Improving the use of perennial ryegrass swards for dairying in Ireland

A thesis presented in partial fulfilment of the requirements for the degree of:
Doctor of Philosophy in Agricultural Science
at Massey University, Palmerston North, New Zealand

by

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2013

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Dedicated to my wife Berenice and my son Felipe

Abstract

The main objectives of this thesis were to investigate the effects of grazing severity, treading damage, re-growth interval and pre-grazing herbage mass (HM) on sward and animal performance in four experiments during 2009 and 2010 in Ireland. Experiment 1 investigated three post-grazing sward heights ranging from 3.6 to 4.9 cm during the main grazing season. Herbage accumulated and harvested (11.3 and 11.2 t dry matter (DM)/hectare (ha), respectively) were not significantly affected by grazing severity but there were sward morphological and structural differences. Experiment 2 quantified the effects of treading damage during two seasons, ranging from light to severe damage (3.3 to 13.3-cm hoof-print depths, respectively). Treading damage in a perennial ryegrass (PRG) sward on a well-drained soil did not reduce annual grass DM production. Treading in a creeping bent-dominated sward on a poorly-drained soil resulted in 14 to 51% reductions in cumulative yields depending on frequency and season. Experiment 3 examined the effects of 2-, 3- or 4-week re-growth intervals on herbage production, characteristics and tissue turnover of a PRG sward using marked tillers (n = 240) under a cutting regime. Cumulative HMs were 6.7, 9.1 and 10.4 t DM/ha for the 2-, 3- and 4-week re-growth treatments, respectively. The number of leaves appearing per tiller during the re-growth period was only optimum for the 4-week treatment. Experiment 4 also used marked tillers (n = 360) in a grazing dairy cow experiment during the main grazing season under three target pre-grazing HMs (945, 1,623 and 2,360 kg DM/ha >4 cm). The number of leaves appearing per tiller during the re-growth period was 1.0, 1.9 and 2.4 for low (L), medium (M) or high (H) pre-grazing HM treatments, respectively. Cows grazing L, M or H pre-grazing HM produced 343, 342 and 330 kg milksolids, respectively. Low pre-grazing-HM cows grazed for 90 min/day more than M and H pre-grazing-HM cows but there was no difference in individual intake (16.0 and 15.8 kg DM/cow/day in June and August, respectively). Post-grazing sward height, treading damage, re-growth interval and pre-grazing HM can have a significant impact on the sward and on animal performance. The imposition of best management practice leads to a more effective conversion of grass into milk.

Acknowledgements

First I want to thank Teagasc and Pat Dillon for giving me the opportunity of carrying out experiments in the Animal and Grassland Research and Innovation Centre at Moorepark. I was honoured to be a part of the Walsh Fellowship Scheme that funded the research and my time in Ireland. This thesis is the result of three and a half years of work between Ireland and New Zealand. There remains the pleasant task of expressing my thanks to the people who have contributed and made this work possible.

In Ireland, my supervisors Mick O'Donovan, Emer Kennedy and Deirdre Hennessy trusted me in the task of running the experiments. From each of you I was able to learn some of the art and science of grassland management. Thanks very much for helping on the countless occasions that I knocked on your door to ask questions, in particular to Emer who patiently spent many hours with me. Thanks to Brendan Horan who had huge input, also to Scott Laidlaw and Chris Grainger who gave me very important feedback. The grazing trials would not have been possible without Fergal Coughlan and John Paul Murphy in Moorepark farm, and Aidan Brennan in Curtins farm, and the farm staff, from which I learned a lot, especially during the farm walks with Fergal. Mick Finney was essential for the success of the 'grass cut expeditions', lab analyses and for putting a smile on everyone's faces. Thanks to Flor Flynn who helped me in my first few months at the 'grass lab'. Tom O'Brian and his team were always helpful and gave solutions to every problem.

For reasons of space I will deliberately omit some of the students that helped with different tasks in the different trials but I cannot avoid mentioning some of them: Jeanne Guegan, Camille Terrasse, Valerie Gauthier, Susana Cabral, Edwige Bouvet, Clothilde Coquantin, thanks for many hours under difficult conditions! My office mates Ian Hutchinson, Thomas Herbin, Phill Creighton, Elodie Ganche, Roberta McDonald, and Paul Phelan, thanks for the encouragement, fun moments and glam. Special mention to my friend and favourite scrum half Ian who helped me in many ways during my stay in Fermoy, corrected my English and introduced me to the Fermoy Rugby boys. Also special thanks to Brian McCarthy for all the help, I was always impressed by your attitude, passion and commitment to your project and to your Hurling. Finally, Craig,

Cathal, Brendan, Yris, Eoin, PJ, Daniel and Julia, thanks for the happiness you brought into the work environment.

In New Zealand I joined my main supervisor, Nicolas Lopez-Villalobos. I was blessed to have the opportunity to work with you. With Nicolas I learned a bit about science and a lot about life. I am going to miss your support, the conversations and I will miss the Friday meetings in which you created a space for students to express, share and grow academically. Peter Kemp was amazingly clear and helped me a great deal to think about the experiments, was always available and game me very valuable feedback. Thanks to Colin Holmes and John Hodgson who game me important insights about the experiments. I am very grateful to Kevin Stafford, Debbie Hill, Story Kristen and Wendy Graham who always helped me with anything I needed. Ronaldo Vibart and Javier Baudracco gave me very valuable suggestions on many aspects of the thesis, for which I am very grateful. Ronnie thanks for your rugby, for the wise advice and for your friendship. Javi it is an honour to follow you side by side in this journey. Jose Garcia Muñiz and Penny Back very gently helped me with proof reading and editing.

The friendship of Andres Gomez Rueda, Mariano Battistotti, Celina Bortolotto, Hernan and Veronica Canterna, Natalia Benquet, Francisco and Valentina Sales, Juan and Dani Sanhueza, Jose Solis, and Nicolas and Camila Bitch was fresh air for us and made us feel closer to home. All this would not have been possible without the constant, unconditional and tender love of my wife, with whom I am learning about synergy and is the reason why I arrived to where I am now. Doing a PhD is like running a marathon and I did this one, this is certainly a privilege. I like to think my work contributes to efficient and common sense dairying, for which I committed myself with all my heart. Finally, there is a Maori saying: If you were to ask me "what is the most important thing in the world?" I would reply, "That is people, people, people." He tangata, he tangata, he tangata. This is for those who work the land, work in science and those who extend the learning with passion, and especially for farmers.

Foreword

There is a need to design a grass-based system of production for Irish dairy farmers that is sustainable for animals, people and for the environment, and profitable. It also needs to be socially acceptable, easily replicated with clear guidelines, and sufficiently appealing to attract people to work in the industry. This thesis, however, focuses on grazing management practices.

This thesis is presented in a series of papers which have been published, submitted for publication or are being prepared for submission. Therefore, some repetition, especially in the materials and methods sections, was unavoidable. The references from each chapter are at the end of the thesis. It must be pointed out that this work is only focused on grazing management without taking account of irrigation, sward renewal or nitrogen fertilisation. Ultimately, this thesis aims to provide answers for grassland farmers around the world as a result of work carried out in Ireland.

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Definitions

The following terms may be used in a different way in Ireland and the rest of the world (New Zealand), taken from Allen *et al.* (2011) and Drewry *et al.* (2008):

Herbage: The above-ground biomass of herbaceous plants, other than separated grain. Grasses, grass-like species, herbaceous legumes and other forbs collectively; the foliage and edible stems of herbs.

Sward: A population or a community of herbaceous plants characterised by a relatively short habit of growth and relatively continuous ground cover, including both above- and below-ground parts.

Canopy: The above-ground parts of a population or community of forage plants. It may include both herbaceous and woody vegetation.

Herbage mass: The total dry weight of herbage per unit of land above a defined reference level.

Pasture: A type of grazing management unit enclosed and separated from other areas by fencing or other barriers and devoted to the production of herbage for harvest primarily by grazing.

Paddock: A grazing area, part of a grazing management unit, that is enclosed and separated from other areas by a fence or barrier.

Grazing system: A defined, integrated combination of soil, plant, animal, social and economic features, stocking (grazing) method(s) and management objectives designed to achieve specific results or goals.

Defoliation: Removal of plant tissue by grazing animals or machinery.

Poaching: Slurry-induced soil conditions on very wet soil when trampled with stock.

Pugging: Deep hoof imprints in wet, soft soil, associated with pasture damage.

Glossary of terms

ADF	Acid-detergent fibre
CAP	Common Agricultural Policy
CP	Crude protein
DHA	Daily herbage allowance
DIM	Days in milk
DM	Dry matter
ESH	Extended sheath height
ETH	Extended tiller height
FLL	Free leaf lamina
GLC	Ground level cut
HM	Herbage mass
LAI	Leaf area index
LAR	Leaf appearance rate
LER	Leaf extension rate
LSD	Leaf, stem and dead components in the sward
LWT	Live weight
ME	Metabolisable energy
MS	Milksolids (fat + protein)
N	Nitrogen
NDF	Neutral-detergent fibre
OMD	Organic-matter digestibility
PRG	Perennial ryegrass
SR	Stocking rate
WSC	Water-soluble carbohydrates

Chapter 1: General introduction

By 2050 the world's population will have increased by 25% (UN, 2010), likely resulting in a boost in the global demand for dairy products. Currently, countries such as Brazil, Russia, India and China are experiencing a two-fold increase in income *per capita* (Tilman *et al.*, 2002). In parallel with this there has been an apparent change in dietary preferences from cereals to dairy products (DAFF, 2010; Edmeades *et al.*, 2010) which will increase the demand further. Global consumption of butter is predicted to be 20% greater in 2020 compared to 2011 levels (OECD-FAO, 2011). Consequently, there is an urgent need to supply the world market with more milk. This situation may be compounded since climate and markets are likely to become increasingly unpredictable (Palmer, 2009) and with this milk price (IFCN, 2010). Dairy countries like Ireland will face a volatile environment in terms of milk, feed and fertiliser prices (Rebello, 2010).

Input costs are increasing worldwide. The price of a barrel of oil increased from US$21 in the 1990's to US$77 in 2010. Similarly, to buy 100 kg of concentrate, a farmer from a developed country would have spent US$14 between 1981 and 2006 and US$22 in 2009 (IFCN, 2010). However, costs of production vary globally. For instance, the cost to produce 100 kg of milk is lowest in Africa, moderate in South America, Asia and Oceania and highest in Western Europe (11, 29 and 56 US dollars, respectively; IFCN, 2010). Even with higher milk prices and direct payments, Western European and North American farms do not seem to be as profitable when compared to other milk producing regions across the world (IFCN, 2010). In support of this, a recent report concluded that the key determinant of profit is not milk price but total cost of production (DairyCo, 2012). Therefore, more efficient, profitable and sustainable dairy systems are needed to cope with the increasing demand for milk and milk products throughout the world. Systems that control costs will remain competitive and will go some way towards meeting the demands of the future.

There are many different systems of dairy production, ranging from confined systems of production, where cows are kept indoors all year round and fed on total mixed ration to, at the other extreme, grass-based systems, where cows are outdoors all or most of the year and a high proportion of the diet is based on grazed grass. Ultimately, all systems are centred on the feed eaten and converted into milk (Holmes and Roche, 2007). Grazed grass is the cheapest feed source available for spring milk production (Dillon *et al.*, 2007; Holmes and Roche, 2007). O'Donovan *et al.* (2011a) calculated that, under

Irish conditions, when compared to grazed grass, silage and concentrates are more expensive by factors of approximately 2.5 and 4.0, respectively, and the cost of milk production can be reduced by 1 cent/litre/day through lengthening the grazing season by 27 days. Pasture eaten per hectare (ha; pasture grown × pasture utilisation) remains a key driver of profit for all systems (Dillon *et al.*, 2005; Macdonald *et al.*, 2010). Figure 1.1 shows a strong relationship between the total costs of production and the proportion of grass in the cow's diet in a number of countries (Dillon *et al.*, 2005). The graph also illustrates how increasing the proportion of grazed grass in a system that already utilises a high proportion of grazed grass, such as Ireland, could further reduce the total cost of milk production. This contrasts with countries where grazing only contributes a small proportion of total intake such as Denmark and United States. It seems that, although grain-fed systems of milk production may remain competitive for some internal markets (for countries such as United States and Israel), systems of dairy production that base the diet of their cows on grass will remain competitive in terms of exports. Indeed, Macdonald *et al.* (2010) stated that the areas of the world that can produce milk at low cost will provide the future world export market with milk products.

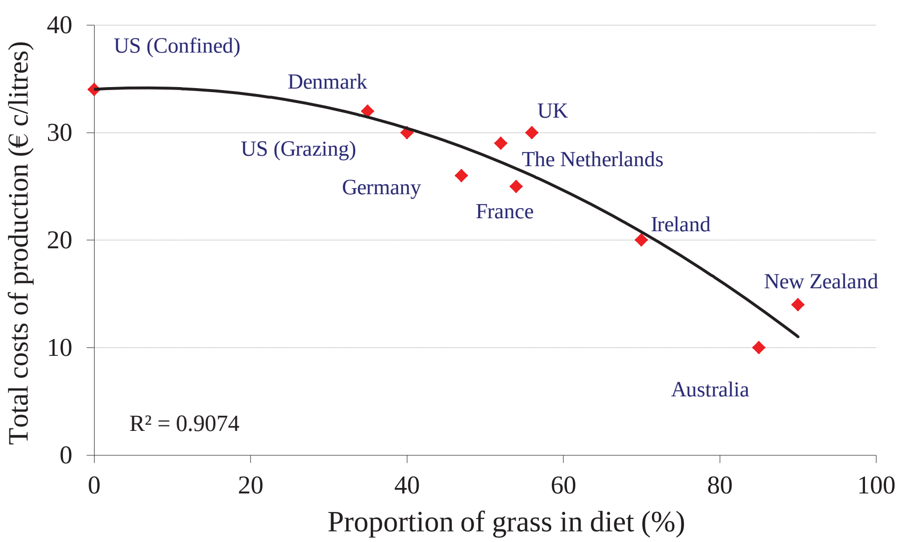


Figure 1.1 Relationship between total costs of production and proportion of grazed grass in the diary cow's diet (from Dillon *et al*. 2005).

Dairying has a long history in Ireland, with domesticated cattle being imported into the island more than 4,000 years ago (Evans, 1954). About 90% of the agricultural land is used for grassland, of which most is long-term pasture. Nowadays, there are fewer than

19,000 dairy farmers, which is half the number that existed 15 years ago. According to the National Farm Survey statistics (NFS, 2010), current average herd size is 57 cows on 30 effective ha, *i.e.*, 1.9 cows/ha. About 80% of exported Irish dairy products go to United Kingdom and mainland Europe, of this 60% is butter (DAFF, 2010). Most dairy farms in Ireland consist of seasonal, spring-calving systems within a relatively long grazing season (more than 240 days) and a predominantly grazed-grass diet (Dillon *et al.*, 1995a). There is potential to produce between 11 and 16 tonnes grass dry matter (DM) per ha over a long growing season (Brereton, 1995; Läpple *et al.*, 2012) which provides Irish dairy producers with a competitive advantage over most European countries (Figure 1.2).

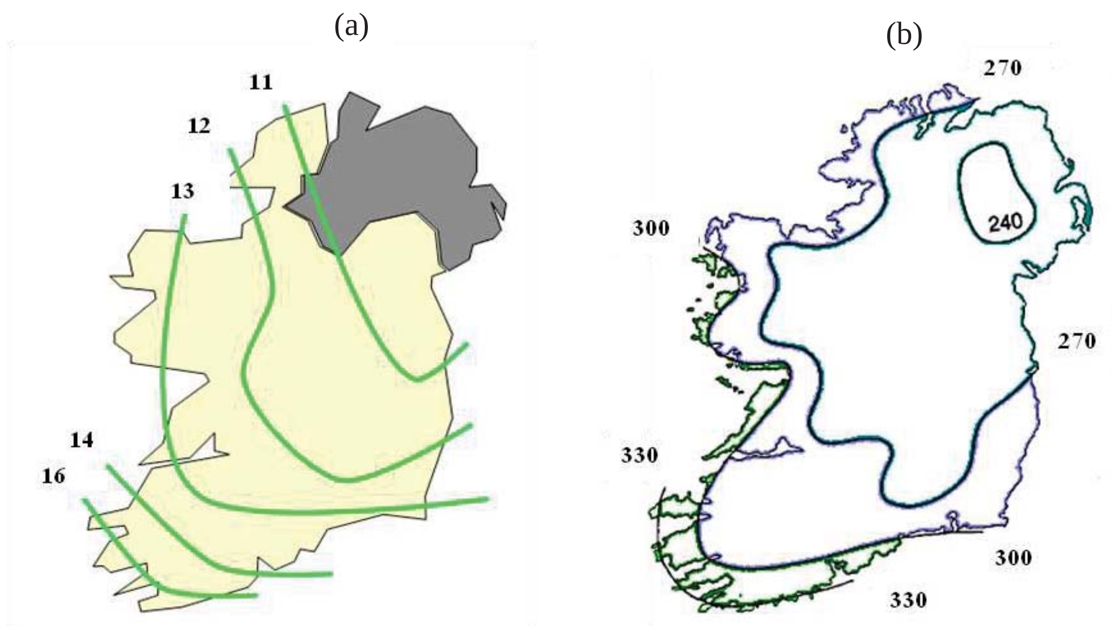


Figure 1.2 (a) Lines connecting points of similar potential for herbage production in annual dry matter grass production (tonnes/hectare) and (b) potential lengths of grazing season in days (adapted from Brereton, 1995).

Effective grazing management can help Irish dairy farmers increase the proportion of grazed grass in the diet of their cows thereby increasing the chances of becoming world leaders in the export market. However, a number of grazing management practices need to be put into place first. For the last 25 years, efficiency levels of dairy farms in Ireland have been a concern (Creighton *et al.*, 2011). This is mainly due to the imposition of a quota system for milk production that was added in 1984 to the dairy policy of the European Union (EU), which was already characterised by import tariffs, export subsidies and intervention buying. Milk quotas tend to slow down structural change and introduce inefficiencies (Huettel and Jongeneel, 2011; VanBerkum and Helmin, 2006). In effect, the quota system led to lower production and utilisation of home-grown feed on Irish dairy farms, as farmers were motivated to increase milk production per cow instead of production per ha. This change was accompanied with, and probably partially responsible for, a decline in dairy cow numbers from 1.65 million in 1984 to 1.04 million in 2007 (Shalloo *et al.*, 2007).

Nevertheless, the EU milk policy is due to change radically in 2015 with the abolition of milk quotas (French and Shalloo, 2010). This will allow production to move to areas of competitive advantage, *i.e.*, grass-producing countries, such as Denmark, Ireland and the Netherlands (Lips and Rieder, 2005). This change will lead to a 'freer' market environment, providing an opportunity for Irish farmers to grow their business, although this will be associated with more price volatility, resulting in increases in the cost of silage production, home produced cereals and imported feedstuffs (French and Shalloo, 2010). The 'Food Harvest 2020 Report' targets a 50% increase in milk output by 2020 in Ireland, adding that this will set the foundation for further expansion in subsequent years (DAFF, 2010). Horan and O'Donovan (2010) proposed that this can be capitalised through effective management of Ireland's competitive advantage which is grass.

Extending the grazing season to capture extra grass will improve profitability of Irish dairy farms. It must be done in a way that allows for effective interaction between the animals and the sward, that is, an efficient management of the timing and intensity of grazing. Grazing severity must be sufficiently high to avoid wasting grass, through increased number of animals per unit of area, while ensuring adequate individual grass DM intakes for production, reproduction and longevity but also competition for intake between animals to maintain sward quality. Grassland management concerns are further compounded by treading damage, which is associated with earlier turnout to pastures, an increased stocking rate (SR) and extended grazing in autumn.

The main objectives of this thesis were to investigate the effects of post-grazing sward height, treading damage, re-growth interval and pre-grazing herbage mass (HM) on the sward, and the impact of pre-grazing HM on cow performance. More specifically, these objectives were achieved by:

1. Examining the effects of level of post-grazing sward height on sward structure, morphology and production, on tiller density and on grass utilisation in a dairy grazing study;
2. Investigating the effects of cow treading damage on temperate swards under different soils, seasons, frequencies, grass species and levels of damage;
3. Exploring the effects of 2-, 3- and 4-week re-growth intervals on perennial ryegrass (PRG) swards during the main grazing season, under a cutting regime;
4. Studying the effects of different levels of pre-grazing HM on tissue turnover, sward structure and morphology[1], tiller density, and herbage accumulation and utilisation, under dairy grazing conditions during the main grazing season in Ireland;
5. Quantifying the impact of three levels of pre-grazing HM on milksolids (MS) production, grass DM intake and grazing behaviour of dairy cows during the main grazing season.

Thesis approach and structure

This thesis provides science background that dairy farmers can use to increase grazing management efficiency. This work aims to support grass-based dairy farms by providing evidence that can help dairy farmers make effective decisions that would lead to increased profitability of their farm businesses. The thesis is presented in eight chapters. The chapters have been prepared for publication meeting the usual requirements of in-depth literature reviews on each specific topic. Therefore, in order to avoid repetition, the literature review is not as in depth but aims to set the scene for the upcoming chapters. This introductory chapter is followed by a review of the literature on how to improve the management of PRG swards for dairy production (Chapter 2).

