LER (Hennessy et al., 2008). This in turn can result in an over reduction in sward quality, as senescent material has a lower nutritional value compared to green material (Binnie et al., 2001), as shown in chapter 4, where earlier closed swards had a lower crude protein (CP) content and organic matter digestibility (OMD). Defoliating high herbage masses earlier in autumn should help maintain CP at a higher level. This will ensure the sward is of suitable quality to meet animal requirements (Garry, 2020). As shown, management practices in autumn and spring impact sward quality (Chapter 2 and 4) however, all herbage (817 g kg DM^{-1}) in the current thesis were of greater quality than grass silage (696 g kg DM^{-1}; Kennedy et al., 2005), which can result in an overall increase in animal production (Kennedy et al., 2005; Claffey et al., 2019; Claffey et al., 2020).

Chapter 3 examined how light penetration to the base of the sward can be affected by the accumulation of herbage mass and the resultant effects on sward morphology. Light penetration does not significantly change from medium to very high THM as swards have reached a ceiling yield at ~1700 kg DM ha^{-1} similar to Brereton et al. (1988). Shading at the base of the sward can have a negative impact on PRG plant morphology as a result of reduced light transmission (Laidlaw and Mayne, 2000). Results in the current thesis showed that although light penetration was the same across three of the THM (medium, high and very high), morphology was more negatively affected the greater the herbage mass and the longer the plant remained undefoliated increasing the length of time with reduced light penetration (DD1 – DD3; Davies and Simons, 1989). Internode elongation is one morphological feature that occurs as a result of increased shading (Korte and Harris, 1987). The greatest amount of internode elongation visible > 4 cm was in the late November in the very high THM as it had the greatest herbage mass and longest level of shading. Internode elongation could have a negative impact on the sward as it moves the growing point up from ground level and this can make tillers more susceptible as a result of damage from grazing, which could have a negative impact on tiller density. Surprisingly, there was no effect of this autumn management in chapter 2 and chapter 3 on spring tiller density. This contrasts to chapter 4 where tiller density in spring was reduced when heavy covers were carried over winter. This is due to carrying high levels of herbage mass over winter where increased shading resulted in tiller mortality (Hennessy et al., 2006). In chapter 2 and 3 defoliation in autumn allowed heavier covers time to recover; light transmission increased to the base of the sward and a proliferation in tillers (Brougham, 1960; Thomas and Norris, 1981) over winter facilitated sward recovery. Previous studies (O'Riordan et al., 1995; Hennessy et al., 2006; Ryan et al., 2010) reported that herbage masses reached a ceiling yield at > 2000 kg DM ha^{-1} however, the current thesis reported varying ceiling yield for light transmission (1700 kg DM ha^{-1}; chapter 3), herbage mass (1800 – 2000 kg DM ha^{-1}; chapter 2) and sward quality (2,100 kg DM ha^{-1}; chapter 2). Defoliating swards with high herbage masses (>2000 kg DM ha^{-1}) in autumn allowed tiller density to recover before spring defoliation, due to the

increased closed period over winter (DD1 – 129 days, DD2 – 106 days, DD3 – 92). Chapter 5 reported that swards with a high herbage mass experienced increased mother and daughter tiller mortality when not given the opportunity to recover, which could have led to a reduction in tiller density. In swards that were shown to have reduced tiller density in spring (chapter 4), there was a possibility there were less growing points available (Garay, 1999), which could have resulted in the reduced growth rates experienced in the second rotation in chapter 4.

Defoliation date in autumn, in chapter 2 and chapter 4, was found to impact the herbage available the following spring similar to other studies (Hennessy et al., 2006; Ryan et al., 2010; Lawrence et al., 2017). Autumn closing date accounted for 50% of the variation in herbage mass in spring (chapter 4), which is a controllable factor for farmers. Closing earlier in autumn was found in both chapters to give the greatest herbage mass in spring (chapter 2, DD1 and in chapter 4, CD1 & CD2). The increase in herbage mass in spring was as a result of an increased LER in autumn (Hennessy et al., 2008) and an extended period of time over winter as a result of the longer closed period. Chapter 2 reported no impact of accumulating herbage mass in autumn to facilitate the extension of the grazing season, on over winter herbage production and spring grass availability. This indicates that you can accumulate herbage mass in autumn, to extend the grazing season, however ensuring that an adequate interval to all swards to accumulate herbage for spring grazing is imperative. This is not the same for accumulating herbage masses over winter and into spring when they are defoliated in mid-late March as shown in chapter 4; growth rates after the first defoliation in spring were found to be reduced in the higher herbage mass swards as the number of growing points were reduced (Garay, 1999). This combined with swards not having an adequate time to recover before the next defoliation (average 38 days; 2nd rotation) compared to over winter (average 92 days from Nov 1st to Feb 1st).