A relatively low SR, as is the case in Ireland, equates with a focus on per-cow production. This means, grass is wasted due to cows leaving high post-grazing sward residuals. In contrast, higher SR is associated with a focus on per-ha production and

[1] In this thesis, sward structure variables are extended tiller and sheath heights; sward morphology variables are the proportion of leaf, stem and dead components.

higher levels of pasture utilisation, due to the cows grazing more intensively, that is, leaving shorter post-grazing residual sward heights. Irish dairy farmers are increasing SR and this will impact on sward production parameters. The objective of Chapter 3 was to investigate the effects of three levels of post-grazing sward heights on sward structure, morphology and quality, tiller density and herbage accumulated and harvested during an entire grazing season. Increasing the length of the grazing season to optimise the proportion of grazed grass in the diet of the herd results in cows grazing during times when soils are usually wet, such as early spring and late autumn. There is no recent information available on the effects of treading in Ireland on herbage production and tiller density. The objective of Chapter 4 was to quantify the impact of cow treading damage on temperate swards, under different grass species, seasons, frequencies, soil types and levels of damage.

As intensity of grazing increases, there is a risk of re-growth intervals becoming too short. It is, however, not clear what the adequate grazing interval is to achieve adequate levels of sward production at different times of the year. The objective of Chapter 5 was to examine the effects of three re-growth intervals under a cutting regime, on production, sward parameters and tissue turnover of a PRG sward, during the main grazing season. There is a need to incorporate the animal effect into the sward growth to study the effects of re-growth intervals for optimum sward productivity. The objective of Chapter 6 was to repeat the experiment examining re-growth intervals on plots, but this time under grazing conditions, using three herds of cows for the main grazing season.

Different swards result from different management practices and this has a subsequent effect on animal performance. In intensive grazing systems, rapid changes in sward conditions can affect how plant and animal factors influence production. An experiment profiling the effects of pre-grazing HM on milk output and grass production was necessary to provide guidelines to Irish farmers. The objective of Chapter 7 was to investigate the effects of different levels of pre-grazing HM on cow MS production, grazing behaviour and grass DM intake during a main grazing season. The final chapter (Chapter 8) presents a summary of the main findings, discusses their implications with particular emphasis on the Irish dairy system and suggests areas for possible future work.

Chapter 2: Improving grazing management on perennial ryegrass swards for dairying in Ireland: a review

2.1 Abstract

The imminent abolition of quotas planned by the European Union for 2015 is an opportunity for the Irish dairy industry to expand using its competitive advantage which is grass. Irish dairy farmers will be focusing on improving the efficiency of their grass-based dairy systems. Within the search for best management practices, this review of the literature had the objective of exploring the principles of grazing management. A revision of the main features of the grass-based system of Ireland and how swards dominated by perennial ryegrass are incorporated into this type of system is developed. Grazing management factors that influence the ability of the system to convert grass into milk are explored: post-grazing sward height, treading damage, re-growth interval and pre-grazing herbage mass.

This review provides justification to investigate the following research questions:

1. What are the effects of post-grazing sward height under modern grazing practices in Ireland over a whole grazing season?
2. What are the actual losses in herbage production after treading damage under different scenarios in Ireland?
3. What are the effects of re-growth interval under a cutting or grazing regime over the main grazing season in Ireland?
4. What effects does pre-grazing herbage mass have on the interaction between the sward and the animal and how does this translate into animal performance?

2.2 Introduction

Only 10% of the dairy cows of the world produce milk on grazing systems (Steinfeld and Maki-Hokonen, 1995). The grass-based dairy farm is a complex biological eco-system in which pastures and cows are integrated to achieve profitability. As Leaver (1985) explained, it is difficult to make changes to one component without producing effects on the ecosystem that may be short- or long-term. In contrast to cows in confined systems, grazing cows interact with the plants through grazing activity, *i.e.*, they must be able to harvest their feed by themselves, which is limited by time, management and the grazing activity itself. This relationship must be balanced; plants must resist grazing to survive, grow and reproduce, and cows must be able to achieve intakes that are sufficiently high to allow them to meet their nutritional requirements for maintenance and production. The system must adapt to the constraints of the environment and remain sustainable. Soils and climate have significant impact, particularly on the sward, in this type of system which is characterised by change. To have a grass-based system in place, the role of the grazing animal, the influence of environmental variables and the dynamics of plant and herbage growth must be understood by the manager (Hodgson, 1985). Managing a successful grass-based farm is challenging and requires a set of skills and careful monitoring of many factors simultaneously in order to maintain a balanced, profitable and sustainable business (Dillon *et al.*, 2007).

Farmers must be able to strike a balance between pastures and cows to achieve sustainable and efficient conversion of feed into milk (Holmes and Roche, 2007). The effective match between feed demand and feed supply determines, to a great extent, the success of the system. Feed demand per hectare (ha) is mainly influenced by stocking rate (SR), genetic potential of the cows and calving and dry-off dates (Holmes and MacMillan, 1982; Holmes *et al.*, 2002). Feed supply, in turn, depends on temperature, rainfall, irrigation, fertilisation, grazing management and pasture species, and on supplementary feed imported into the system. In addition, the grazing system requires a type of cow that is adapted to the constraints of the grazing environment (Bryant *et al.*, 2005; Horan *et al.*, 2005; Lopez-Villalobos *et al.*, 2000).

While Irish farmers are now trying to increase the proportion of grazed grass in the diet of their cows, dairy farmers in New Zealand have been focusing on making the best use of their pastures for decades. Similar to the Irish, New Zealanders have the competitive advantage that they can graze their cows for most of the year (Holmes, 1990). In both countries, most of the milk produced is sold in a processed rather than liquid form, due to the small internal market for liquid and, in the case of New Zealand, large distances from other countries (Bryant, 1993). However, in New Zealand, high transport costs and absence of government subsidies (Camoens, 1993) mean a low return for the milk relative to those countries in more populated regions of Europe and United States (Hurley, 1995). Furthermore, New Zealand farmers do not have access to cheap grain or large quantities of by-products like farmers in Australia, Europe and United States. Therefore, New Zealand farmers have been forced to improve grass utilisation by using animals that are adequate for those requirements, *i.e.*, can graze, produce high proportion of milk solids, and can produce a calf every 365 days. As a result, they have developed a competitive advantage in the management of pastoral systems (Porter, 1990). Thus, in other areas of the world in which pasture can be produced in quantity and quality, such as is the case of Ireland, similar principles and practices of efficient pasture utilisation can be applied.

To manage a profitable grass-based dairy system, a set of decisions must be made on a daily, weekly, monthly and yearly basis. Once the system is in place, what the manager can control are the rules of his business that will allow for an optimisation of the resources and, ultimately, a profitable, sustainable system. This thesis explores farmers' decisions that can impact on the production and utilisation of grass, the maintenance of a high-quality sward and the avoidance of excessive damage to the soil and pastures when the herd is out grazing. These management factors are key to the success of the post-European Union (EU) quota grass-based dairy system in Ireland. Figure 2.1 illustrates the conceptual framework of this literature review.

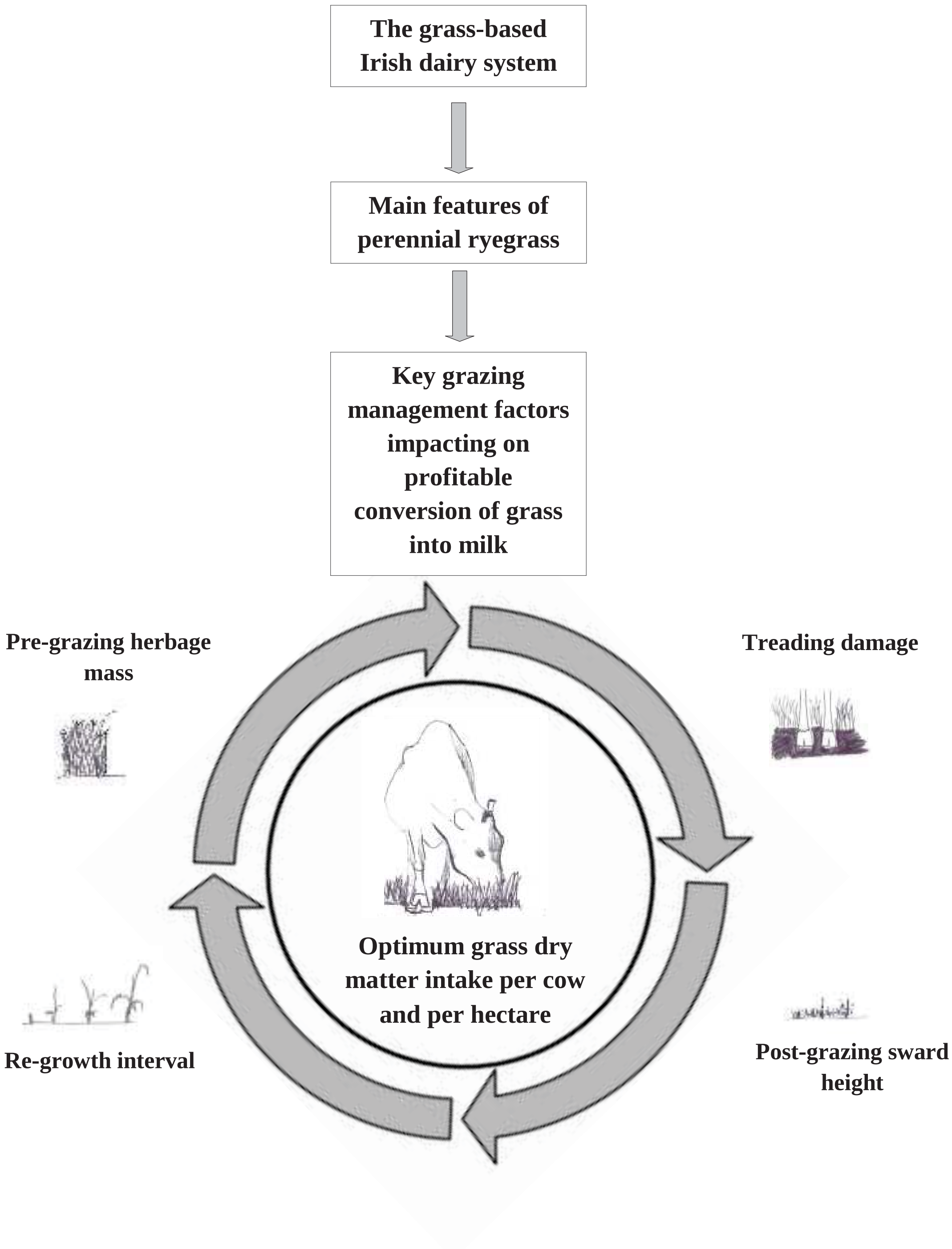


Figure 2.1 Conceptual framework of the literature review subsequently developed in the thesis.

2.3 Main features of the Irish grass-based dairy farm

2.3.1 Environmental conditions

Ireland is located between 50°N and 57°N latitude. An annual mean rainfall of 750 to 1,200 mm (O'Reilly, 1992) and a temperate, humid climate, as well as proximity to the Atlantic Ocean, the Gulf stream and the prevailing westerly wind, all make up the ideal conditions for grass production. Figure 2.2 shows the average daily temperature and rainfall at Teagasc, Moorepark, Animal and Grassland Research and Innovation Centre, Fermoy, Co. Cork in the south of Ireland (latitude 52°09'N, longitude 08°16'W), where most of the work presented in this thesis was undertaken.

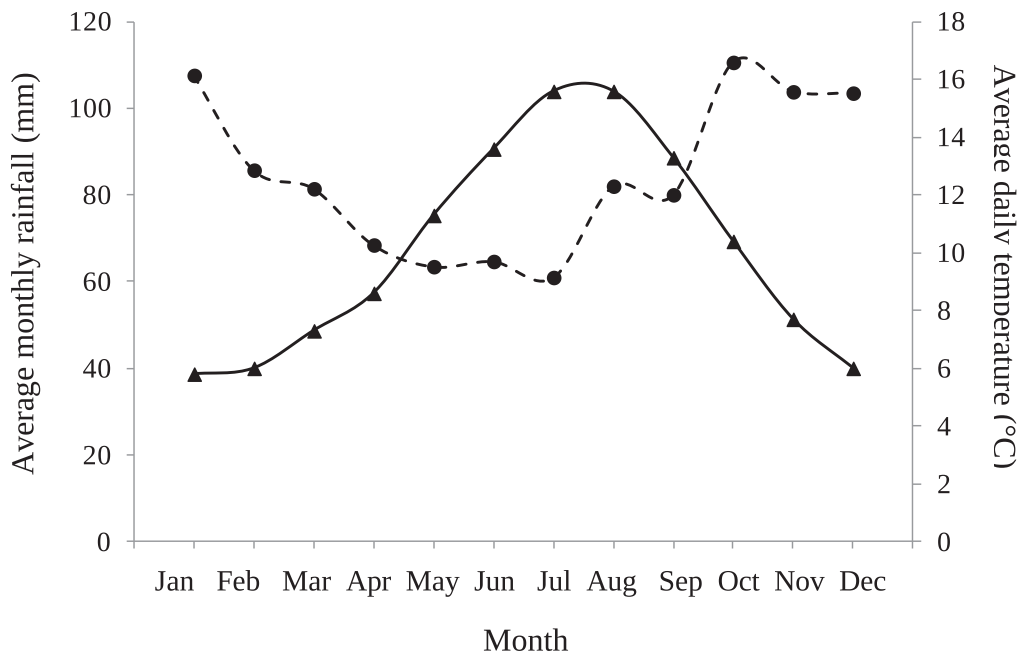


Figure 2.2 Average daily temperature (°C ▲) and monthly rainfall (mm ●) at Teagasc, Moorepark, Animal and Grassland Research and Innovation Centre, Fermoy, Co. Cork, Ireland.

More than 60% of the total agricultural area of Ireland is covered by dry lowland mineral soil, this corresponding to south, midlands and east, where most dairy farms are located. The rest of the area is divided into 20% moderately-wet mineral soils and about 17% wet impermeable mineral soils (Coulter *et al.*, 1996). A descriptive map of the soils in Ireland is included in Appendix 1.

Keane (1992) defined the growing season as the period when air and soil temperatures consistently exceed the minimum value associated with the growth of a particular crop. As it can be seen in Figure 2.3, the grass-growing season in Ireland can fluctuate between 270 and 349 days because it is mainly determined by temperature (O'Donovan *et al.*, 2010). Mean daily air temperature ranges from 4°C in January to 14-16°C in July and August (Keane 1992). In spring, when soil temperature increases up to 15°C and air temperature is between 18 and 24°C, the grass-growing season is optimum (Frame, 1992). The growing season concludes in autumn, when air temperature falls below 8°C (Brereton *et al.*, 1985). Figure 2.3 represents the grass-growth curve of three consecutive years from Moorepark Research Station. In general, grass growth rate increases in May to about 90 kg dry matter (DM)/ha/day, decreases at the time of flowering, increases again in late summer, and then decreases again in the autumn, to reach a minimum during the winter (Brereton, 1992).

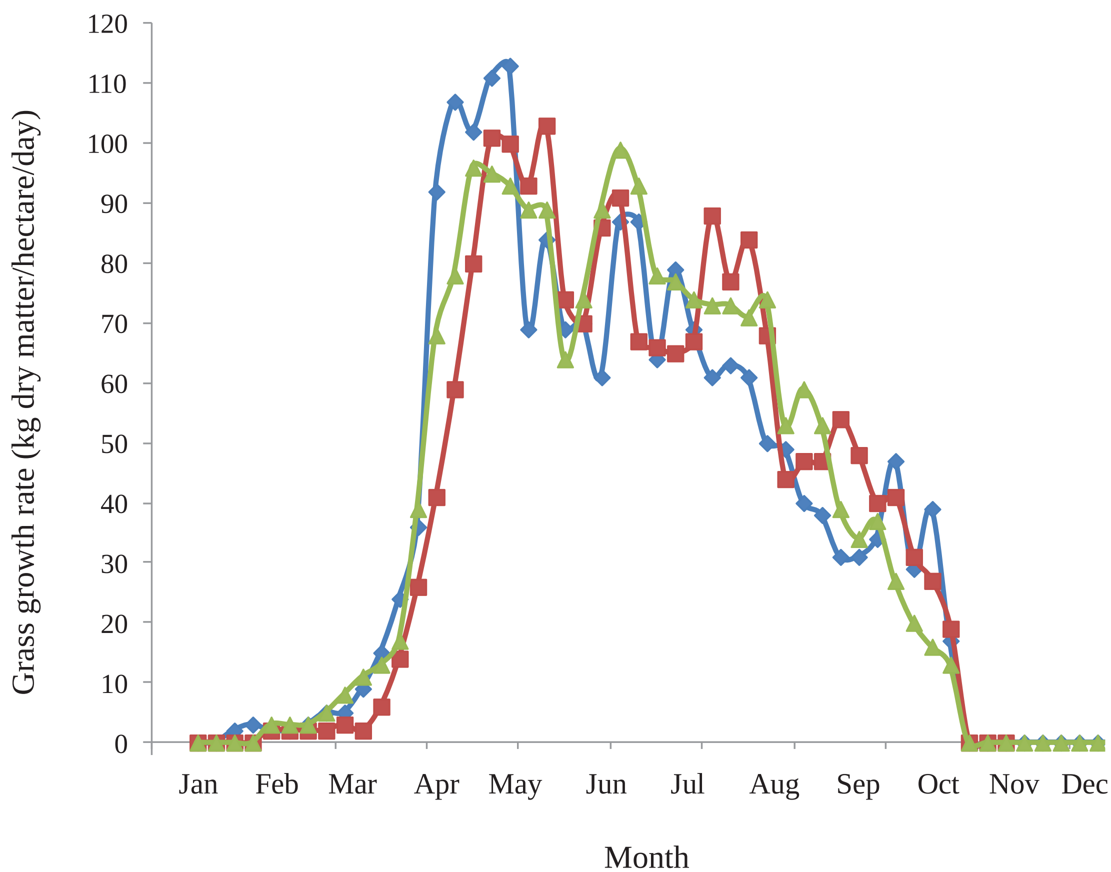


Figure 2.3 Average grass growth rates for 2009, 2010 and 2011 at the Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland (▲ 2009 ■ 2010 ◆ 2011; from http://www.agresearch.teagasc.ie/moorepark/grassgrowth).

In this thesis, seasons are defined as early spring (1 February to 15 April), mid-season (16 April to 1 August), autumn (2 August to 1 November) and winter (2 November to 31 January). Before going further, it is important to clarify that the definition of herbage mass (HM) differs between countries. In New Zealand and Australia, HM is expressed as kg DM from ground level. In other places however, HM may be expressed as HM from 3.5 cm (Dillon *et al.*, 2002), 4 cm (Kennedy *et al.*, 2007b) or 5 cm above ground level (Delaby *et al.*, 2001). The methodology used in Ireland considers that HM below the measurement horizon changes throughout the season due to accumulation of stem and dead material. For instance, Tuñon *et al.* (2010b) working with Irish perennial ryegrass (PRG; *Lolium perenne* L.) swards over a year, estimated a mean of 2,376 kg DM/ha for pre-grazing HM below 3.5 cm, with a range going from 1,618 to 3,134 kg DM/ha. Likewise, other experiments in Ireland and France, also using PRG swards, reported 2,200 to 3,700 kg DM/ha <4 to 5 cm (Delagarde *et al.*, 1997; Kennedy *et al.*, 2007c; Ribeiro *et al.*, 2005). The method used in Ireland, therefore, aims to take into account only the 'grazeable' horizon, minimising errors at the time of estimating herbage allowances. This is a critical consideration, since, throughout this thesis, studies will be referred to that used either methodologies to estimate pre-grazing HM.

2.3.2 The match between grass supply and feed demand

Balancing the rate of the herbage growth, varying seasonally with herbage consumption and varying with animal productivity is the essence of grassland management to maximise the proportion of grazed grass in the diet of the cow (Hodgson, 1990). In other words, the grass-based production system aims to achieve a close-as-possible match between the pasture growth curve and the curve of DM requirements of the herd, *i.e.*, feed demand and feed supply (Dillon *et al.*, 1995a). However, both curves are far from perfectly matching. Generally, in early spring, the grass supply in Ireland is not sufficient to meet the requirements of the spring calving herd. As spring progresses, there is a subsequent peak in pasture growth rates, which is associated with the onset of reproductive growth, increasing temperatures and high soil moisture availability.

This results in a surplus of pasture production in relation to animal requirements. Managing the large peak in grass growth in the May-to-June period is probably the greatest challenge to increasing the efficiency of herbage utilisation in Ireland (Dale *et al.*, 2008). Likewise, pasture surpluses may also occur during the autumn, coupled with decreased animal demand in late season. In contrast, pasture growth rates over the summer frequently fall below stock requirements and, in winter, due to low temperatures, growth rates may not be sufficient for the daily feed requirements of the animals (Hennessy *et al.*, 2006). Therefore, supplementary feeds, including silage harvested from surplus grass, are used to fill periods when pasture supply is below animal demand (Holmes *et al.*, 2002). The availability of herbage can be increased through the use of nitrogen (N). Managing application rates helps improving the curve of feed supply (Cowling and Lockyer, 1970). For instance, N application can be used to enhance grass growth during early spring (O'Donovan *et al.*, 2002b) thereby capturing the benefits of early grazing during the season (Kennedy *et al.*, 2007b).

The key to success of the grass-based system relies, to a great extent, on the farmer's ability to achieve synchrony between the curve of grass growth and the curve of herd requirements. These curves can be manipulated by animal factors such as SR, mean calving date of the herd and by sward factors such as use of pasture species, fertilisation and irrigation. Figure 2.4 illustrates a hypothetical curve of grass growth, matched with two levels of demand which are the result of different SRs.

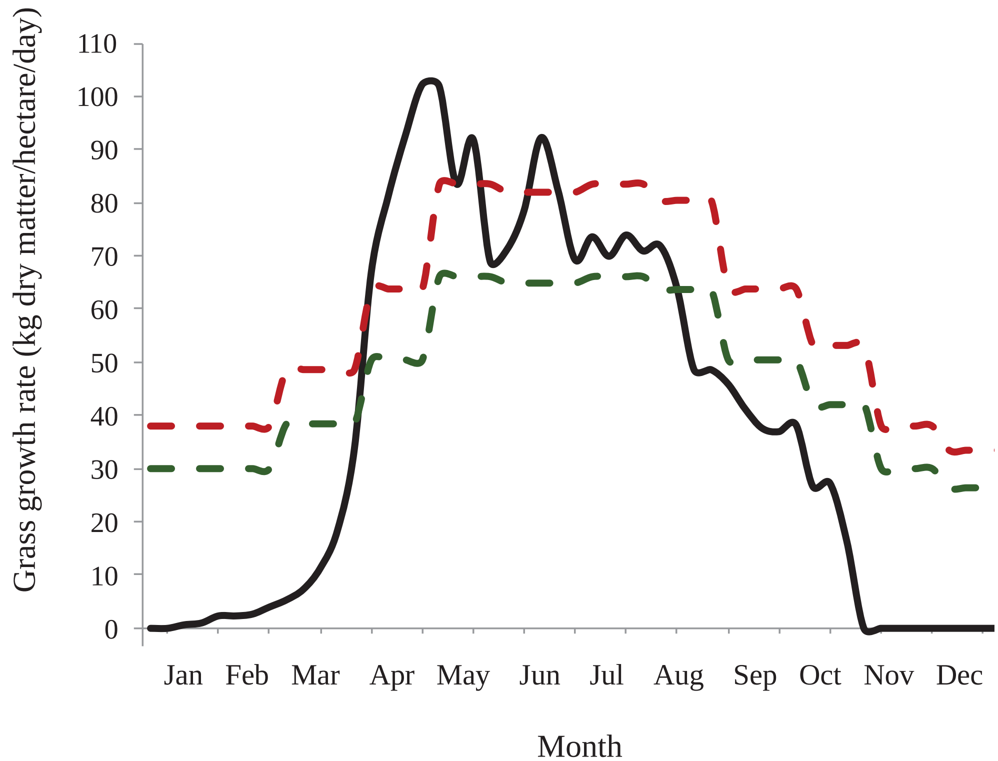


Figure 2.4 Average grass growth rate of three years of Figure 2.3 (—) and herd dry matter requirements from two hypothetical stocking rates (_ _ 3 and _ _ 3.3 cows per hectare).

2.3.2.1 Stocking rate and calving date

Stocking rate, traditionally expressed as cows per ha, is widely recognised as the major factor governing productivity from grass, as stated by McMeekan (1961). The optimum SR is that which maintains a balance between the quantities of quality feed grown on farm and the feed requirements of the herd. In Ireland, there is significant scope for improvement, since current mean SR is around 1.9 cows/ha (Creighton *et al.*, 2011). In effect, recommended SR for the average Irish dairy farm is 2.9 cows/ha (Horan and O'Donovan, 2010). Cows at a low SR select herbage of higher quality than cows at a higher SR (O'Donovan and Delaby, 2005) allowing for increased production per cow. An increase in SR of one cow per ha will result in an increase in milk production per hectare of 20% (Baudracco *et al.*, 2010; McCarthy *et al.*, 2011). Ultimately, a compromise exists between achieving high pasture utilisation through high grazing intensity, associated with some underfeeding of the herd or, conversely, low relative pasture utilisation with better-fed cows.

Increasing the SR has evident effects on the sward. The findings reported in the literature, however, have been conflicting. For example, McFeely and McCarthy (1979) showed that herbage accumulation was reduced by 9 to 12% when SR was increased. Macdonald *et al.* (2008), conversely, reported increased pasture production from increases in SR. Stocking rate also has an effect on sward quality through the level of post-grazing residuals, which may lead to improved sward quality (Michell and Fulkerson, 1987). In addition, increased SR can lead to many changes in soil and plant properties (Drewry *et al.*, 2008) including increased bulk density, reduced macroporosity, changed soil fauna, decreased N fixation, soil surface disturbance leading to tiller and stolon death, and plant burial with long-term effects on DM yield and subsequent weed invasion. Increased SR also results in more urine and dung patches which can have an impact on the environment (Clark, 2011).

To capture the greatest benefit from optimum SR, mean calving date of the herd must be targeted to coincide with the curve of grass growth (García *et al.*, 2000). Calving date is another powerful tool to maximise the use of grass, increase sward quality and decrease dependence on other feeds. Mean calving date determines when the peak requirements fall, making this event another key factor influencing grass utilisation. In Ireland, an increase in the length of the grazing season requires an earlier start of calving than has traditionally been the case. Each day that cows are out grazing means an increase in the profitability of the dairy farm business (O'Donovan and Kennedy, 2009). On the other hand, a relatively early start of calving means that there is a risk of damage to the soils, in particular when ground is soft during wet times. When the appropriate mean calving date is applied along with the optimum SR, this results in high all-season levels of milk production from grazed grass with minimal use of supplements (Clark *et al.*, 2009). In Ireland, optimum mean calving date may be 15 to 25 February, with 90% of the animals calving in 42 days (Horan and O'Donovan, 2010). This illustrates the room for improvement that exists because current mean calving date is 15 March (*i.e.*, three to four weeks later).

2.3.3 Feed budgeting and seasonal management

Budgeting the amount of grass that will be available in each period of the year enables the manager to match the feed required by the herd over a given period to the feed available. This allows for optimum use of grass and increased profitability (Milligan *et al.*, 1987). Budgeting can be annual, intermediate and short term. The annual feed budget requires an understanding of herbage availability, animal responses to changing daily herbage allowance (DHA) and sward conditions for optimum intake and performance. Daily herbage allowance, expressed in kg DM/cow/day is the quantity of herbage allotted to the animal for a period of 24 hours (Greenhalgh *et al.*, 1966) and has an influence on herbage intake (Mayne and Laidlaw, 1999). As DHA increases, herbage intake will also increase although at a declining rate (Combellas and Hodgson, 1979). Generally, as DHA increases the milk response to extra herbage decreases (Delaby *et al.*, 2001). This, therefore, dictates decisions on SR, calving date, drying-off date and the conservation and supplementation strategies. The intermediate feed budget involves targets for grazing and conservation. These estimations depend on the number of animals. For example, for a spring-calving herd at 2.5 cows/ha, the four critical levels of pasture cover (above 4 cm) are more or less: i) the autumn closing cover (560 kg DM/ha), ii) the spring opening cover (798 kg DM/ha), iii) the cover at the end of the first grazing rotation (568 kg DM/ha), and iv) the farm cover during the main grazing season (806 kg DM/ha) (Stakelum and O'Donovan, 1998; Teagasc, 2009). Nonetheless, the main objective in each of the seasons within the production season is to maximise the proportion of grazed grass in the diet of the cow.

2.3.3.1 Early spring

A major objective for the first grazing rotation is to achieve high grass utilisation plus an effective inclusion of supplements. Pasture management in early season (February/March) conditions the swards that are being grazed for subsequent grazing rotations (Hennessy and Kennedy, 2010; O'Donovan *et al.*, 2004). Another major focus of this time of the year is maintaining the growth of vegetative tillers and minimising that of reproductive tillers. That is why spring management of pasture has a great influence on subsequent sward composition, sward quality and herbage production throughout the main grazing season (Korte *et al.*, 1982; L'Huillier, 1987; Matthew *et al.*, 1989; O'Donovan and Delaby, 2005). A severe grazing regime in spring can increase leaf proportion in the sward (Holmes *et al.*, 1992), enhancing herbage quality for the subsequent grazing rotations (Kennedy *et al.*, 2007c) and leading to increased milk production (Michell and Fulkerson, 1987). The farmer can use 'the spring rotation planner' which allows him to budget the available grazing area until the end of the first grazing rotation (usually 7 April in Ireland, the 'magic day', when grass growth equals grass demand; O'Donovan *et al.*, 2011a).

2.3.3.2 Mid-season

The main objective during this part of the grazing season is to optimise cow performance on an only-grass diet. Mid-season management is focused on controlling grass supply using another tool named 'the grass wedge'. This is a method used to interpret the data collected during farm walks that was developed in New Zealand by A. Bryant and T. Phillips in 1976 (Unpublished). It provides a graph of the amount of grass available in each paddock (kg DM/ha), from highest to lowest paddock (Appendix 2). The use of the grass wedge becomes critical during the time of rapid growth, so it is recommended to do a farm walk at least once a week, to keep updating it (O'Donovan *et al.*, 2011a).

2.3.3.3 Autumn and winter

Autumn management has a direct impact on the amount of grass available for early-spring grazing (O'Donovan *et al.*, 2002b). O'Donovan *et al.* (2011a) identified two main objectives for this season. The first is to keep focusing on maximising the grass DM intake; the second is to finish the grazing season with the desired farm cover. In order to build farm cover, rotation length may be increased from 24 days in mid August to 40 days in mid September. As a general rule, depending on location, the first paddock should be closed on 15 October. This allows grass to be stored *in situ* in late autumn and winter for either winter grazing or early-spring grazing (Hennessy *et al.*, 2006). The final grazing rotation should commence 10 October, with every paddock grazed afterwards being closed (O'Donovan *et al.*, 2011a). An effective grass-based system would not need more than 1.2 tonnes of silage DM per cow over the winter period, according to the Moorepark blueprint for spring milk production (Kennedy *et al.*, 2007a). A risk of losses in DM yield due to treading damage exists in this period, as well as in spring, particularly at times of inclement weather.

Finally, the short-term grass budgeting monitors DHA and grazing severity (Butler *et al.*, 2003), monitoring milk production levels and making sure levels of pre-grazing HM are adequate to achieve target DHA (Stakelum and O'Donovan, 1998). It also involves assessment of post-grazing sward height to have an idea of herd DM intake and levels of herbage utilisation, which impacts on sward quality throughout the grazing season.

2.3.3.4 Conservation strategy and supplementation

Any grass surplus is harvested as silage and deficits are corrected by strategic supplementation or inclusion of grazeable silage paddocks in the grazing area (O'Donovan *et al.*, 2002b). The use of supplements during periods of feed deficit can result in cows expressing more of their potential for milk yield during early lactation and also reduce excessive losses in live weight (Delaby *et al.*, 2001). However, grass DM intake is usually reduced when supplements are consumed, meaning that the animals leave some of the grass uneaten because they prefer the other feed. This effect is called substitution. Substitution rate increases as DHA increases (Meijs and Hoekstra, 1984). Bargo *et al.* (2003) calculated the rate of substitution as: (pasture DM intake in non-supplemented treatment − pasture DM intake in supplemented treatment)/supplement DM intake.

2.4 Perennial ryegrass for dairying in Ireland

Perennial ryegrass is the main forage grass species sown in northwest Europe, New Zealand, and in other temperate regions, such as Japan, Australia, South Africa and South America (Humphreys *et al.*, 2010; Kemp *et al.*, 2000), providing the major supply of nutrients for grazing cows. This grass species is sufficiently important to have been heavily researched. For example the reviews of PRG growth and dynamics by Chapman and Lemaire (1993) and Richards (1993). In this section, a description of the morphology, growth and tiller dynamics of the PRG plant is provided.

The PRG plant is compact with dark green leaves that can form many leafy tillers and, consequently, a dense sward. It is a winter-active grass with a flush of production in early spring (McKenzie *et al.*, 1999). The root system is shallow, the ligule is short and not easily seen and leaf lamina can be up to 7-mm wide and 450-mm long (Lamp *et al.*, 1990). This grass species needs a fertile soil of heavy texture, plus adequate rainfall or irrigation for optimum production and persistency (Lamp *et al.*, 1990). Depending on soil fertility and on environmental conditions, annual herbage accumulation of PRG can range from 10 to 25 t DM/ha, while digestibility is typically 75 to 85% (Kemp *et al.*, 2000). Digestibility is very much influenced by the stage of growth (Stakelum and Dillon, 1990) and decreases from the top to the base of the sward (Delagarde *et al.*, 2000). Quality and quantity of grass are inversely related. For example, Waghorn and Barry (1987) reported 12 mega joules (MJ) of metabolisable energy (ME) of 1 kg DM of pasture two weeks after defoliation. The ME content dropped to 8.9 MJ after eight weeks. The effect of re-growth interval on sward characteristics will be further developed later in the review. Table 2.1 describes the composition as percentage of the DM and digestibility of PRG at four stages of maturity. The information from Table 2.1 helps understand why it is so important to try to maintain a high proportion of leaf in the sward. It can be seen that digestibility, protein and non-structural carbohydrates decrease with time, leading to reduced nutritive value of the sward.

Table 2.1 Composition (% of dry matter) and digestibility of perennial ryegrass at four stages of maturity (adapted from Waghorn and Barry, 1987).

	Young leaf	Mature leaf	Head emergence	Seed setting
Non-structural carbohydrates	14	12	11	10
Organic acids	4	5	5	3
Protein	15	12	11	6
Non-protein nitrogen	4	4	3	3
Pectin	2	2	2	2
NDF[1]	40	45	47	60
ADF[2]	24	26	28	34
Lignin	3	4	4	7
Ash	8	8	7	6
Lipid	9	8	7	5
Digestibility of dry matter	86	83	79	62

[1] Neutral-detergent fibre (cellulose + hemicelluloses + lignin).
[2] Acid-detergent fibre (cellulose + lignin).

Perennial ryegrass can be easily incorporated into grazing systems, giving it a major advantage over many other grass species. It is easy to establish and can rapidly adjust tiller population in relation to grazing management (Bircham and Hodgson, 1983). Relative to most other grass species, PRG is extremely tolerant of treading damage and hard grazing due to its vigorous tillering and rapid leaf production (Table 2.2). This confers adaptability to this grass species when subjected to contrasting defoliation managements (Chapman and Lemaire, 1993). Persistence of PRG ranges from five to 20 years. However, it has limitations, such as an ever changing nutritive value, low tolerance to drought (Garwood *et al.*, 1979), an excessive supply of N relative to soluble carbohydrates in spring and autumn, and lower nutritive value in the summer (Kemp *et al.*, 2000).

Table 2.2 A general ranking of the treading tolerance of pasture species, with some of the reasons for the ranking shown in the right column (from Kemp *et al.*, 2000).

Most tolerant	
Perennial ryegrass	○ low growing point
	○ prostrate tiller bases
Tall fescue	○ fibrous leaves
Italian ryegrass	
Poa annua	○ invades bare patches
	○ prolific seed production
White clover	○ stolons with rooted nodes
	○ vegetative reproduction
Browntop	
Cocksfoot	○ prostrate forms most tolerant
Red clover	○ high growing point
Yorkshire fog	○ soft weak leaves
Prairie grass	○ brittle and few tillers
Least tolerant	

2.4.1 Morphology and growth

The grass sward is a collection of individual plants. Management practices are applied at the sward level. It is therefore important to understand the morphology and growth dynamics within a PRG sward, in order to make adequate and effective grazing management decisions. The PRG plant is made up of a collection of tillers that arise from a single primary tiller (Skinner and Nelson, 1994). The tillers, in turn, are composed of phytomers. Phytomers constitute the leaf blade and sheath, the internode, the node and the associated axillary bud below the point of sheath attachment (Briske, 1991; Figure 2.5). Morphology and growth rate are determined by the position and specific activity of the meristems. These are localised areas from where cell division occurs (Körner, 1991). They control where, how much and what sort of tissue is developed, determining the final size and shape of the plant. The meristems are usually inaccessible to grazing animals and are protected from damage because they are positioned at, or below, the soil surface (Chapman and Lemaire, 1993). This has important implications with regard to grazing management.

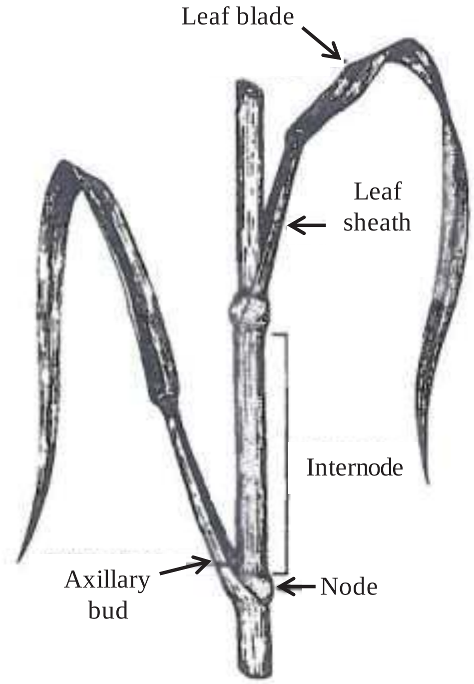


Figure 2.5 Illustration of the grass phytomer (from Silsbury, 1970).

Energy for growth is derived from photosynthesis. Photosynthesis is the process by which grass captures solar radiant energy and transforms it into chemical energy (carbohydrates) through chlorophyll and other pigments that are present in the chloroplasts (McKenzie *et al.*, 1999). Light energy goes through a series of reduction/oxidation reactions which split water into oxygen and hydrogen ions, and carbon dioxide and water are converted into carbohydrate after a complex series of chemical reactions. Carbohydrate reserves are mainly located in the stem (Richards, 1993). The shoot system supplies the plant with labile carbohydrates for root growth, respiration and nutrient absorption. Half of the carbohydrates produced in photosynthesis provide a source of energy to support the growth of new tissue in leaves, stems and roots and to maintain the life processes in established tissue (Hodgson, 1990).

Leaves are the primary photosynthetic organs. It has been estimated that growing and fully-expanded leaves contribute up to 77% of the net photosynthesis of the sward canopy, while sheaths contribute less than 5% (Parsons *et al.*, 1983ab). As age increases, the photosynthetic capacity of grass leaves declines (Woledge, 1971). Most of the light must be intercepted by photosynthetically-active leaf material throughout periods of active growth in order to achieve maximum accumulation of herbage over time (Chapman and Lemaire, 1993). Therefore, the efficiency of growth of a sward can be increased by increasing the amount of radiant energy that can be intercepted by green, active leaves. This can be achieved by managing pre-grazing HM, density of tillers and proportion of leaf in the sward in order to capture the maximum amount of solar radiation.

Growth of ryegrass occurs between 5 and 30°C of air temperature, with an optimum temperature for growth of 18 to 20°C (Mitchell, 1956). There are relatively simple changes during the growth of the PRG plant that cause variations in their morphology. Understanding these changes is vital for applying principles of effective grazing management. The plant has a genetically determined pattern of growth but the final plant form is ultimately a reflection of environmental factors (*i.e.* spatial and temporal constraints) affecting growth (Valentine and Matthew, 2000). Factors that influence grazing management such as growth stages, tissue turnover, leaf stage, tiller density are explained below.

2.4.1.1 Growth stages

The ontogeny of a PRG tiller can be divided into four growth periods: vegetative, elongation, reproductive and seed ripening (Moore *et al.*, 1991). The vegetative grass tiller (Figure 2.6 a) consists, as described above, of a chain of phytomers which are constantly developing in a sequenced fashion (Figure 2.6 d). This confers both protection of meristems from damage or loss by defoliation and a capacity for replacement of tillers that die (Valentine and Matthew, 2000). The tiller axis is wrapped around by the leaf bases forming the pseudo-stem, which also protects the meristem in the centre and holds the leaves up to the light, while conferring flexibility to bend and spring back after treading (Valentine and Matthew 1999). The true stem may branch and form tillers, apart from producing its own leaves (Figure 2.6 c). Tillers are buds that become externally visible above the subtending leaf sheath. Each leaf of the PRG tiller is attached through a node. During the vegetative growth period there is a successive appearance of leaves. The interval of time between the appearances of the leaves is relatively constant during this stage (Langer, 1979) although is highly influenced by temperature and photoperiod (Davies and Thomas, 1983). This stage is followed by elongation which is the period during which internodes elongate, and is considered a transition between the vegetative and the reproductive stages (Moore and Moser, 1995).

During reproductive development taking place in spring (Figure 2.6 b), the terminal meristem shows a characteristic change in development, producing an inflorescence and there is an increase in growth rate (Valentine and Matthew, 2000). Internodes begin to extend, exposing the stem apex to defoliation; this being removed, the remaining tiller stubs cannot grow and will ultimately lose weight and die (Davies, 1977; Jewiss, 1993). Most of the new tillers produced during the reproductive phase survive the winter, thereby playing an important role in the biology of the grass because they ensure perenniality, and they also form the majority of the tiller population in the following season (Lambert and Jewiss, 1970). These stages occur gradually, so a single plant could have vegetative and reproductive tillers present at the same time (Moore *et al.*, 1991).