The benefit of defoliating the PRG plant at the optimal time point (once the three-leaf stage has been achieved; Fulkerson and Donaghy, 2001) in the rotation was reinforced

in chapter 2 and 3, which can be applied to the management of swards in spring (chapter 4 and 5). Swards with a low herbage mass in autumn (~ 500 kg DM ha^{-1}), should not be defoliated, until they have reached the 3 leaf stage (Fulkerson and Donaghy, 2001) and have accumulated a herbage mass that meet target grazing requirements (Wims et al., 2013). This can be seen in chapter 2 and 3 in autumn and chapter 4 at spring defoliation. When herbage mass is accumulated it is important to target swards that have been closed for the greatest length of time first for defoliation in spring and autumn. These swards have gone past their time for 'optimal' defoliation (three-leaf stage) and to reduce the impacts identified above on sward structure (increased internode elongation, mother and daughter tiller mortality, senescence and reduced tiller density) these swards needs to be targeted for earlier defoliation in autumn and spring.

6.1 Practical implications, limitations and future work

Practical implications

- Accumulating herbage masses in autumn, for the extension of the grazing season should begin in autumn and does not have a negative effect on herbage availability in spring
- Autumn defoliation of swards should target herbage masses above 2000 kg DM ha^{-1} before early November to maintain sward quality and reduce the decline in herbage
- Each day delay in closing from late September reduced spring grass availability by 16 kg DM ha^{-1} day^{-1}
- Defoliation/closing date in autumn has the greatest impact on spring herbage availability at turnout, with management responsible for 50% of the variability
- Higher herbage masses from earlier closing in autumn should be targeted for defoliation at the earliest point possible in spring to maintain sward quality and allow light transmit to the base of the sward
- Earlier closed sward have a lower growth rate once grazed in spring compared to later closed swards

Limitations

The studies carried out in chapter 2 and 3 were carried out under mechanical defoliation which has been shown in previous studies (Cashman et al., 2016) to be a good predictor of animal grazing for DM yield. However, due to variation in weather and soil trafficability, the experiments in the current thesis may have experienced greater variation than previous studies. Animal grazing may have added additional information rather than mechanical defoliation, due to variation in soil condition and pasture utilisation under animals. However, this may have added increased complexity in terms of tillers measurements due to poaching damage. In the study, reducing sward quality in high herbage masses is well analysed however, leaf, stem and dead ratios would have added another dimension to the data set as it would be valuable to help identify a time point to reduce the amount of dead material in the sward. Chapter 2 and 3 represent defoliation dates during autumn in the final rotation. The trial could have added a replicate plot undefoliated until the end of February to investigate the effect of such a lengthy time period undefoliated on internode elongation. This may have been helpful to represent on farm practices when paddocks are not grazed due to environmental conditions.

While it is beneficial to have an overall farm systems study in chapter 4 the study of tiller mortality can be impacted by animal grazing. Tillers cannot be measured again after defoliation to investigate their recovery as it difficult to relocate the grazed tillers. It would be beneficial to relocate tillers after defoliation to investigate tiller survival, daughter tiller production, post-defoliation LER and LAR. Therefore it may have been more beneficial to carry out investigations in a more controlled environment or under mechanical grazing to quantity carryover effects.

Future work

Results from this thesis have contributed to improving management recommendations for autumn and spring. However, future work should focus on establishing time points for defoliation and strategies for grazing high herbage masses in spring need to be

investigated further as discussed in chapter 4 and chapter 5. The negative effects of accumulating high herbage mass as shown in thesis, need to be avoided where possible while meeting herd demand in spring. This will help to increase herbage utilisation and improve sward structure through developing the grazing management recommendations in spring.

The studies completed on autumn and spring management both showed negative effects in tiller health when accumulating high herbage mass on internode elongation (chapter 3) and tiller mortality (chapter 5). Both internode elongation and tiller mortality could contribute to reduced tiller density. Both studies only investigated tiller density over a two-year time frame. Future work should focus on investigating the potential of management practices reducing tiller density and in turn reducing the overall persistency of swards, over a multiyear approach. Reduced persistency of swards can allow weed ingression leading to a reduction in annual herbage production leading to the reseeding of swards (Shalloo et al., 2011).