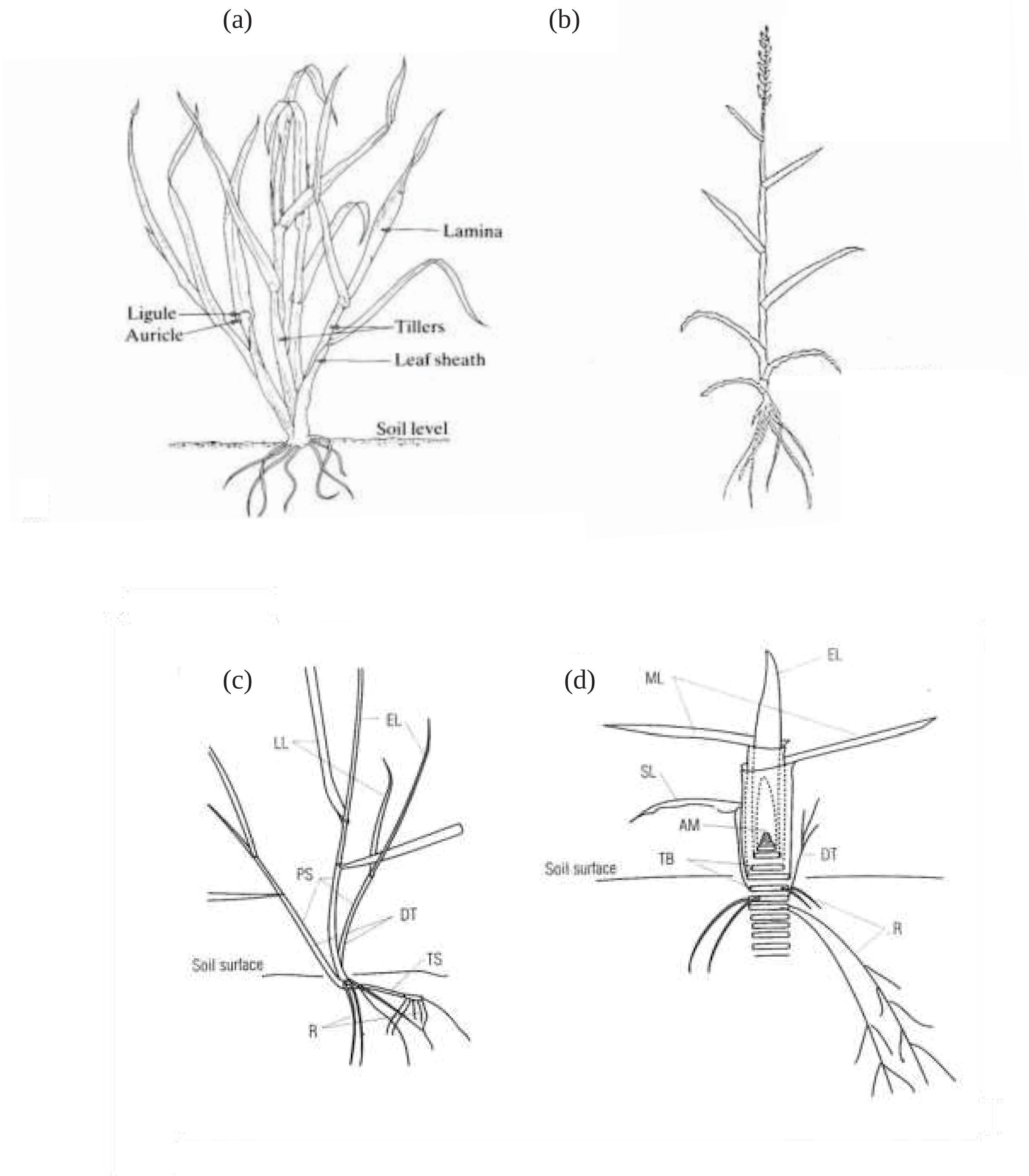


Figure 2.6 (a) Illustration of an established plant of perennial ryegrass with four tillers (from Hodgson, 1990); (b) the morphology of a temperate-region perennial ryegrass plant at the flowering stage (from Jewiss, 1972); (c) organs of the tiller that are visible externally and (d) arrangement of phytomers on the tiller axis. DT = daughter tiller, EL = elongating leaf, ML = mature leaf, SL = senescent leaf, LL = leaf lamina, PS = pseudo-stem composed of leaf sheaths, TS = true stem, AM = apical meristem, TB = axillary tiller bud, R = root (from Valentine and Matthew, 2000).

As mentioned previously, the apical meristem of vegetative grasses is inaccessible to grazing animals and protected from damage because it is positioned at, or below, the soil surface. Thus, even under repeated defoliation, new leaves can continue to be produced. However, the apical meristem is raised into the grazed horizons of the pasture at the onset of reproductive growth and stem elongation (Chapman and Lemaire, 1993), this being a critical point of management of PRG swards. The management of pasture to manipulate quality, composition and density, according to timing of reproductive growth, have previously been reported extensively (Brougham, 1961; Korte *et al.*, 1984). During the months of May and June, in the temperate regions of the Northern Hemisphere, when the PRG plant turns from vegetative to reproductive growth, there is a decrease in digestibility (Johnston *et al.*, 1993; Tallowin *et al.*, 1989). This, in turn, reduces herbage DM intake, milk yield and milk-protein concentration of dairy cows. For example, Peyraud *et al.* (1996) found that a 1% decline in herbage digestibility resulted in a reduction of grass DM intake by 0.2 kg and milk production by 1 kg. The developmental stages of plants within a sward can be managed. For example, an early turnout date allows for a better control of reproductive development in mid-season, thereby increasing leaf DM yield and decreasing stem yield (Carton *et al.*, 1989; Kennedy *et al.*, 2007c). Hence a key objective of grazing management is to maintain the sward at a vegetative stage, avoiding going to the reproductive stage.

2.4.1.2 Tissue turnover

Leaves are continuously produced in each individual grass tiller, each leaf having a period of active extension leading to maturity, and then to senescence and death, regardless of whether the leaf has been grazed or not (Hodgson, 1990). Davies (1993) named the movement of material through the system as tissue turnover. The new leaves emerge from the centre of the pseudo-stem and dying leaves are outside. While the tip of a new leaf emerges into the light, two events occur simultaneously, first the leaf that is attached below ceases elongation and, second, elongation of the next leaf primordium above begins.

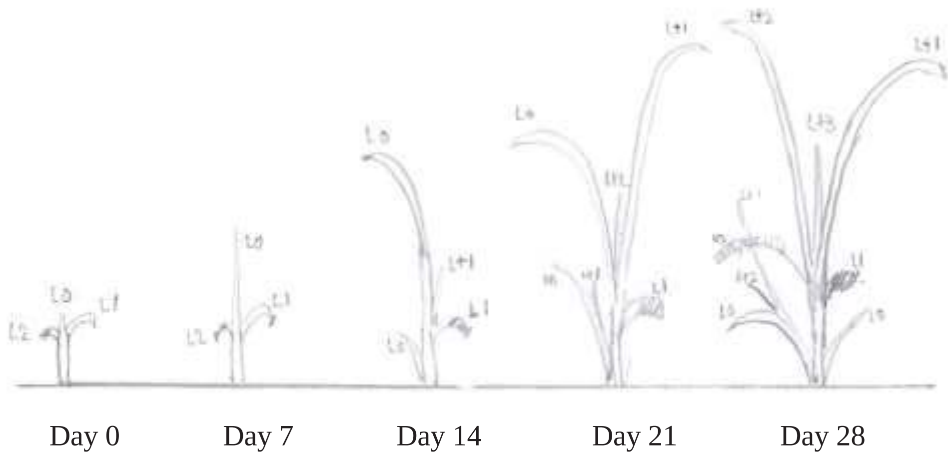


Figure 2.7 Re-growth of a perennial ryegrass tiller after defoliation.

The pattern of PRG growth is sigmoidal; the first leaf emerges slowly, followed by an exponential phase of rapid growth, a slower final phase following emergence of the third leaf and the onset of senescence. Figure 2.7 illustrates the re-growth of an individual PRG tiller during the vegetative stage. The days have been chosen arbitrarily as rate of re-growth of an individual tiller is highly dependent on environmental conditions and other factors. At day 0, the defoliation day, the youngest leaf is called L0, the second youngest leaf is L1, followed by L2 (eventually L3 and L4, depending on the defoliation severity). Each new leaf appearing during the re-growth period is thereafter called L+1, L+2, etc. Hence, following the progression of the figure, at day 7 there is no new leaf, although there is an extension of the two youngest leaves. By day 14, there is a new leaf (L+1) and the appearance of a secondary tiller (L0). By day 21, a second new leaf appears on the main tiller, while a new leaf appears on the secondary tiller as well. By day 28, a third new leaf appears in the main tiller, a second new leaf appears in the secondary tiller, while another secondary tiller is growing, and also dead matter is building up.

Thus, in a vegetative grass sward, when only leaves are produced, leaf appearance rate (LAR), leaf extension rate (LER) and leaf life span determine the amount of leaf present, thereby influencing light interception and re-growth dynamics (Chapman and

Lemaire, 1993). As mentioned previously, the environment has a major effect on these parameters. Temperature, radiation, soil moisture and mineral nutrition control LAR (Anslow, 1966). For example, in the North Island of New Zealand, LAR can vary from six to seven days in summer to more than 40 days in winter, the result being that each tiller produces around 40 leaves per year (Davies, 1977). In the Northern Hemisphere, LAR is also fastest in spring, with a new leaf every seven to ten days (Alberda and Sibma, 1968). Tissue turnover does not stop during winter, with leaves appearing continuously at a rate of one per four to five weeks (Davies, 1977). Table 2.3 shows LAR from two different studies in United Kingdom and Ireland.

Table 2.3 Comparison of the number of days for a new leaf to appear between two studies with marked tillers.

Country	Month												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Reference
United Kingdom	35.0	31.8	23.3	18.4	9.1	10.8	11.7	12.5	14.9	19.4	26.9	29.2	(Davies, 1977)
Ireland	22.8									21.7	30.3	66.7	(Hennessy *et al.*, 2008a)

LAR remains constant under controlled and field conditions over most of the growth period for most species of temperate grasses (Silsbury, 1970) but it may be influenced by re-growth interval and defoliation height, and temperature. For example, Hume (1991) reported a reduction in LAR of PRG when cutting frequency increased (from four to two weeks and from two to one week) and cutting height decreased (from 6 to 3-cm stubble height). Grant *et al.*, (1981), in agreement, reported that short swards were associated with more leaf appearance but lower leaf size than taller swards. Nevertheless, swards with high density of small tillers have higher LAR than swards with lower density of large tillers (Chapman and Lemaire, 1993). On the other hand, LER, although it is affected by temperature, it does not seem to be affected by light level in the initial stages of re-growth and the amount of green leaf remaining on a tiller after defoliation is positively associated with LER (Grant *et al.*, 1981). However, the increased shade of relatively high HM results in greater LER by promotion of the main tiller (Grant *et al.*, 1981).

2.4.1.3 Leaf stage

The number of green leaves per tiller in a vegetative sward increases up to three, thereafter leaf appearance is balanced by death (Robson, 1973; Valentine and Matthew, 2000). Leaves continue to be produced, but each time a new leaf appears, the oldest leaf on that tiller dies (Gay and Thomas, 1995; Hunt, 1965). Provided that residuals are low, approximately 10, 30 and 60% of potential pasture growth occurs during the first, second and third-leaf emergence stages, respectively (Voisin, 1959). This recycling of old leaves is crucial because it allows nutrients such as N and sugars to be reused elsewhere in the plant (Valentine and Matthew, 2000). Thus, allowing a sward to produce three leaves would result in maximum sward production, utilisation and persistence (Fulkerson and Donaghy, 2001). The 3-leaf stage, therefore, sets the biological optimum grazing interval for PRG-dominated pastures after which point there are negative consequences. If, in contrast, tillers are defoliated before the 2-leaf stage, they must use energy that is stored in the roots and pseudo stem to prioritise leaf growth, even when they are in positive energy balance (Donaghy and Fulkerson, 1998).

2.4.1.4 Leaf area index

Leaf area index (LAI) was defined by Thomas (1980) as the green leaf area per unit of area of ground and this determines how much light is intercepted. It is a function of leaf size, leaf number per tiller and tiller density (Figure 2.8). Since only leaves are produced during vegetative phases, the components of leaf turnover can describe plant morphogenesis. Thus, the rates at which leaves grow and die are crucial, as when light interception is lower than 95%, an increase in LAI will generally increase light interception and sward growth rate (Parsons *et al.*, 1988). Therefore, maximum production over the season would result from a sward that is maintained by cutting or grazing at close to full light interception. However, HM accumulation may decrease due to lower tissue growth and tiller population when LAI is low. When LAI is less than 1.0 there is a limitation on growth due to suboptimal light interception (Parsons *et al.*, 1983a). Brougham (1958) reported that the build up of dead matter and HM accumulation are optimum when a pasture of ryegrass and white clover was kept between 1.9 and 4.5 LAI. This author described that optimum LAI is that at which net photosynthesis by the plant canopy is maximised.

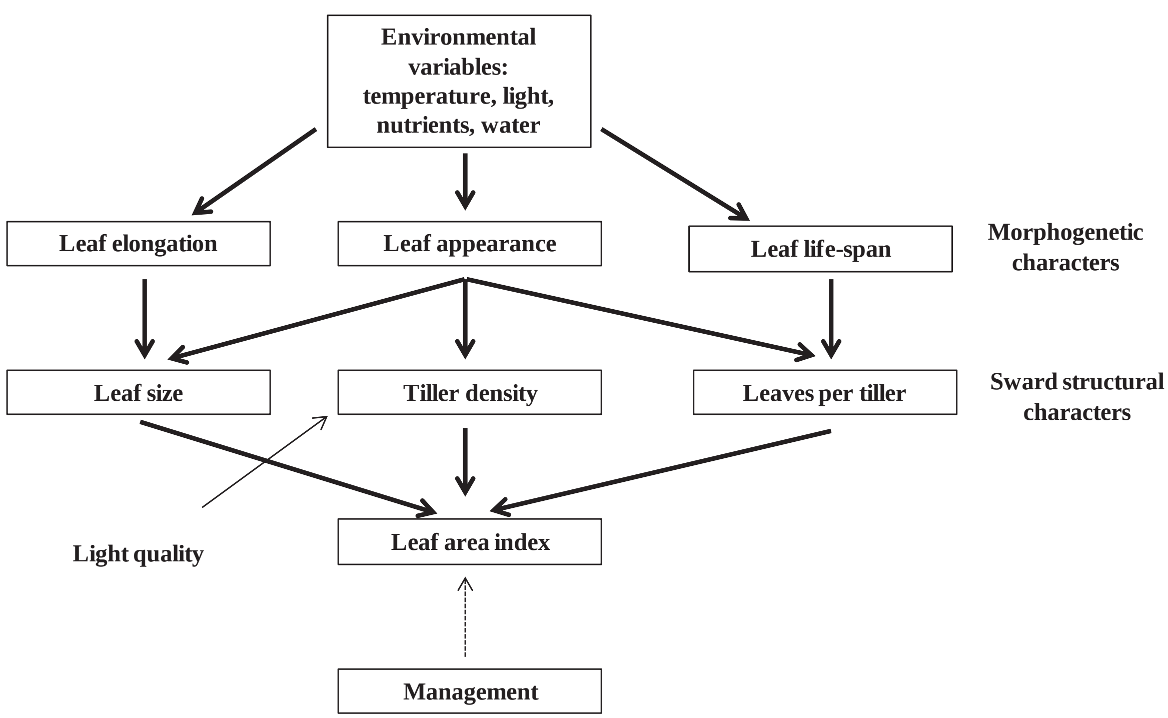


Figure 2.8 The relationship between the main morphogenetic characteristics of grasses and sward structural components (from Lemaire and Chapman, 1996).

The number of axillary buds available to develop into tillers is determined by leaf production. Leaf appearance rate, therefore, is one factor determining the rate of development of secondary tillers (Davies, 1974; Figure 2.8) and consequently, influences tiller density. The number of tillers per unit area of land and the yield per individual tiller determine herbage production (Volenec and Nelson, 1983). Persistence of PRG is mainly determined by tiller population dynamics, meaning tiller initiation and tiller death, which results in a continuous change in the population. Perennial ryegrass tillers persist either through tillering or through reseeding, the former being predominant in moist temperate pastures (Matthew *et al.*, 1993). Tiller re-growth and initiation of new tillers from axillary buds determine plant persistence (Davies, 1977). This leads to differences in tiller initiation and appearance, resulting in differences in tiller density (Mitchell, 1953).

2.4.1.5 Tiller density

Tiller density can be a good indicator of the agronomic status of a sward, provided that is adjusted for herbage mass, since the numbers can be extremely variable between different swards and within one sward. As an example of this, some tiller density values are given in Table 2.4 for New Zealand and Ireland. The tiller population within a sward is constantly changing and is very vulnerable to management factors. For example, Laidlaw *et al*. (2000) and Hennessy *et al*. (2008b) found that, in contrast to low HM swards, swards that had high HM on 1 December had a lower tiller density the following April. L'Huillier (1987) found values of 2,000 to 6,000 tillers/m^2 during summer in New Zealand. In winter, the limited environmental resources cause an increase in the competition between tillers, and therefore a reduction in tillering, which is then re-activated in early spring. Even though this depends on the management context, in the Northern Hemisphere, there is a peak in March/April, followed by a reduction during May/June coinciding with the main flowering period and again a second peak during June/July (Davies, 1977; Ryan *et al.*, 2010). The highest tillering activity has been observed from late spring to summer, especially soon after defoliation of the apices of the main group of reproductive tillers (DaSilva, 1994).

Table 2.4 Tiller density (number of tillers/m^2) in Ireland and New Zealand.

Country	Month												Reference
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
Ireland	8,299	6,264		5,522									(Hennessy *et al.*, 2008a)
Ireland	3,550	3,386		2,406									(Hennessy *et al.*, 2008a)
Ireland		6,564	7,326	8,316	7,292		9,930					8,518	(Ryan *et al.*, 2010)
New Zealand	4,639	5,229	4,224	7,764	10,674	6,620	13,383					6,541	(Hernandez-Garay, 1995)
New Zealand	4,445			5,006		3,156							(Bluett *et al.*, 1999)
New Zealand								4,430					(Pande, 2002)
New Zealand	5,145			4,470		4,435				4,775	5,500		(L'Huillier, 1987)

It has been postulated that substantial ranges of variation in grazing management have little effect on the rate of net herbage production of PRG (Korte *et al.*, 1987; Parsons *et al.*, 1988) because grass growth is maintained by compensating size and production per unit of area (Bircham and Hodgson, 1983). Thus, even though it remains difficult to modify herbage accumulation, it has been proven that management can modify tiller density (Chapman and Lemaire, 1993). Perennial ryegrass tiller density in spring pastures can be manipulated by grazing frequency (Bryant and L'Huillier, 1986) and intensity (Matthew *et al.*, 1989). The question is whether an increase in tiller density can result in increased herbage production. This is important because, as Hodgson (1989) stated, significant changes in grazing management may not have a great impact in animal output every time pasture production exceeds demand. However, the situation is different when the balance between pasture supply and demand is poor. In this case, minor management adjustments could have a substantial effect on animal performance (Bircham, 1984).

2.4.1.6 Herbage accumulation

From the sketch of the re-growth of the individual tiller (Figure 2.7), it can be seen that the growth of new tissue results from the continuous sequence of phytomer development and this occurs in parallel to the loss of mature tissue due to senescence and decomposition (Valentine and Matthew, 2000). There is, therefore, a constant trade-off between quantity and quality. The advantages of growth given by relatively high leaf proportions are certainly associated with an increase in dead material (Hodgson *et al.*, 1981). Thus, grass accumulates all the time but the proportion of dead material in the DM increases with time, so minimising the losses in death and decay are key for optimising utilisation of grass. Herbage production is the net result of growth and senescense, therefore, grazing management may have an effect on growth, senescense or both (Bircham, 1981).

(a) (b)

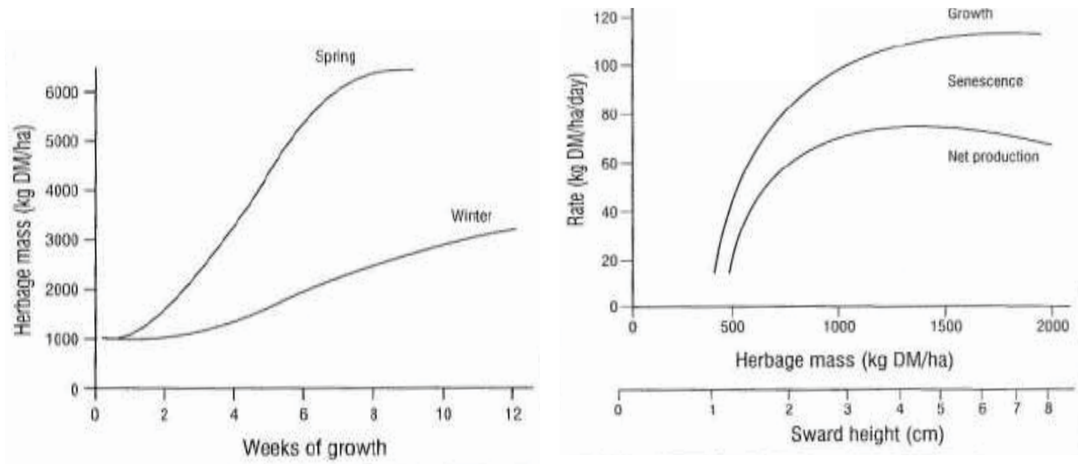


Figure 2.9 (a) Herbage accumulation following grazing in a rotationally-grazed sward and (b) relationship between herbage mass and leaf growth, leaf senescence, and net herbage production in continuously grazed swards (from Bircham and Hodgson, 1983; redrawn from Brougham, 1957) .

At the beginning of the vegetative stage, growth and loss rates are low, but growth rate then accelerates, to be ultimately balanced out by a later acceleration of dead material accumulation, as mature plant material accumulates (Hodgson, 1990). Figure 2.9 (a) shows the increase in HM accumulation over time in two seasons: spring and winter. Figure 2.9 (b) illustrates the difference between growth and net herbage production. These two figures aid in understanding the concept that simple growth is not an adequate measure of sward quality because it includes dead herbage accumulated. Net production of green HM is maintained relatively constant due to a homeostatic mechanism which involves compensatory changes in species population density and tissue turnover on individual plant units (Hodgson, 1990).

2.4.2 The response of perennial ryegrass plants to defoliation

Defoliation or removal of the herbage may be by various means such as grazing, cutting, fire, cultivation, treading and extreme frost or drought. This interaction between the method of defoliation and the sward can be thought of as a predator-prey relationship (Noy-Meir, 1975). In plants that are intact, there is an accumulation of reserves from nutrients that are transported from photosynthetically active tissues. Defoliation causes a reduction in leaf area that is associated with an impact on carbohydrate storage and also a decrease in tiller development, leaf and root growth (Davidson and Milthorpe, 1966), in addition to the impact on the microenvironment of light intensity, soil temperature and moisture (Watkin and Clements, 1978). To what extent defoliation affects re-growth will depend on frequency, intensity (severity, duration, height, residual leaf area and re-growth reserves) and timing in relation to the developmental phases of plants and season of the year. This is vital because modern PRG swards may need to resist a number of defoliations (probably between eight and 12) each season.

Productivity of PRG swards are highly dependent on the ability of the individual plant to regrow after these repeated and partial defoliations. This is possible due to morphological adaptations of PRG plants (Hyder, 1973). The mechanisms behind these have been widely researched (Brougham, 1957; Fulkerson and Donaghy, 2001; Parsons and Chapman, 2000). In addition, Richards (1993) and Chapman and Lemaire (1993) provided detailed reviews on the physiological responses of forage plants to defoliation and how they recover quickly.

Re-growth of PRG after defoliation involves two physiological periods, provided that N is not limiting (Donaghy and Fulkerson, 2001). During the first six days there is an initial phase that is characterised by the mobilisation of 60 to 90% of soluble carbohydrates. Between days 7 and 28, there is a second phase in which carbohydrate levels are recovered. Therefore, the plant undergoes a period of negative energy balance after it has been defoliated. In order to survive, the plant uses its stored energy reserves to produce its first leaf so the roots stop growing and new tillers stop emerging. As the second leaf appears during re-growth, energy stores are replenished and the plant returns to a positive energy balance (Holmes and Roche, 2007) provided the plant has the photosynthetic capacity to meet the energy requirements for maintenance and re-growth, due to adequate leaf area. Depending on temperature, N availability and cultivar, this period could last between two and 13 days after defoliation (Davies, 1965; Morvan-Bertrand *et al.*, 1999). Thus, defoliation disturbs the carbohydrate supply for plant growth by removing photosynthetic tissues, after which the energy supply becomes generally insufficient for maintenance and re-growth. However, plants usually respond to defoliation with a rapid and marked reallocation of nutrients from root to leaf meristem (Ryle and Powell, 1975) and a mobilisation of stored N and carbohydrates to sustain both growth and existing tissue (Culvenor *et al.*, 1989; Morvan-Bertrand *et al.*, 2001). The size of the mobile reserves in the stubble influences the re-growth ability of PRG (Davidson and Milthorpe, 1966; Gonzalez *et al.*, 1989). When adequate leaf area remains for continuing photosynthesis, the dependence of re-growth following defoliation upon carbohydrate reserves will be minimal and of short duration (two to four days; Caldwell, 1984). These responses of the plant to defoliation are further influenced by frequency, severity and timing of defoliation.

2.4.2.1 Frequency and severity of defoliation

If defoliation is infrequent and/or lenient, the aforementioned energy limitation exists for only a short period. The replenishment of energy stores would be short-term and will successfully maintain balanced growth of the whole plant. This situation allows plants to be able to re-establish their original carbohydrate supply rate and growth patterns well before defoliation is repeated (Chapman and Lemaire, 1993). In contrast, frequent defoliations may result in tillers not achieving an adequate leaf stage (Fulkerson and Donaghy, 2001).

In addition, the amount of residual leaf remaining per plant, has a direct effect on subsequent re-growth after defoliation (Chapman and Lemaire, 1993). Broughama (1956) concluded that, for maximum production of herbage, the amount of leaf remaining following mowing or grazing should be sufficient to ensure complete interception of light so that pasture growth is maintained at the maximum rate. The reason for this was that, after a severe defoliation, the rates of photosynthesis and production of new leaves increase rapidly but there is a delay before a corresponding increase in the rate of leaf death (Parsons *et al.*, 1988).

As explained above, the amount of green leaf remaining on tillers after defoliation positively influenced LER (Grant *et al.*, 1981), and the photosynthetic activity of the residual leaf area (Brougham, 1956; Davies, 1974). Thus, as severity of defoliation increases, the dependence on protein and carbohydrates for re-growth increases

(Vickery, 1981). Organic reserves that were accumulated before defoliation facilitate to a great extent the re-growth of plant tissue, especially in the early stages of recovery (Brougham, 1956). Caldwell (1984) concluded that relatively small quantities of carbohydrate reserves may be needed for re-growth, but that they are crucial when the plant is unable to support re-growth directly from photosynthesis. When carbohydrate suddenly limits growth rate, the train of physiological responses described by Richards (1993) ensues to restore homeostatic growth. Alberda (1966) reduced the level of carbohydrate reserves in the stubble of PRG plants by keeping them in the dark for 3.5 days and found that re-growth in these plants was substantially less than control plants receiving continuous light. The length of the sheath tube also seems to play an important role in the plastic response of PRG to defoliation (Grant *et al.*, 1981). Davies and Thomas (1983) reported increases in simulated sheath tube length, promoting leaf extension while senescent sheath tissues remaining at the base of the tiller could lead to a decrease in tillering rate and an increase in LER. A similar effect is found in tall fescue (Kemp and Valentine, 1998).

2.4.2.2 Timing in relation to plant development

Age of the leaves is an important factor affecting re-growth. The younger the leaves lost by defoliation, the greater the effect on growth rate (Davies, 1974; Richards, 1993). The reduction in photosynthesis is more directly related to leaf area loss when young leaves remain after defoliation (Parsons *et al.*, 1983b). This may have implications for swards grazed at a low pre-grazing HM. Davies (1974) found that removal of all laminae resulted in a subsequent reduction in tiller production, relative growth rate and leaf appearance. These findings indicate that there is a re-allocation of plant growth resources to re-growing leaf tissue, with the plant using this mechanism to compensate for leaf removal (Richards, 1993).

As described in previous sections, the sward is in a constant dynamic equilibrium between the amount of light available in the environment and the amount and dimensions of leaf present to intercept that light. This concept underlies all modern recommendations on how best to manage pastures for optimal growth and harvesting of forage (Brougham, 1958; Brougham, 1962; Chapman and Lemaire, 1993). Pasture management for maximum herbage accumulation over time, hence, requires that most of the light present in the environment is captured by leaf material that is photosynthetically active throughout periods of active growth (Richards, 1993).

2.5 Management practices for optimal sward and cow performance

A conflict of interests exists for the grassland manager between the requirements of grazing animal and those from the grass sward. The farmer can implement management practices that will impinge on the sward, on the DM intake of the herd and, ultimately, on the conversion of grass into milk. The most important management practice to maximise the proportion of grazed grass in the cows' diet is to have an adequate number of cows with a compact calving pattern to coincide with the start of the grass-growing season. Management practices, through the effects on sward structure and morphology, influence grass DM intake to a greater extent than herbage accumulation (Hodgson, 1986). For example, Wade *et al.* (1995; 1989) found that increased proportion of green leaf in the bottom of the sward post-grazing caused an increase in herbage availability. Likewise, Peyraud *et al.*(2004) showed that daily allowance of green leaf was a better predictor of DM intake than daily herbage allowance.

In the animal/sward interface, the grazing cow is often faced with a range of species with varying proportions of leaf, sheath, stem, inflorescence and seed (Watkin and Clements, 1978). It has long been acknowledged that cows select leaf in preference to stem, and young leaves in preference to older leaves (Stapledon, 1927; Van-Dyne *et al.*, 1980) when given the opportunity. During the grazing process cows selectively remove green leaf. However, DHA can be managed to achieve an optimum grazing pressure, thereby avoiding excessive selection by the animals.

In a grazing system, where weather is an important factor, Sheath *et al.* (1987) outlined the main objectives of grazing management as the ability to maintain a desirable pasture composition, pasture density and pasture quality; and to be flexible. According to Macdonald *et al.* (2010) there are three key grazing management decisions that need to be made on farm: i) when to graze (determines the grazing interval); ii) how hard to graze (the grazing intensity); and iii) how long to graze (also determines the grazing intensity). All these management requirements can be met by the use of SR, grazing severity and frequency of grazing (Hodgson, 1989).

2.5.1 Post-grazing residual height

The farmer must decide if grazing will be severe or lax on a daily basis, and post-grazing sward height is the most common measure of grazing intensity. Extremes of over- and under-grazing must be avoided, basically because insufficient HM limits herbage growth, and low utilisation leads to wastage of feed (Sheath and Bircham, 1983). Thus, the manager must monitor grazing intensity constantly to ensure high animal productivity while maintaining adequate amounts of high-quality grass and a sward that is properly conditioned for subsequent grazings. This was discussed above with short-term grass budgeting.

Targets for residuals have been advocated in different parts of the world. For example, Holmes (1974) advocated 1,200 kg DM/ha from ground level for the autumn. More recently, Macdonald and Penno (1998) suggested 1,500, 1,700 and 2,000 kg DM/ha from ground level, for September, October and November (spring), in the Southern Hemisphere, respectively. In New Zealand there is an extension rule of seven to eight clicks of the plate meter (Holmes and Roche, 2007). In Ireland, post-grazing sward height in cm is the most commonly used way of estimating the residuals after grazing. It is recommended to graze to 4 cm during the first grazing rotation in spring (McEvoy *et al.*, 2008). When post-grazing residual is maintained at 4 to 5 cm the sward can maintain sufficient plant energy reserves, maximum pasture re-growth and quality, and tiller initiation due to increased light penetration. More than 4.5 cm in the second part of the grazing season can allow for an adequate expression of cows' potential for milk production.

Experiments have been carried out examining the effects of SR on sward characteristics through post-grazing sward height (Baker and Leaver, 1986; Michell and Fulkerson, 1987). Different levels of pre-grazing HM (Dillon *et al.*, 1998; McEvoy *et al.*, 2009), DHA (Bargo *et al.*, 2003; Lee *et al.*, 2008) or SR (Michell and Fulkerson, 1987; Stakelum and Dillon, 2007) result in differences in post-grazing sward heights. There is not a wealth of literature published on the long-term effects of post-grazing sward height on sward production and quality. Moreover, those studies investigating the effects of post-grazing sward height on the sward have used relatively high post-grazing sward heights such as 5 cm (Grant *et al.*, 1981) or 4.2 to 5.9 cm (Mayne *et al.*, 1987).

Some authors (Brougham, 1956; L'Huillier, 1987; Tainton, 1974) have found that when defoliation is lenient, herbage accumulation after grazing or cutting is higher than when defoliation is severe. Lower post-grazing sward heights lead to an increased tiller number and nutritive content of swards in the early season and also to a reduction in the ratio of reproductive to vegetative tillers during the early-summer period (Carton *et al.*, 1989; Mayne *et al.*, 1987). Tallowin *et al.* (1981) tested two intensities of continuous grazing (severe to 3.5 cm and lenient to 7.5 cm) during the spring (phase I), followed by a uniform continuous grazing management from mid-summer onwards (phase II). The authors observed an increased density of tillers in the severe compared to the lenient treatment at the end of phase I, this was attributed to enhanced daughter tiller production in the severe treatment. Reduced pasture re-growth and persistence due to removal of plant energy reserves resulted from more severe grazing (shorter than 3 cm) (Lee *et al.*, 2008).

A positive consequence of short post-grazing residuals is minimal pasture wastage. Short post-grazing sward heights also lead to a reduction in leaf size and in leaves positioning below grazing height (Sheath and Hodgson, 1989). This provides the sward with an increased amount of overall leaf which can replace the material that was removed (and may explain an apparent increased leaf elongation in high-SR treatments, which have lower post-grazing residuals, a benefit of increased grazing intensity). However, the detrimental consequences of very short post-grazing sward heights have long been reported. Donald (1941), cited in Brougham (1956), concluded that yield of shoot decreases as intensity of defoliation decreases. Repeated over-grazing, particularly in the summer, leads to reduction in herbage accumulation, as a result of decreased tiller density and tiller weight. This leads to a decrease in pasture growth through reductions in LAI, longevity of individual leaves and photosynthetic efficiency, and a shortage of carbohydrate reserves (Bircham and Hodgson, 1983; Brougham, 1961).

Hodgson (1990) stated that maintaining sward height above 5 cm has advantages, although these must be set against the longer-term risks of accumulation of dead material and reduction in tiller populations and tillering activity. Kerrisk and Thomson (1990) reported higher growth rates as a result of lenient defoliation in contrast with severe for PRG. However, high HM swards resulting from frequent lenient defoliation adversely affect long-term pasture growth and utilisation, grass tiller density declines (Grant *et al.*, 1983; Hunt and Brougham, 1967) and proportion of green leaf:stem decreases progressively (Hunt and Brougham, 1967; Korte *et al.*, 1982). This ultimately limits the photosynthetic efficiency of residual herbage, and also limits animal intake (Hodgson *et al.*, 1977) and, hence, harvested yield. For example, a 5-cm post-grazing sward height resulted in greater DM yield accumulation than an 8-cm post-grazing height in PRG (Ollerenshaw and Hodgson, 1977). Lax infrequent grazing during dry-summer periods resulted in a 20% increase in pasture production, and alternate lax and hard grazing during the vegetative growth period in autumn resulted in 63% more grass than hard grazing (Tainton, 1974). However, lax grazing resulted in low levels of herbage utilisation, resulting in excessive senescence losses, a rapid decline in tiller populations and, eventually, a decreased productive potential of the pasture (Hodgson, 1989). Consistent with this, Lee *et al.* (2008) reported that, with post-grazing sward heights higher than 6 cm, there was a subsequent reduction in herbage availability, which would have resulted in a less productive pasture if this occurred frequently during the season.

Achieving the correct post-grazing sward height ensures that the compromise between sward quality, DM intake and milk production is optimised. Too low a post-grazing sward height results in compromised cows' DM intake and milk yield. For example, when dairy cows were forced to graze to a residual height of 5 cm in a rotational grazing system, individual herbage intake was depressed by 10 to 15% (Kennedy *et al.*, 2006). On the other hand, high post-grazing residuals lead to increased herbage production but lower subsequent milk production due to lower pasture quality (Hoogendoorn and Holmes, 1992). Therefore, the milk-production potential of the cow dictates to a great extent the critical post-grazing sward height (Mayne *et al.*, 1987).

Severe grazing may result in a decreased milk yield per cow in the short-term (Kennedy *et al.*, 2007b; McEvoy *et al.*, 2008). Nevertheless, a short post-grazing sward height leads to leafier swards and is likely to increase subsequent DM intake (Wade, 1991) leading to increased sward utilisation, herbage quality and ease of grazing management in mid-season (O'Donovan *et al.*, 2004). Ganche *et al.* (2012 in press) forced dairy cows to graze to 2.7 cm during the first 10 weeks of lactation and this reduced milk yield by 11%, and also LWT when compared to cows grazing to 3.5 cm. The authors also found that decreasing post-grazing sward height from 4.8 to 3.8 cm in mid-season increased the proportion of leaf in the sward by 10%. Therefore, the longer-term benefits of decreased post-grazing heights can result in higher milk production (Kennedy *et al.*, 2006). It remains, however, to be determined, where the limit is from where post-grazing sward heights become too low so as to punish the sward and cow grass DM intake. A higher post-grazing sward height, associated with increased DHA, resulted in increased milk production (Wales *et al.*, 1999). Delaby *et al.* (2001), for an extra cm in plate meter height (5.7 to 6.8 cm) reported a response of 1.09 kg of milk per cow per day. However, this is dangerous, as this short-term benefit with lenient grazing (higher than 5.5 cm) on cow performance may end up, in the long term, in a reduction in the nutritive value of the sward (Michell and Fulkerson, 1987; Stakelum and Dillon, 1990).

2.5.2 Treading damage

Treading is defined in this thesis as the physical impact of the cows' hooves on the soil and plants. Treading and the positive association with SR has interested scientists for a long time (Bates, 1935; Edmond, 1958a). The grazing activity is inevitably associated with the potential risk of damaging soils and pasture. This has become particularly problematic in Ireland as farmers are willing to increase SR and also extend the grazing season, and both have an impact on the soils and pastures. Treading damage is complex. Animal, soil characteristics, plants, soil moisture content and other environmental components together act upon the sward. For example, as it would be expected, the effect of treading is more detrimental when soils are wet (Brown, 1968). The effects of treading are direct, over plants and tillers, and indirect over the soil. Gradwell (1956) observed that soils that were compacted when wet hardly had any change in bulk density but the reduction in aeration was critical for plant growth. When soils are wet, there may be direct root damage (Edmond, 1966). There are different ways of measuring the negative impact of treading: reduced pasture utilisation and re-growth, decline in soil structure, and change in pasture species. However, due to the complexity of treading it is difficult to generalise results.

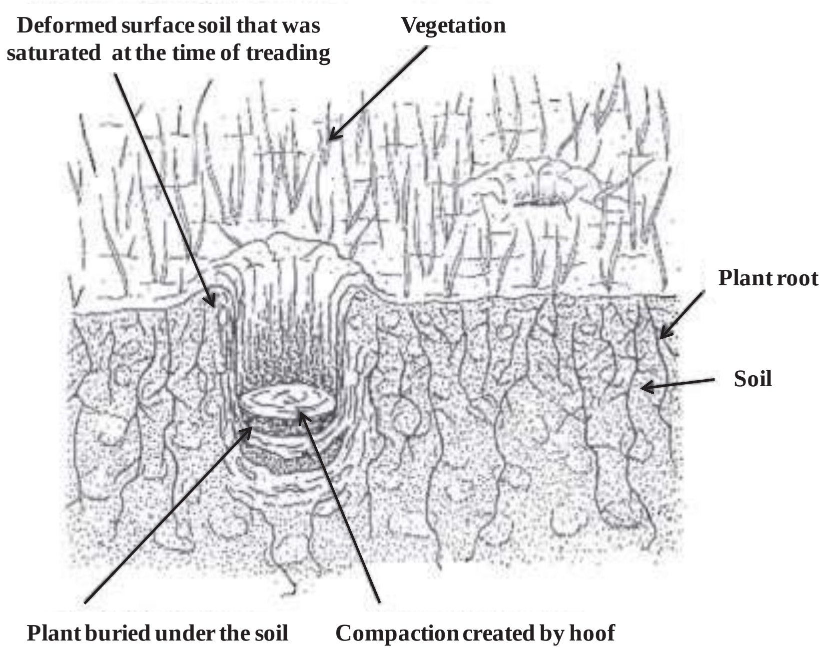


Figure 2.10 Treading damage and soil compaction caused by the cows' hooves (from Batey, 1988).

The reduction in herbage production after cow treading may range from 30 to 90% and last for two years (Singleton and Addison, 1999). As can be seen in Figure 2.10, plant tissues are damaged when treading occurs. The whole or part of the plant is pushed down into the soil by the hoof during treading. Under wet conditions, Sheath and Carlson (1998) reported that 300-350 kg herbage DM/ha got buried in the surface soil, resulting in reduced growth rates of 5-10 kg DM/ha/day during early mid-spring. Destruction of plant growing points and photosynthetic surfaces (Brown and Evans, 1973) leads to the death of the damaged plant parts (Gradwell, 1965). In addition, Horne and Hooper (1990) reported that pasture utilisation decreased by 20 to 40% after treading damage. The lower palatability of the treaded pasture is one of the factors influencing utilisation (Kellet, 1978).

The resulting lower density of tillers led to decreased DM yields (Brougham, 1960; Edmond, 1958a). After treading, tillers gradually build up in numbers. The speed at which the sward recovers is influenced by residual leaf tissue, carbohydrate reserves and meristematic activity of the surviving tillers, and also by nutrient status and water uptake ability of the soil (Pande, 2002). The recovery of plants can be slow after heavy treading in wet soil conditions (Edmond, 1958a). After moderate treading damage, recovery can take six months (Sheath and Carlson, 1998) although it may be longer (Singleton and Addison, 1999).

Some pasture species are more vulnerable to treading than others, as was shown in Table 2.2. After ranking 10 grass species according to the decrease in number of tillers or nodes, Edmond (1964) found ryegrass the most tolerant compared to other species following heavy treading by sheep. Also, young tillers are more vulnerable to treading damage than older tillers (Edmond, 1966). Furthermore, treading damage is more detrimental in some soil types than in others. For example, in Ireland, treading by grazing bullocks over three years in poorly-drained clay loam resulted in increased bulk density and surface roughness, decreased aggregate stability and soil penetrability, and lower herbage production than treading on a loam soil (Mullen *et al.*, 1974).

Pasture utilisation on wetter soils is challenging. On-off grazing has been advocated to minimise treading damage without significantly affecting the amount of grass eaten by the animals (Kennedy *et al.*, 2009; Ward *et al.*, 2003). In Kennedy's study, the cows seemed to quickly adapt to the short periods available for grazing. There is a need to quantify treading damage with today's pasture species and management within the new dairy system in Ireland.

2.5.3 Re-growth interval and pre-grazing herbage mass

Defoliation frequency responds to changes in HM (Brougham, 1961; Holliday and Willman, 1965; Reid, 1986) and the length of the re-growth interval is a better predictor of pre-grazing HM than grazing residuals (Cosgrove, 1992). As explained previously, pre-grazing HM is important because it has an impact on the nutritive value of the sward (Delagarde *et al.*, 2000) thereby influencing the nutrient intake of the grazing cow. This can influence, in turn, milk output. For example, relatively low pre-grazing

HM resulted in increased herbage quality and subsequent increased milk output (Holmes *et al.*, 1992).

In Ireland, the fundamental changes in recent years have impacted on the level of pre-grazing HM offered to the herd (McEvoy *et al.*, 2009). Relatively low pre-grazing HM (1,200 to 1,600 kg DM/ha above 4 cm) facilitates the achievement of low post-grazing sward heights (Kennedy *et al.*, 2007b). The level of pre-grazing HM the farmer can allow his cows to graze without impacting negatively on the sward and/or on the animals is a question that needs to be addressed in modern grazing management practices.