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Chapter 7 – Publications

7.1 Scientific Publications

Looney, C., Wingler, A., & Egan, M. (2021). The Impact of Herbage Mass on Perennial Ryegrass Swards in Autumn on Autumn and over Winter Production and Characteristics. *Agronomy*, *11*(6), 1140. https://doi.org/10.3390/agronomy11061140

Looney, C., Hennessy, D., Wingler, A., Claffey, A., & Egan, M. (2021). An examination of the effect of autumn closing date on over-winter herbage production and spring yield. *Irish Journal of Agricultural and Food Research*. DOI: 10.15212/ijafr-2020-0129 IJAFR

Looney, C., Hennessy, D., Wingler, A., & Egan, M. (2021). The effect of autumn closing date on over winter tissue turnover in perennial ryegrass (*Lolium perenne* L.) swards. *Grass and Forage Science*. https://doi.org/10.1111/gfs.12550

7.2 Conference Proceedings

Looney, C., A., Wingler and M., Egan. 2018. A tale of two winters: Comparison of winter survival and senescence rates in perennial ryegrass tillers in the field and under simulated winter conditions in a growth chamber. In: Plant Growth and Development at the Irish Plant Scientist Association Meeting June 2018.

Looney, C., A., Wingler, D.J. Donaghy and M., Egan. The effect of altering autumn closing management on the water soluble carbohydrate composition of perennial ryegrass (*Lolium perenne* L) the following spring. In: Improving sown grasslands through breeding and management, Proceedings of the European Grassland Federation-Eucarpia Joint Symposium, p 167-169, 24-27 June 2019.

Looney, C., A., Wingler, A. Claffey and M., Egan. The effect of autumn management on perennial ryegrass sward quality and morphology in spring. In: Fit for the Future, British Society of Animal Science Annual Conference, 9-11 April 2019.

Looney, C., A., Wingler, D.J. Donaghy and M., Egan. Shade avoidance response by perennial ryegrass (*Lolium perenne* L) in delayed autumn defoliation. In: Plant Growth and Development at the Irish Plant Scientist Association Meeting, 24-27 June 2019.

Looney, C., A., Wingler, D.J. Donaghy and M., Egan. Investigation of autumn defoliation date on shade avoidance response in perennial ryegrass. In: New Phytologist next generation scientists conference, p 46, 22-25 July 2019.

Looney, C., A., Wingler and M., Egan. Building high herbage masses in autumn for the extension of the grazing season. In: Proceedings of the 28th General Meeting of the European Grassland Federation, June 2020 (online).

7.3 Technical notes

Egan, M., C. Looney and A. Claffey. 2018 The effect of autumn closing date of pasture on spring herbage availability and sward characteristics. In: Sustainable meat and milk production from grasslands, Proceedings of the 27th General Meeting of the European Grassland Federation, p 166-168, 17-21 June 2018.

Looney, C., D. Hennessy, A. Claffey and M., Egan. Effects of autumn grazing management on over-winter growth, sward quality and sward structure. In: Irish Dairying *Growing Sustainably,* Proceedings from the Moorepark Open Day, p 68- 69, 3 July 2019

Claffey, A, C. Looney and M. Egan. 2019. Effects of autumn grazing management on spring grass availability. In: Irish Dairying *Growing Sustainability*, Proceedings from the Moorepark Open day, p 70 – 71, 3 July 2019.

Looney, C., D. Hennessy, A. Claffey and M., Egan. Building herbage masses in autumn - the effect on sward quality and production. In: Irish Dairying *Delivering Sustainability,* Proceedings from the Moorepark Open Day, p 68- 69, September 2021.

7.4 Travel Scholarships

Stapledon Memorial Travel Fellowship was awarded in 2018, to the value of €4,700, to facilitate a 3 month research visit to Massey University, New Zealand where I gained experience in research and education, alongside an established national and international network. The funding secured facilitated a glasshouse experiment with

Prof. Danny Donaghy and research visits to observe trials on plantain to offset nitrogen losses within their system, mixed species swards and the Forage Value Index in Dairy NZ.

Stapledon Early Researcher Award was received to attend the European Grassland Federation – Eucarpia Conference, Zurich 2019 and present my research on water soluble carbohydrate reserves in the base of the Perennial Ryegrass plant.

Irish Grassland Council funding was secured to attend and present research on autumn grassland management at the European Grassland Federation Conference in 2020 to the value of €1,100.