As defoliation frequency increases, water-soluble-carbohydrate content, tiller weight and root growth decrease (Fulkerson and Slack, 1995). Shorter re-growth intervals in the period of maximum grass growth increase the amount of grazed grass, resulting in a 13% decrease in herbage accumulation over the grazing season (Dale *et al.*, 2008). Perennial ryegrass swards produced 20% more DM under 28-day defoliation interval, than under a 14-day interval (Judd *et al.*, 1990). Canopy photosynthesis is markedly reduced at very low levels of LAI or pre-grazing HM, because there is insufficient young green leaf tissue present to intercept light, and much of the light may fall on bare ground (Parsons *et al.*, 1983b). In contrast to defoliation at two weeks, defoliation at 4-week re-growth intervals, or when the sward is ready (before the onset of senescence), resulted in increases in herbage accumulation of 18 and 32% in year 1 and of 41 and 59% in year 2, respectively, on ryegrass-white clover swards (Fulkerson *et al.*, 1993).

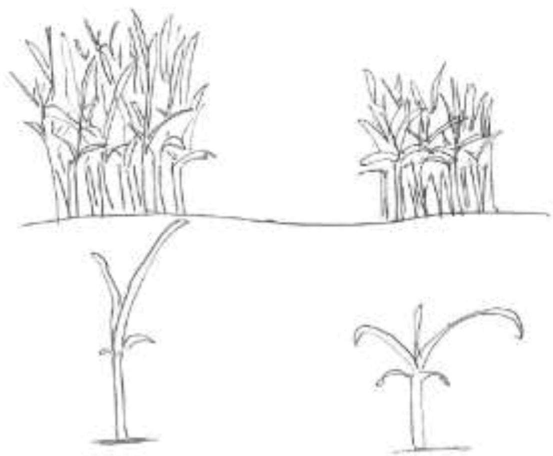
Less than 2-week re-growth intervals can reduce herbage accumulation by up to 40%, while 4-week re-growth intervals can result in a 15 to 17% increase in herbage accumulation (Hodgson and Wade, 1979), provided that post-grazing sward height is controlled. Increases in rotation length lead to a decline in nutritive value of the sward, this association being strongest in the April-to-June period for the Northern hemisphere (Stakelum and O'Donovan, 1998). In contrast, Dillon *et al.* (1995b) reported that decreasing rotation length from 35 to 21 days in the June-to-August period resulted in increased organic-matter digestibility and live leaf and lower acid-detergent fibre and neutral-detergent fibre contents, combined with higher milk yield and protein. However, short grazing rotations (eight days) in May to June resulted in low pre-grazing HM and this was associated with reduced DM intake and milk output per cow (Dale *et al.*, 2008) due to increasing difficulties in prehending the herbage. Similar findings were reported by Rossi *et al.* (2005). Identifying the optimum level of pre-grazing HM across the grazing season is critical to maximising DM intake and MS production of spring-calving dairy cows in any pastoral environment.

2.5.4 Indicators of defoliation

Rotation length, sward height, level of HM and leaf re-growth stage are indicators of defoliation (Fulkerson and Donaghy, 2001). The 3-leaf stage can be considered as the maximum grazing interval for PRG pastures because delaying grazing beyond the emergence of the third leaf does not result in increased growth of digestible herbage (Fulkerson and Donaghy, 2001). Maximum production of digestible pasture occurs on emergence of the third new leaf on the ryegrass plant or prior to canopy closure. As discussed above, if the PRG tiller is defoliated before the emergence of the second leaf, this will result in a reduction in growth and the plant will not be able to stand repeated grazing because the energy reserves will be depleted (Holmes and Roche, 2007). Leaf area index was also proposed as an indicative for defoliation. For example, cutting at 95% light interception resulted in increased herbage accumulation in comparison with cutting every three weeks (Korte *et al.*, 1985). Chapman *et al.* (2011) supported the rule of grazing after at least two and no more than three leaves have appeared in each tiller in a sward.

The risk of assessing the optimum time for defoliation solely on level of pre-grazing HM is explained using the review of Fulkerson and Donaghy (2001) and Figure 2.11. At first look it seems that sward A is closer to be ready for defoliation than sward B. However, in this particular situation, sward B is under stress due to low N, causing plant size to be reduced (Ryle, 1964). Therefore, sward B is closer to reaching the ceiling yield than sward A. This means that, if sward B is not grazed soon, there will be wastage of feed due to accumulation of stem and dead material, leading to decreased quality. Sward A, in contrast, is not limited by N and has conditions for rapid growth. In this scenario, plants may not yet be at optimum leaf stage for defoliation. The instinctive decision would be to say that sward A is closer to be ready for defoliation.

However, under the circumstances mentioned above, sward B should be defoliated before sward A.



A B

Figure 2.11 A hypothetical scenario showing two swards at two levels of pre-grazing herbage mass with their leaf stage below.

The grassland farmer must achieve an optimum level of pre-grazing HM through management of re-growth intervals that focus on tiller behaviour as affected by environmental constraints. In addition, this must be coupled with adequate levels of post-grazing sward heights and management of treading damage. All these will allow for a sum of efficiencies that would lead to high levels of grass utilisation. The manager of this system needs a set of skills to integrate the factors (Figure 2.12). Skill is the ability of translating knowledge into action (Katz, 1974). It is this comprehensive knowledge which is used to develop the heuristics behind effective planning and control procedures (Gray, 2001).

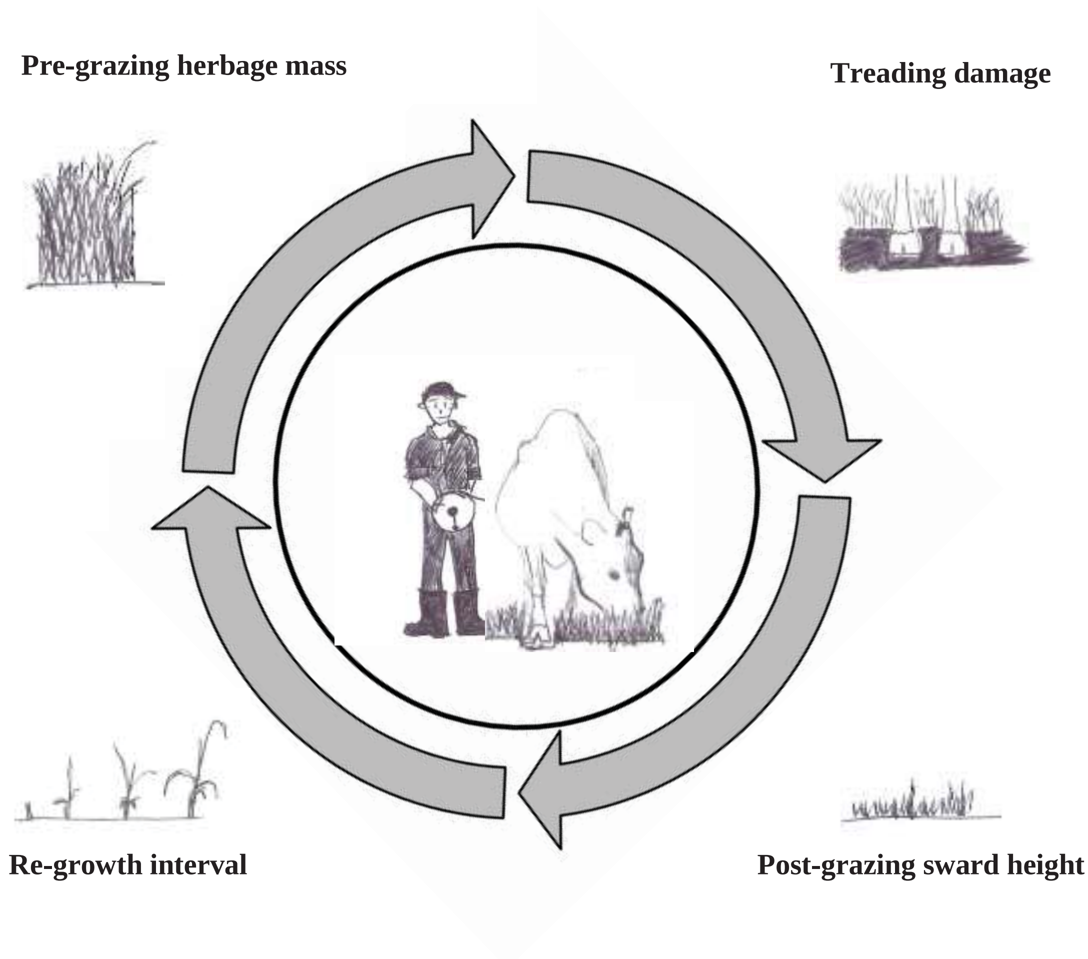


Figure 2.12 Grassland farmer integrating management decisions on some of the key factors of the grass-based dairy system.

There is a need for information on Irish grassland to meet the forthcoming challenges, if Ireland is going to be a key player in the world market. Most of the principles of grazing management of pastoral-based temperate dairy systems are common to all grass-based dairy systems around the world. However, how these principles apply within the Irish dairy industry requires evaluation in the Irish environment including climate, soils, cultivars and cow type.

2.6 Conclusions

This literature review demonstrates that profitable conversion of grass into milk depends on: i) adequate grazing pressure, through management of post-grazing sward height to achieve a high-quality, productive and persistent sward; ii) minimal negative impact of treading that can be achieved with understanding of the vulnerability of different soils, different seasons and different grass species and iii) application of best management practices to match requirements of the sward with the requirements of the herd and, ultimately, achieve a profitable grass-based dairy system. The principles of grazing management are vital for the efficient use of grass. These principles cannot be understood separately. This provides the justification for the studies included in this thesis.

Chapter 3: Effect of grazing management practices on perennial ryegrass herbage production and sward structural characteristics throughout an entire grazing season

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Accepted in Grass and Forage Science

3.1 Abstract

The impending abolition of European Union milk quotas will require intensive dairy-production systems to develop grazing management practices to provide greater quantities of higher quality pasture over an extended grazing season. The objective of this study was to investigate the cumulative impact of alternative grazing management practices on sward production, utilisation and structural characteristics over a complete grazing season. As a part of a larger dairy grazing-system experiment, this study focused on the effects of three levels of grazing severity on herbage production and sward characteristics. Target post-grazing sward heights were 4.5 to 5 cm, 4 to 4.5 cm and 3.5 to 4 cm, corresponding to lax (L), intermediate (I) and severe (S) grazing treatments, respectively. Detailed sward measurements were undertaken on 8% of each farmlet area. Pastures were rotationally grazed by dairy cows from 10 February to 18 November 2009. Post-grazing sward heights achieved were 4.9, 4.2 and 3.6 cm for L, I and S, respectively. While there was no significant difference between treatments in accumulated or harvested herbage (11.3 and 11.2 t dry matter/ha, respectively), grazing severity had a significant effect on sward structural and morphological characteristics. Above the 3.5-cm horizon, L, I and S swards had 0.56, 0.62 and 0.67 leaf proportion and 0.30, 0.23 and 0.21 stem proportion, respectively. As grazing severity increased, non-perennial ryegrass (PRG) tiller density decreased (from 3,350 to 2,780 and to 1,771 tillers/m^2 for L, I and S paddocks, respectively) and rejected area decreased (from 0.27 to 0.20 and to 0.10 for L, I and S paddocks, respectively). These results add further credence to the important impact of grazing management practice on sward structure and quality, and endorse the concept of increased grazing severity as a grazing strategy to maintain high-quality grass throughout the grazing season, while reducing the build up of senescent material and proliferation of non-PRG grasses. This study demonstrated that, under the production environment of post-quota dairy systems in Ireland, grazing management practice can have a major impact on structural characteristics and nutritive value of the sward.

Keywords: stocking rate, post-grazing sward height, grazing, tiller density, entire season, rejected area, leaf yield.

3.2 Introduction

Worldwide demand for dairy products is expected to increase as a result of projected population growth and increases in per capita disposable income (Delgado, 2005). Grass-based dairy production systems, based on converting cheaply-produced grazed-grass into milk, are highly profitable and provide pastoral dairy farmers with a competitive advantage over other production systems within an increasingly competitive global milk-production environment (Dillon *et al.*, 2005). Grazed grass remains the cheapest source of feed (Shalloo *et al.*, 2004) and a key profit driver for all dairy systems (Macdonald *et al.*, 2011a). Dillon *et al.* (2008) suggested that, in countries in which grass makes up a high proportion of the diet of dairy cows, a 10% increase in the proportion of grazed grass included in the cow's diet reduces total production costs per litre by 2.5 euro cent. As pastoral farming systems develop and expand, increased quantities of herbage are required to feed larger herds and so grazing management practices must focus on increasing herbage production and utilisation within such systems. Additionally, within an European Union (EU) context, the abolition of constraining milk quotas in 2015 will allow increased milk production partially through increased milk production per cow but also higher stocking rates (SR), resulting in increased feed demand on farm.

While grass-based production systems focused on high per-animal productivity during the EU milk-quota era, per-hectare (ha) grassland productivity will increasingly limit grass-based milk production post milk quotas (Shalloo *et al.*, 2004). Consequently, grazing management practices will need to be adopted to realise increased grass production and quality, and sustain higher overall SR even at the expense of individual animal performance (McCarthy *et al.*, 2011). Improvements in grass production, utilisation and digestibility arising from changes in grazing pressure could also positively impact on the environmental sustainability of grazing if increased quantities of milk production can be achieved with a reduced requirement for chemical fertiliser or the importation of feed supplements to the grazing system (Dillon and Delaby, 2009; Soussana *et al.*, 2004).

Efficient exploitation of grass by grazing will require the development of grazing systems designed to achieve high per-cow intakes while producing a greater quantity of high-quality pasture over a long grazing season (Peyraud *et al.*, 2001). Achieving the correct balance between herbage quality and quantity is critical in grass-based production systems and changes in defoliation severity impact on sward growth, morphology and structure. Michell and Fulkerson (1987) found that high relative grazing severity produced higher growth rates of grass leaf but at the expense of total growth, due to a reduction in stem production. Other studies have reported reduced pasture growth in association with lax grazing, mainly due to increased plant senescence and decay (Hunt and Brougham, 1967; Tainton, 1974). More recently, Lee *et al.* (2008) and Macdonald *et al.* (2008) have both reported reduced herbage production through repeated lax defoliation. In addition to the effects on herbage accumulation, the severity of grazing may also affect sward components. Both Stakelum and Dillon (1990) and O'Donovan and Delaby (2005) observed significantly more green leaf and less dead material in severely-grazed swards resulting in increased sward nutritive value in comparison to laxly-grazed swards.

Many classical studies have reported the impact of grazing severity, typically investigating the effects of large differences in grazing severity (often in excess of 3 cm) on traditional mixed-species pastures (Binnie and Harrington, 1972; Brougham, 1956; Grant *et al.*, 1981). While these studies provide the basis for our understanding of grazing management impacts, the differential in defoliation severity was usually outside the practical range implemented on efficiently-managed grazing dairy farms (O'Donovan *et al.*, 2011b). Most grazing management studies investigating the effects of defoliation severity on herbage characteristics have been limited to small scale plot and glass-house studies (Fulkerson, 1994; Fulkerson and Slack, 1995) or, if performed under grazing, were limited in time (Baker and Leaver, 1986; Hoogendoorn and Holmes, 1992; Pulido and Leaver, 2003). Additionally, much of the emphasis within these studies focused on animal performance (Greenhalgh *et al.*, 1966) or overall system efficiency (Macdonald *et al.*, 2001) rather than specifically on the agronomic effects.

The objective of the present experiment was to examine the cumulative effects of consistently applying three levels of grazing severity within the practical range of grazing management used under modern grazing management practices (4 cm; Kennedy *et al.*, 2007b; Lee *et al.*, 2008) on sward dry matter (DM) production, structure, morphology and chemical composition, under an intensive grazing regime, across an entire grazing season and using modern best practice grazing management techniques (Kennedy *et al.*, 2006; Kennedy *et al.*, 2007c; Läpple *et al.*, 2012; McCarthy *et al.*, 2012). The hypothesis of this study was that increasing grazing severity would increase the annual productivity and utilisation of modern high productivity perennial ryegrass (PRG; *Lolium perenne* L.) pastures.

3.3 Materials and methods

The experiment was conducted at Curtins Research Farm, Teagasc, Animal & Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork, Ireland (52^{o}7'N; 8^{o}16'W; 46 m above sea level). This experiment focused on sward characteristics and was a component of a larger study (48.1 ha) investigating the effect of SR and calving date on dairy cow performance (McCarthy *et al.*, 2012). A temporary grassland site with 2- to 3-year old PRG swards was used to measure the effects of three grazing-severity levels on sward production and characteristics. The original cultivars sown were *cv.* Tyrella (diploid) and *cv.* Bealey (tetraploid). No clover was present in the sward. The three blocks used in the study were sown between 2006 and 2009 in the autumn period. Seeding rate was 28 kg/ha. The soil type was a free-draining acid-brown-earth soil with a sandy-loam-to-loam texture. The experiment was undertaken from 10 February to 18 November 2009. Rainfall and air and soil temperatures were recorded daily at a meteorological station less than 1 km away from the experimental site. The findings of this study are reported as three seasons: spring (10 February to 15 April), mid-season (16 April to 31 July) and autumn (1 August to 18 November). The effect of grazing severity is considered in each season separately as well as over the entire grazing year.

3.3.1 Experiment and treatments

A 4.1-ha grazing area (8% of the farm) was used to compare the effects of three levels of grazing severity on pasture production and sward characteristics. Holstein-Friesian dairy cows were used in this experiment and were described previously by Coleman *et al*. (2009). Further information on animal performance during the larger study was reported by McCarthy *et al.* (2012). The three grazing severity treatments were: lax (L), intermediate (I) and severe (S) grazing, with target post-grazing sward heights of 4.5 to 5 cm, 4 to 4.5 cm and 3.5 to 4 cm, respectively, obtained by variations in SR.

Three grazing blocks of similar size were selected within the farm (1.36 ha ±0.092). Within each block there were three paddocks, one assigned to each treatment (0.40 to 0.52 ha, depending on the grazing-severity treatment). Artificial fertiliser application rates were kept constant for each treatment at 250 kg nitrogen (N)/ha/year (30 kg N/ha ±0.9 kg following each grazing) in the form of calcium ammonium nitrate (CAN; 0.27 N). Soil fertility status was similar and adequate (soil index 3 for phosphorus and potassium; soil pH 6.5) during the study for each block selected, and recommended maintenance macro-nutrient applications were made during the grazing season (Teagasc, 2008).

3.3.2 Grazing management

Paddocks within each treatment were rotationally-grazed for the 10-month grazing season and restricted access time to pasture was practiced during periods of inclement weather to avoid pasture damage (Kennedy *et al.*, 2009). The decision rules applied to the larger experiment, including the selected paddocks, are outlined in McCarthy *et al.* (2012). The residency time within each paddock ranged from 1.5 to 2.5 days/paddock and was dictated by the time required to reach the desired post-grazing sward height. Rotation lengths also varied between treatments. The experimental paddocks were exclusively grazed and no silage or mechanical topping took place in these paddocks during the study. The number of grazing rotations was 12, 11.7 and 11 for L, I and S treatment paddocks, respectively.

3.3.3 Measurements

3.3.3.1 Pre- and post-grazing herbage mass, herbage accumulated and herbage harvested

Pre-grazing herbage mass (HM) above 3.5 cm was determined by cutting two strips per paddock (1.2 m × 10 m) with a motor Agria mower (Etesia UK Ltd., Warwick, UK; Figure 3.1) and taking the average of the two harvests similar to Kennedy *et al.* (2009) and McEvoy *et al.* (2010). The herbage yielded from each cut strip was collected, weighed and sampled, and a sub-sample (100 g) was dried overnight at 90ºC in a forced-draught oven to determine DM content. Ten grass-height measurements were recorded before and after harvesting on each cut strip using a folding pasture plate meter with a steel plate meter (diameter 355 mm and 3.2 kg/m^2; Jenquip, Fielding, New

Zealand; Earle and McGowan, 1979). Based on the above measurements, sward density (kg DM/ha per cm >3.5 cm) was calculated by dividing ore-grazing HM above 3.5 cm by compressed pasture height.

Pre-grazing HM below 3.5 cm was measured within each cut strip using a 0.5m×0.2m quadrat and scissors (Figure 3.1) and all collected material was washed to remove any soil contamination and dried overnight at 90^{o}C in a forced-draught oven to determine DM content. Total HM was then calculated by adding pre-grazing HM above and below 3.5 cm. Post-grazing HM above 3.5 cm was determined after grazing by cutting a 20-m strip per paddock, following a similar procedure to pre-grazing HM.

(a) (b)

Figure 3.1 (a) Herbage mass measurement above the 3.5-cm horizon and (b) herbage mass measurement below the 3.5-cm horizon.

Herbage accumulated between grazings was calculated as the pre-grazing HM less the post-grazing HM of the previous rotation. Herbage harvested (kg DM/ha utilised; above 3.5 cm) was calculated as the pre-grazing HM less the post-grazing HM within the same rotation. Total herbage accumulated and harvested during each period and over the entire grazing season was calculated as the sum of all herbage accumulated and harvested. Pre- and post-grazing sward heights were measured with the rising plate meter, taking 35 measurements across the diagonals of each paddock. Finally, the proportion of available herbage utilised (harvesting efficiency) was calculated on an individual paddock and grazing event basis as the proportion of the pre-grazing HM which is harvested. The proportion of available herbage utilised reflects the grazing severity of an individual grazing event (and approaches 1.00 when paddocks are grazed to 3.5 cm).

3.3.3.2 Sward structure, sward morphology and tiller density

Extended tiller height (ETH) and extended sheath height (ESH) were measured on 200 random primary tillers immediately pre- and post-grazing across the diagonals of each paddock using a graduated ruler (Figure 3.2). The ETH was measured from ground level to the highest point of the tiller. The ESH was measured from ground level to the point of the highest ligule (longest leafed sheath). Free leaf lamina (FLL) was then calculated by subtracting the ESH from the ETH, as described by Gilliland *et al.* (2002). The proportion of rejected area or those areas laxly grazed due to the presence of faecal and urine deposits, was visually assessed using a 1m×1m quadrat placed randomly at 10 points along the diagonal of each paddock, when ETH and ESH were measured (Figure 3.2). The number of tillers that were selected from rejected (taller grass) or non-rejected areas (grazed at the expected grazing height) to measure ETH and ESH was consistent with the proportion of rejected area previously measured with the quadrat.

(a) (b)

(c) (d)

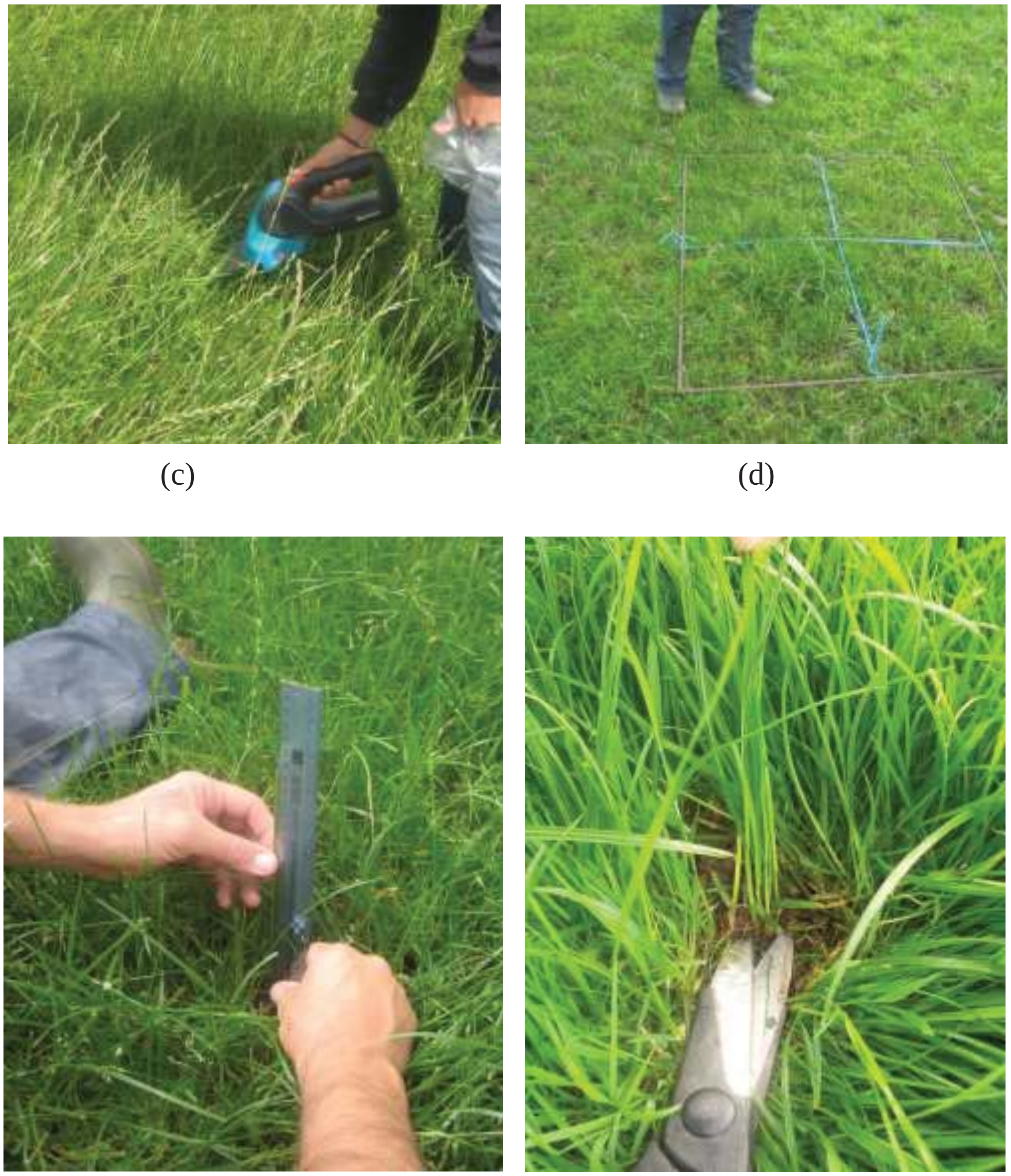

Figure 3.2 (a) Sampling with hand shears; (b) assessment of grazing rejected areas; (c) extended tiller height measurement and (d) sampling procedure for morphological measurement.

The morphological composition of the herbage was determined before each grazing. Twenty grab samples (approx. 80 g in total) were cut at random to ground level with scissors in each paddock (Figure 3.2). By securing the sample with an elastic band and placing it in a bag, the vertical structure of the cut sward was preserved. A 40-g sub-sample was selected from the sample while fresh and separated into two portions – above and below 3.5 cm. Each portion was subsequently separated into leaf, stem (including true stem, pseudo-stem and flower head, if present) and dead material. Each component was dried overnight in an oven at 90^{o}C to determine morphological composition on a DM basis. The DM weight of each component was divided into the total DM weight of the sample to estimate the proportion of each component in the sample. Leaf, stem and dead yields were estimated using the proportion of each component from the herbage accumulated. To estimate tiller density, 10 turves per paddock (10 cm × 10 cm) were taken on 5 February, 17 June and 2 November. The tillers were separated into PRG or other-grass species (*Poa pratensis*, *Poa trivialis* and *Agrostis stolonifera*) and counted, and then multiplied by 100 to estimate number of tillers/m^2 (Jewiss, 1993). The daily net change in tiller density was calculated for each treatment as the difference between the number of tillers on measurement dates divided by the number of days between measurements.

3.3.3.3 Sward quality

Herbage, representative of that removed by animals during grazing was sampled weekly from each paddock with hand shears (Accu 60, Gardena International GmbH, Ulm, Germany; Figure 3.2), taking cognisance of the previous defoliation height recorded from each treatment, i.e., after careful observation of post-grazing residuals of previous grazing. A sub-sample was dried at 40°C for 48 hours and subsequently milled through a 1-mm screen prior to chemical analysis, which consisted of ash, neutral-detergent fibre (NDF; Ankom Technology, Macedon, New York, USA), organic-matter digestibility (OMD; Fibered Systems, Foss, Ball mount, Dublin, Ireland) and crude protein (CP) analyses (Lecco FP-428, Lecco Australia Pty Ltd., Castle Hill, New South Wales, Australia).

3.3.4 Statistical analysis

All sward measurements were analysed using the SAS (Statistical Analysis System, version 9.2; SAS Institute Inc., Cary, NC, US). Analysis of variance was performed using the MIXED procedure with a mixed model that included the fixed effects of block, treatment and rotation, and their interaction, and the random effect of paddock.

Alternative covariance structures were investigated based on biological plausibility including compound symmetry, unstructured and autoregressive options both with homogenous or heterogeneous variances. Using the Akaike's information criterion, a compound symmetry error structure was determined as the most appropriate residual covariance structure. Rotation length was analysed using the GLM procedure with a linear model that included the effects of treatment, block and rotation. The proportion of herbage available utilised was analysed after root-square transformation. Means and 0.95-confidence intervals (CI) are presented after back transformation.

3.4 Results

3.4.1 Weather

Compared to the period from 1999 to 2008 (913 mm), total rainfall during the study was 33% higher (1,213 mm). Mean daily temperature (9.5ºC) was 1.1ºC lower than the 10-year average (10.6ºC). Average daily soil temperatures from February to November were 5.1, 7.3, 10.2, 13.4, 18.3, 17.7, 17.5, 14.9, 12.8 and 8.0ºC.

3.4.2 The effect of grazing severity on sward productivity

Grazing severity had no significant effect on herbage accumulation. Block had a significant effect on sward structure and productivity however, as there were no interactions between grazing severity treatment and block, only the main effects of grazing severity treatment are reported.

3.4.3 Spring (10 February to 15 April)

Each treatment was grazed twice during the spring period. The average re-growth interval between grazings was 46 ±3.5 days, and average herbage growth rate was 12.7 kg DM/ha/day during this period.

3.4.3.1 Pre- and post-grazing herbage mass, post-grazing sward height, sward density, herbage accumulated and herbage harvested

Average HM above and below 3.5 cm, pre-grazing sward height and sward density were similar for all treatments (means 881 and 1,137 kg DM/ha, 6.7 cm and 261 kg DM/cm, respectively). Post-grazing sward height, herbage accumulated and herbage harvested were similar for each grazing severity treatment during spring (means 3.6 cm, 1,076 and 1,701 kg DM/ha, respectively). The effect of grazing severity on herbage utilisation of pre-grazing HM approached significance ($P = 0.13$) at 0.87 (CI 0.76-0.99) for L, 0.93 (CI 0.81-1.05) for M and 1.08 (CI 0.96-1.22) for S treatments.

3.4.3.2 Sward structure, sward morphology, tiller density and sward quality

Above and below the 3.5-cm horizon, the proportions of leaf (0.72 and 0.05, respectively), stem (0.14 and 0.56, respectively) and dead material (0.15 and 0.38, respectively) were not affected by treatment. There was also no effect on PRG and non-PRG tiller densities (Figure 3.3; means 4,259 and 953 tillers/m^2, respectively). Grazed-herbage quality was unaffected by treatment during spring (means OMD = 785.4 g/kg, NDF = 439.7 g/kg and CP = 229.0 g/kg; Table 3.1).

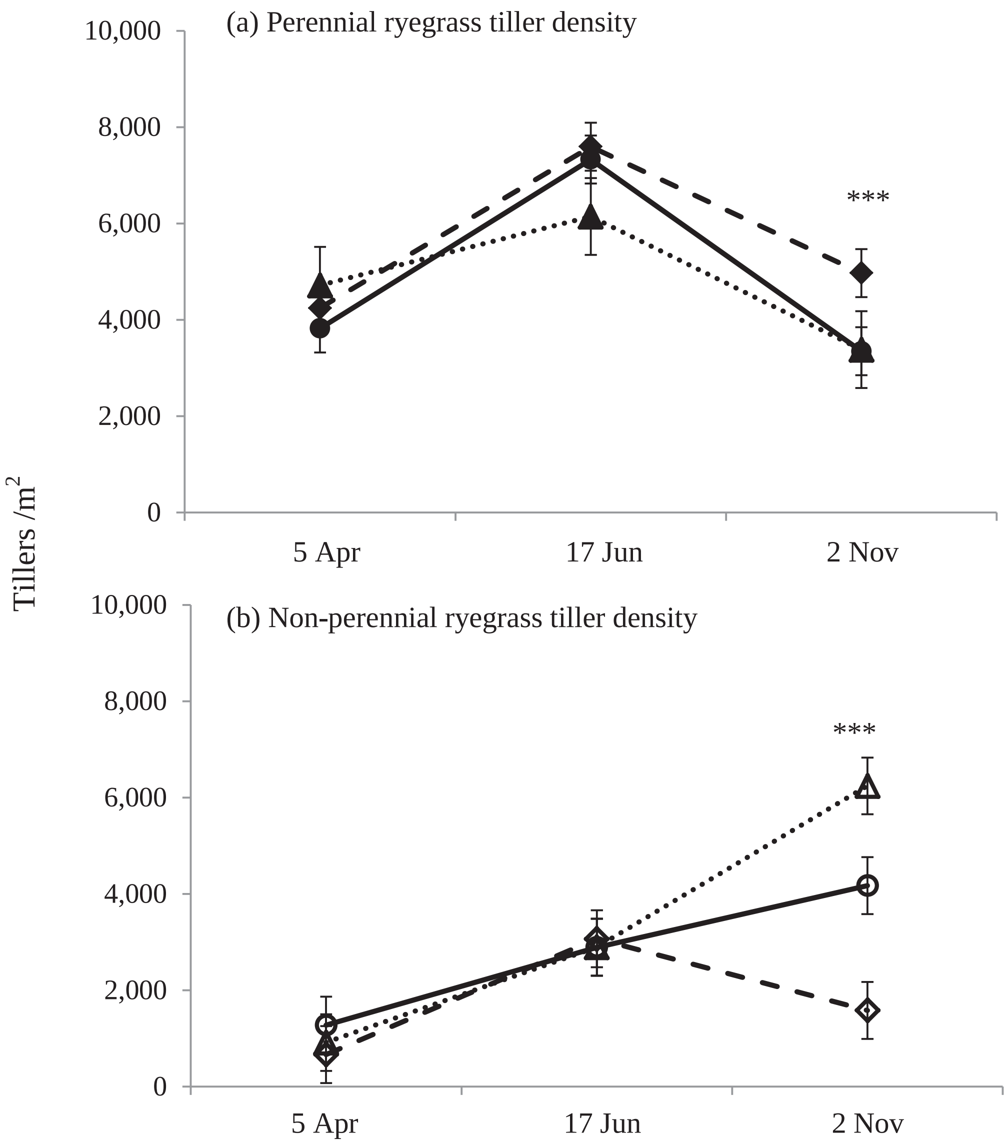

Figure 3.3 Effect of grazing severity on (a) perennial ryegrass tiller density (lax ▲, intermediate ● and severe ◆) and (b) non-perennial ryegrass tiller density (lax △, intermediate ○ and severe ◇) during the grazing season. Treatment (T) by season (S) interaction (*** corresponding to treatment-by-season interaction, $P < 0.001$).

Table 3.1 Effect of lax (L), intermediate (I) or severe (S) grazing treatments on sward chemical composition (CP = crude protein; OMD = organic-matter digestibility; NDF = neutral-detergent fibre).

	Treatment				Level of
	L	I	S	s.e.m.	significance
Spring					
CP	0.23	0.23	0.23	0.004	NS
OMD (g/kg)	786.0	783.3	786.8	15.95	NS
NDF (g /kg)	437.2	453.8	428.0	8.47	NS
Ash (g/kg)	143.0	136.7	148.7	5.13	NS
Mid-season					
CP	0.19	0.19	0.19	0.004	NS
OMD (g/kg)	760.6[a]	770.7[ab]	782.9[b]	7.34	*
NDF (g/kg)	464.3[a]	469.6[a]	448.8[b]	4.53	*
Ash (g/kg)	129.8	123.7	127.1	3.61	NS
Autumn					
CP	0.21	0.19	0.21	0.007	NS
OMD (g/kg)	721.2[a]	706.7[a]	751.4[b]	11.20	**
NDF (g/kg)	511.0[a]	505.3[a]	485.7[b]	7.44	*
Ash (g/kg)	109.2	110.7	121.9	5.90	NS
Entire grazing season					
CP	0.20	0.20	0.20	0.003	NS
OMD (g/kg)	752.6[a]	750.8[a]	769.5[b]	5.95	†
NDF (g/kg)	472.1[a]	484.5[b]	462.7[a]	3.00	***
Ash (g/kg)	125.4[ab]	121.9[a]	129.1[b]	2.16	†

Within rows means not showing a common superscript differ significantly ($P < 0.05$).
s.e.m.; standard error of the mean.
NS, not significant; † $P < 0.1$; * $P < 0.05$; **, $P < 0.05$; ***, $P < 0.001$.

3.4.4 Mid-season (16 April to 31 July)

There were 6.1 ±0.2 grazing rotations completed by each grazing severity treatment during the mid-season period. The interval between grazings (mean 16.6 days) and herbage growth rate (mean 60.6 kg DM/ha/day) were also unaffected by treatment.

3.4.4.1 Pre- and post-grazing herbage mass, herbage accumulated, sward density and herbage harvested

There was no difference between treatments in pre-grazing HM (mean 1,109 kg DM/ha), herbage accumulated (mean 5,704 kg DM/ha) or sward density (mean 248 kg DM/cm) during the mid-season period (Table 3.2). Stem yield tended to be higher on L paddocks, lower on S paddocks and intermediate on I paddocks, with a difference of 1,062 kg DM/ha between the L and S treatments ($P < 0.1$). Dead yield tended to be lower on S paddocks, compared to the other treatments, by 208 kg DM/ha ($P < 0.1$). Post-grazing HM was highest for L, intermediate for I and lowest for S paddocks ($P < 0.001$). The effect of grazing severity on herbage harvested during mid-season approached significance ($P = 0.08$) with reduced herbage harvested on the L treatment (4,761 kg DM/ha) compared to both I and S treatments (mean 5,864 kg DM/ha). The S treatment achieved the highest ($P < 0.001$) level of available herbage utilisation while I was intermediate and L lowest. The proportion of grazing area rejected by the cows was lowest (0.08) in S paddocks, highest in L paddocks (0.21) and intermediate in I paddocks (0.16; $P < 0.001$;Figure 3.4). Below the 3.5 cm grazing height, pre-grazing HM was similar for all treatments (mean 2,344 kg DM/ha).

Table 3.2 Effect of lax (L), intermediate (I) or severe (S) grazing treatments on mean pre- and post-grazing herbage mass, sward structure and sward morphology during mid-season (16 April to 31 July 2009).

	Treatment				Level of
	L	I	S	s.e.m.	significance
Pre-grazing					
Herbage mass (kg DM/ha >3.5 cm)	1,138	1,187	1,001	112.1	NS
Height (cm)	7.7	8.1	7.4	0.31	NS
Sward density (kg DM/cm)	247	250	248	11.4	NS
Herbage accumulated (kg DM/ha)	5,320	5,959	5,834	398.2	NS
Extended tiller height (cm)	23.7	23.6	22.4	0.68	NS
Extended sheath height (cm)	12.1[a]	10.4[ab]	9.5[b]	0.67	*
Free leaf lamina (cm)	11.7	13.2	12.8	0.45	0.12
Leaf proportion above 3.5 cm	0.56[a]	0.60[b]	0.64[c]	0.016	**
Stem proportion above 3.5 cm	0.33[a]	0.27[b]	0.24[b]	0.019	*
Dead proportion above 3.5 cm	0.11	0.13	0.12	0.011	NS
Leaf yield (kg DM/ha >3.5 cm)	4,024	4,441	3,888	201.7	NS
Stem yield (kg DM/ha >3.5 cm)	2,475	1,880	1,413	224.4	†
Dead yield (kg DM/ha >3.5 cm)	933	848	683	45.7	†
Post-grazing					
Herbage mass (kg DM/ha >3.5 cm)	401[a]	263[b]	103[c]	36.7	**
Height (cm)	5.1[a]	4.5[b]	3.7[c]	0.12	***
Extended tiller height (cm)	14.8[a]	14.0[a]	10.8[b]	0.53	**
Extended sheath height (cm)	10.0[a]	9.1[a]	6.7[b]	0.47	**
Free leaf lamina (cm)	4.8[a]	5.1[a]	4.1[b]	0.30	0.11
Herbage harvested (kg DM/ha)	4,761	5,969	5,758	286.4	†
Herbage available utilised	0.65[a] (0.61-0.69)	0.81[b] (0.77-0.86)	0.95[c] (0.90-1.01)		***

Within rows means not showing a common superscript differ significantly ($P < 0.05$).
s.e.m.; standard error of the mean.
NS, not significant; † $P < 0.1$; * $P < 0.05$; **, $P < 0.05$; ***, $P < 0.001$.
Numbers between brackets are 0.95 confidence intervals after back transformation.

3.4.4.2 Sward structure, sward height, sward morphology and tiller density

There was no significant difference in pre-grazing sward height between treatments (mean 7.8 cm; Table 3.2). Compared to spring, leaf proportion above 3.5 cm was lower in mid-season (0.60) while the proportion of stem was greater (0.28). The I and S treatments had significant greater leaf (0.62) and lower stem (0.26) proportions, compared to the L treatment (0.56 and 0.33, respectively). Below the 3.5-cm horizon, leaf (0.05), stem (0.53) and dead proportions (0.42) were similar for the three treatments. Laxly-grazed paddocks had a lower PRG tiller density (6,144 tillers/m^2; $P < 0.05$) than the other two treatments (mean 7,461 tillers/m^2) during mid-season, while there was no difference in non-PRG tiller density (mean 2,951 tillers/m^2; Figure 3.3). Post-grazing sward height was highest for L, intermediate for I and lowest for S treatments. Extended sheath height was significantly ($P < 0.05$) higher for L paddocks (12.1 cm) compared to I and S paddocks (10.4 and 9.5 cm, respectively). Post-grazing ETH and ESH were lowest in S paddocks (10.8 and 6.7 cm, respectively) in contrast to the means of the other two levels of grazing severity (14.4 and 9.6 cm). Post-grazing FLL was unaffected by treatment during mid-season (mean 4.7 cm).

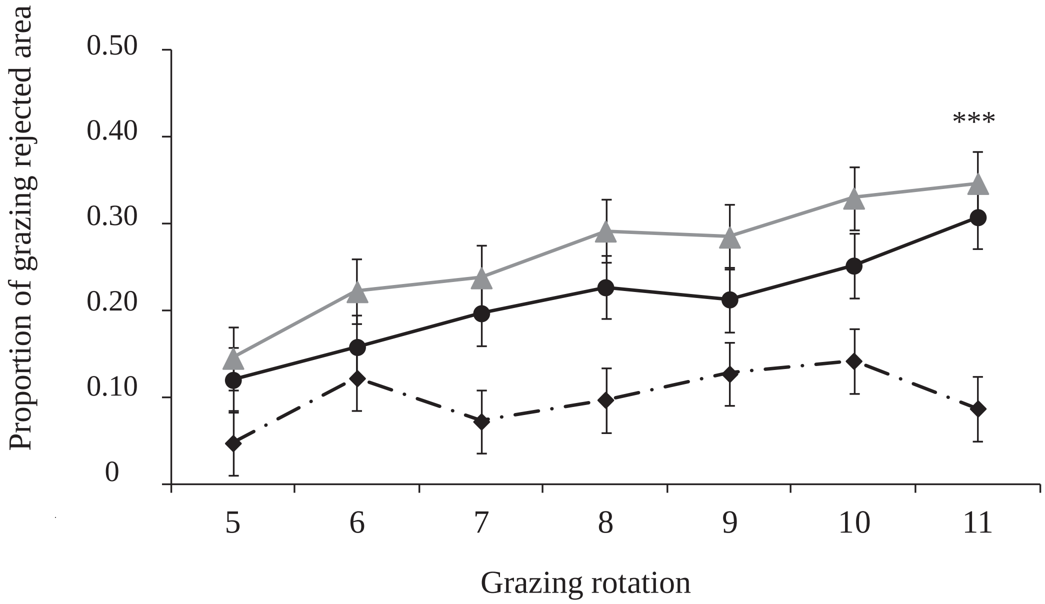

Figure 3.4 Effect of grazing severity on the proportion of rejected area at each grazing rotation (rotation 5, mid/late June; rotation 11, late October/early November; lax ▲, intermediate ● and severe ◆; *** corresponding to treatment-by-rotation interaction, $P < 0.001$).

3.4.4.3 Sward quality

The chemical composition of the swards in mid-season is shown in Table 3.1. Neither CP content nor ash were influenced by treatment (means 0.19 and 126.9 g/kg, respectively). While OMD was reduced for all treatments in mid-season, the S treatment achieved a higher OMD (782.9 g/kg; $P < 0.05$) compared to both the I (770.7 g/kg) and L (760.6 g/kg) treatments, respectively. Similarly, the NDF content of the L and I treatments (464.3 and 469.6 g/kg, respectively) was higher ($P < 0.05$) than S (448.8 g/kg) during mid-season.

3.4.5 Autumn (1 August to 18 November)

There were 3.3 grazing rotations completed during the autumn period. The average rotation length was 27.0 days and mean daily herbage growth rate was 46.8 kg DM/ha/day.

3.4.5.1 Pre- and post-grazing herbage mass, herbage accumulated and herbage harvested

There was no effect of treatment on pre-grazing HM (mean 1,395 kg DM/ha), sward density (mean 239 kg DM/cm) or herbage accumulated (mean 4,538 kg DM/ha; Table 3.3). There was also no significant effect of grazing severity on leaf yield (mean 3,004 kg DM/ha), however both stem and dead material yields were higher ($P < 0.05$) for the L treatment (1,702 and 1,045 kg DM/ha, respectively) compared to both I (970 and 722 kg DM/ha, respectively) and S (652 and 364 kg DM/ha, respectively) during autumn. Post-grazing HM was highest for L (395 kg DM/ha), intermediate for I (115 kg DM/ha) and lowest for S paddocks (8 kg DM/ha). The L treatment harvested more herbage (4,516 kg DM/ha; $P < 0.05$) during autumn compared to both I and S (3,870 and 3,771 kg DM/ha, respectively).

Table 3.3 Effects of lax (L), intermediate (I) or severe (S) grazing treatments on pre- and post-grazing herbage mass, sward structure and sward morphology during autumn (1 August to 18 November 2009).

	Treatment				Level of
	L	I	S	s.e.m.	significance
Pre-grazing					
Herbage mass (kg DM/ha >3.5 cm)	1,466	1,371	1,349	142.2	NS
Height (cm)	9.4	9.1	9.0	0.35	NS
Sward density (kg DM/cm)	233	247	238	12.4	NS
Herbage accumulated (kg DM/ha)	4,597	4,440	4,576	303.2	NS
Extended tiller height (cm)	26.9	26.2	25.2	0.99	NS
Extended sheath height (cm)	12.4[a]	7.2[ab]	4.8[b]	1.25	**
Free leaf lamina (cm)	15.8	17.7	19.6	1.71	NS
Leaf proportion above 3.5 cm	0.55[a]	0.60[ab]	0.73[b]	0.042	*
Stem proportion above 3.5 cm	0.28[a]	0.23[ab]	0.17[b]	0.023	*
Dead proportion above 3.5 cm	0.18[a]	0.18[a]	0.10[b]	0.025	†
Leaf yield (kg DM/ha >3.5 cm)	3,118	2,862	3,033	196.4	NS
Stem yield (kg DM/ha >3.5 cm)	1,702[a]	970[b]	652[b]	195.6	*
Dead yield (kg DM/ha >3.5 cm)	1,045[a]	722[b]	364[b]	136.6	†
Post-grazing					
Herbage mass (kg DM/ha >3.5 cm)	395[a]	115[b]	8[c]	40.6	**
Height (cm)	5.2[a]	3.9[b]	3.5[c]	0.13	***
Extended tiller height (cm)	19.6[a]	14.6[b]	9.6[c]	0.68	***
Extended sheath height (cm)	14.6[a]	8.3[b]	5.1[c]	0.81	***
Free leaf lamina (cm)	5.5	5.6	4.2	0.72	NS
Herbage harvested (kg DM/ha)	4,516[a]	3,870[b]	3,771[b]	121.3	*
Herbage available utilised	0.69[a] (0.59-0.79)	0.83[ab] (0.73-0.95)	0.92[b] (0.81-1.04)		*

Within rows means not showing a common superscript differ significantly ($P < 0.05$).
s.e.m.; standard error of the mean.
NS, not significant; † $P < 0.1$; * $P < 0.05$; **, $P < 0.05$; ***, $P < 0.001$.
Numbers between brackets are 0.95 confidence intervals after back transformation.

The S treatment achieved the highest level of available herbage utilisation (0.92; $P < 0.05$) compared to L (0.69), while I (0.83) was intermediate. The proportions of grazing area rejected during autumn were 0.33, 0.24 and 0.13 for L, I and S treatment paddocks, respectively ($P < 0.001$; Figure 3.4). Below-3.5 cm pre-grazing HM was not different between treatments (mean 2,226 kg DM/ha).

3.4.5.2 Sward structure, sward height, sward morphology and tiller density

Pre-grazing sward height was similar across treatments (mean 9.2 cm) while post-grazing sward height decreased with increasing levels of grazing severity (Table 3.3). Pre-grazing, neither ETH nor FLL length differed significantly between treatments (26.1 and 17.7 cm, respectively), however ESH was highest ($P < 0.05$) for L paddocks (12.4 cm) lowest for S paddocks (4.8 cm) and intermediate for I paddocks (7.2 cm). Although grazing severity had no effect on post-grazing FLL length (mean 5.1 cm), L paddocks had the greatest post-grazing ETH (19.6 cm; $P < 0.001$) and ESH (14.6 cm; $P < 0.01$), while S were shortest (9.6 and 5.1 cm, respectively; $P < 0.05$) and I were intermediate (14.6 and 8.3 cm, respectively).

Sward structure and morphology were affected by treatment during autumn. Leaf proportion above 3.5 cm in the pre-grazing sward was highest ($P < 0.05$) for S (0.73), lowest for L (0.55) and intermediate for I (0.60). Conversely, stem and dead proportions above 3.5 cm in the pre-grazing sward were lowest for S (0.17 and 0.10; $P < 0.05$) and highest for L (0.28 and 0.18; $P < 0.05$), while I was intermediate (0.23 and 0.18, respectively). The proportion of leaf, stem and dead material above 3.5 cm in the post-grazing sward was unaffected by grazing treatment. During autumn, S paddocks had the highest PRG tiller density (4,969 tillers/m^2; $P < 0.001$) compared to L and I treatments (3,381 and 3,347 tillers/m^2; respectively). Non-PRG tiller density was highest in L paddocks (6,242 tillers/m^2; $P < 0.001$), lowest in S (1,581 tillers/m^2; $P < 0.001$) and intermediate for I (4,172 tillers/m^2; Figure 3.3).

3.4.5.3 Sward quality

Neither CP content nor ash were influenced by treatment (means 0.20 and 113.9 g/kg, respectively; Table 3.1). The S treatment achieved a higher ($P < 0.05$) OMD (751.4 g/kg) and lower ($P < 0.05$) NDF (485.7 g/kg) content compared to both the I

(706.7 and 505.3 g/kg, respectively) and L (721.2 and 511.0 g/kg, respectively) treatments.

3.4.6 Entire grazing season (10 February to 18 November)

There were 11.4 grazing rotations during the study, with a mean rotation length of 24.9 days.

3.4.6.1 Pre- and post-grazing herbage mass, herbage accumulated and herbage harvested

Grazing severity had no significant effect on pre-grazing HM, sward density, total herbage accumulated or harvested during the grazing season (Table 3.4). While there was no significant effect of grazing severity treatment on leaf yield (mean 8,405 kg), the L treatment produced more stem (4,439 kg DM/ha; $P < 0.05$) and dead (2,230 kg DM/ha; $P < 0.05$) material compared to both the I (3,072 and 1,808 kg DM/ha) and S (2,275 and 1,297 kg DM/ha) treatments. Average herbage utilisation was 0.71, 0.83 and 0.97 for L, I and S, respectively ($P < 0.01$), while the proportion of area rejected was 0.27, 0.17 and 0.10, respectively ($P < 0.001$; Figure 3.4). Pre-grazing HM below 3.5 cm did not differ between treatments (mean 2,099 kg DM/ha).

Table 3.4 Effects of lax (L), intermediate (I) or severe (S) grazing treatments on pre- and post-grazing herbage mass, sward structure and sward morphology over the entire season (10 February to 18 November 2009).

	Treatment				Level of
	L	I	S	s.e.m.	significance
Pre-grazing					
Herbage mass (kg DM/ha >3.5 cm)	1,254	1,268	1,127	63.4	NS
Height (cm)	8.2	8.6	8.0	0.65	NS
Sward density (kg DM/cm)	246	236	231	12.3	NS
Herbage accumulated (kg DM/ha)	11,055	11,609	11,291	514.1	NS
Extended tiller height (cm)	24.8	24.0	23.4	0.46	†
Extended sheath height (cm)	11.2[a]	8.2[b]	7.3[b]	0.53	**
Free leaf lamina (cm)	13.6	15.1	15.5	0.84	NS
Leaf proportion above 3.5 cm	0.56[a]	0.62[b]	0.67[b]	0.021	*
Stem proportion above 3.5 cm	0.30[a]	0.23[b]	0.21[b]	0.016	*
Dead proportion above 3.5 cm	0.14	0.15	0.12	0.010	NS
Leaf yield (kg DM/ha >3.5 cm)	8,569	8,629	8,019	285.1	NS
Stem yield (kg DM/ha >3.5 cm)	4,439	3,072	2,275	391.4	†
Dead yield (kg DM/ha >3.5 cm)	2,230[a]	1,808[b]	1,297[c]	152.4	*
Post-grazing					
Herbage mass (kg DM/ha >3.5 cm)	340[a]	163[b]	26[c]	27.2	***
Height (cm)	4.9[a]	4.2[b]	3.6[c]	0.07	***
Extended tiller height (cm)	15.7[a]	13.8[a]	10.6[b]	0.49	***
Extended sheath height (cm)	10.7[a]	8.5[b]	6.3[c]	0.43	***
Free leaf lamina (cm)	5.1[a]	5.2[a]	4.2[b]	0.22	*
Herbage harvested (kg DM/ha)	11,043	11,506	11,200	554.9	NS
Herbage available utilised	0.71[a] (0.65-0.76)	0.83[b] (0.78-0.90)	0.97[c] (0.91-1.03)		**

Within rows means not showing a common superscript differ significantly ($P < 0.05$).
s.e.m.; standard error of the mean.
NS, not significant; † $P < 0.1$; * $P < 0.05$; **, $P < 0.05$; ***, $P < 0.001$.
Numbers between brackets are 0.95 confidence intervals after back transformation.

3.4.6.2 Sward structure, sward morphology and tiller density

Pre-grazing sward height did not differ between treatments (mean 8.3 cm). Laxly-grazed paddocks had the greatest pre-grazing ETH ($P < 0.01$; Table 3.4) and ESH ($P < 0.001$). Severely grazed paddocks were grazed 0.6 cm shorter than I and 1.3 cm shorter than L paddocks ($P < 0.001$). Post-grazing FLL was shortest in S paddocks (1 cm shorter, $P < 0.001$). Above the 3.5-cm horizon, S paddocks had the greatest proportion of leaf and the lowest proportion of stem (0.67 and 0.21, respectively; $P < 0.001$). Conversely, L paddocks had the lowest proportion of leaf and the greatest proportion of stem (0.56 and 0.30; $P < 0.001$). Below the 3.5-cm horizon, grazing severity did not affect the proportions of leaf, stem or dead components (means 0.04, 0.51 and 0.46, respectively). Severely-grazed paddocks tended to have a more dense PRG population than the other treatments (4,746, 4,832 and 5,602 PRG tillers/m^2 for L, I and S paddocks, respectively; $P < 0.1$) and contained the least number of non-PRG tillers (1,771/m^2; $P < 0.001$). Total tiller density was not different between treatments (mean 7,694 tillers/m^2; Figure 3.3).

3.4.6.3 Sward quality

Grazing severity had a significant effect on sward nutritive value during the study (Table 3.1). While there was no significant treatment effect on CP content (mean 0.20), the S treatment achieved the highest ($P = 0.06$) OMD content. Over the entire grazing season, the ash content of S swards was highest (129.1 g/kg; $P = 0.06$) compared to I (121.9 g/kg) which was lowest, while L was intermediate (125.4 g/kg).

3.5 Discussion

In intensive grass-based dairy systems, such as the likely Irish dairy system post-EU milk quotas, grazing management aims to achieve maximum performance of the whole farm system by optimising the interaction between pasture plants and grazing animals. Herbage productivity and sward characteristics within the grazing system are rarely studied. This is due to the variability in the biological material and inability to isolate the individual effects of factors such as pre-grazing HM, post-grazing residual height and rotation lengths being investigated, as well as the significant resource and measurement detail requirements. The overall impact of grazing management on system performance is complex, as the management practices to optimise grass growth may not achieve maximum performance from the farm system if they adversely impact upon animal performance.

The present experiment was undertaken to assess the cumulative effects of three grazing severities on the physical (DM production, sward structure, morphology and tiller density) and nutritional (CP, NDF, OMD) characteristics of mixed diploid and tetraploid swards across an entire grazing season. Similar to many previous grazing experiments (Baker & Leaver 1986; Hennessy *et al.*, 2008; Lee *et al.*, 2008; McEvoy *et al.*, 2009), the study was undertaken during a single grazing season and so the potential longer term effects of the imposed grazing regimes are not considered.

Temperatures in February were below the 10-year average resulting in low pasture growth rates, feed shortages and, consequently, similar low post-grazing residual sward heights for all treatments during the spring period. As a result, all treatments exhibited similar sward structure and morphology in spring, while differences in grazing management practice only became evident from mid-season onwards. Differences in post-grazing residual sward heights became significant thereafter. This resulted in increasingly different swards, particularly in terms of structure and morphology as the grazing season progressed. While the differential in post-grazing sward height between treatments is small, this difference had a significant effect on animal performance (resulting in lactation milk production levels of 5,757, 5,191 and 4,800 kg of milk per cow for the L, I and S treatments, respectively; McCarthy *et al.*, 2012). The grazing severity differentials imposed represent the biologically meaningful spectrum of grazing severity for well-managed pasture systems (Horan *et al.*, 2004; Kennedy *et al.*, 2006; O'Donovan *et al.*, 2011b). It is important to bear in mind that compressed sward heights were measured in this experiment when comparing with other experiments. The defoliation severities achieved (expressed as ETH post-grazing as a proportion of ETH pre-grazing) were 55, 43 and 37% for L, I and S treatments, which is indicative of normal, intermediate and severe grazing intensity, respectively (Wade, 1991).

3.5.1 Pre- and post-grazing herbage mass, herbage accumulated and herbage harvested

Total pasture DM yield and leaf accumulation above 3.5 cm were unaffected by grazing severity in the current study. This contrasts with previous results reported by Carton *et al.* (1989) and Stakelum and Dillon (2007) who found higher leaf yields with increased grazing pressure, but this was observed on swards with significantly greater pre-grazing HM than reported here. Due to low spring growth, mean pre-grazing HM in spring and mid-season were low (881 and 1,108 kg DM/ha, respectively above 3.5 cm) for all treatments and below the levels recommended for optimum plant growth by McEvoy *et al.* (2009), Curran *et al.* (2010) and Tuñon *et al.* (2011b). In addition, both Fulkerson *et al.* (1994) and Lee *et al.* (2008) concluded that optimal net herbage accumulation is achieved at a post-grazing residual height of approximately 5 cm. The increased grazing severity of I and S swards in this study (4.2 and 3.6 cm, respectively, compared to 4.9 cm for L) may have deleteriously impacted upon net herbage accumulation in comparison to maintaining a 'plant optimal' post-grazing residual. However, the increased grazing severity of I and S swards increased herbage utilisation, sward leaf content and PRG tiller density and, similar to Hernandez-Garay *et al.* (1999), may have conditioned the sward for superior long-term growth. The results of the present study agree with Bircham and Hodgson (1983) and Stakelum and Dillon (2007) and suggest that pasture production above 3.5 cm is insensitive to grazing management over a broad range of grazing conditions. Similarly, Fariña *et al.* (2011) has suggested that, while resulting in increased herbage utilisation and quality, grazing treatment has little effect on net herbage accumulation above 3.5 cm.

3.5.2 Sward quality, structure, morphology and tiller density

The decline in OMD and associated increase in NDF, was more pronounced within the L and I treatments compared to the S treatment, which is consistent with the differences in leaf, stem, and dead proportions of the various swards, and similar to previous results (Hoogendoorn and Holmes, 1992; L'Huillier, 1987; Michell and Fulkerson, 1987; Stakelum and Dillon, 2007). Hoogendoorn and Holmes (1992) and Hurley (2007) showed that severe grazing in the early-to-mid-summer period reduces the ratio of reproductive to vegetative tillers, thereby avoiding large accumulations of stem in the sward. Likewise, Stakelum and Dillon (1990) and O'Donovan and Delaby (2008) also found greater OMD values with swards that were grazed to low relative post-grazing sward heights and hence had greater proportions of leaf. The results of this study indicate that grazing to a post-grazing residual height to 3.5 to 4 cm (similar to I and H swards) over the entire season can be an effective management strategy to reduce the proportion of stem and dead material in PRG dominant swards, and arrest the decline in sward digestibility and green leaf content, typically observed during the grazing season.

The different post-grazing sward heights imposed within the current study resulted in swards of differing morphology emerging over the season. The proportion of leaf, stem and dead material observed compares favourably with previous studies at this location (Curran *et al.*, 2010; Stakelum and Dillon, 2007). Increased grazing severity in I or S swards (grazed to 4.2 and 3.6 cm, respectively) produced swards which contained higher concentrations of green leaf and digestible nutrients, but lower concentrations of grass stem and senescent material compared with swards that were grazed more laxly (5.1 cm). Johnson and Parsons (1985) reported that high levels of death and decay accompany poor utilisation of herbage. This concurs with the findings of this study as the L swards had greater accumulations of dead material above 3.5 cm due to a higher post-grazing sward height and lower levels of utilisation than both other treatments.

The increase in stem and dead material content of laxly-grazed swards has been widely reported (Hoogendoorn and Holmes, 1992) and has been explained by the greater age of the plant tissue (Korte *et al.*, 1984). Another cause of an increase in dead proportions is the reduced penetration of light into the lower strata of laxly-grazed swards due to canopy closure (Curll, 1982) which causes death of tillers (Ong, 1978). As grazing severity increased in both I and S swards, greater cow intake restriction resulted in increased grass utilisation while little residual herbage tissue remained after grazing. In contrast, the lax grazing of the L treatment allowed animals to selectively remove leaf in preference to stem and dead material while Frame and Hunt (1971) observed that 15 to 40% of the leaf that remains un-grazed within the sward eventually senesces causing a decrease in leaf proportion. Consistent with Baker and Leaver (1986), the severe grazing treatments resulted in less rejected area (0.10) compared to L (0.27).

The positive effects of increased grazing severity on the dynamics of grass growth and sward quality above 3.5 cm are further evidenced using structural data from the current experiment. In autumn, all treatments had similar pre-grazing FLL but the post-grazing ETH and ESH were lower on S and I swards compared to L swards. This indicates that, while leaf yield was similar for each treatment, the reduction in stem yield was mainly responsible for the increase in leaf proportion associated with increased grazing severity during mid-season and autumn. In addition, while S swards achieved a consistently lower post-grazing FLL length during the entire grazing season (4.2 cm), they also achieved a similar pre-grazing FLL length compared with L and I treatments (15.5 cm; Table 3.4). These results are similar to Davies (1974) and indicative of an increased leaf appearence rate in S swards during the re-growth interval between grazings. This can be associated with a high photosynthetic activity of young leaves (Gay and Thomas, 1995) whereas lax grazing is associated with higher proportion of older leaves with decreased photosynthetic capacity (Woledge, 1978). However, the findings differ from Grant *et al.* (1981) who reported lower leaf extension rate with lower ESH. These authors reported that leaf extension rate was greater in shaded plants due to promotion of growth of the main tiller and depression of tiller buds. Perhaps, the sheath heights in the present study were not sufficiently high so as to promote the increased growth of the main tiller, which was also reported by Grant *et al.* (1981).

Perennial ryegrass plants can adapt to severe defoliation regimes by growing leaves from lower insertion points on the tiller axis, to maintain plant carbon supply, this having the effect of restoring rates of photosynthesis and minimising the lag in DM accumulation during re-growth (Chapman *et al.*, 2011; Parsons *et al.*, 1988). A unique feature of PRG plants is that they can adopt a prostrate growth rapidly following defoliation, which allow them to maintain a higher level of residual leaf area index to survive intensive grazing regimes (Brock *et al.*, 1996). This could have contributed to the S treatment achieving a lower post-grazing sward height consistently across the grazing season.

Perennial ryegrass swards can also use their tillering ability to adapt to defoliation regimes. Differences in tiller density caused by management are generally due to changes in the amount of light that penetrates to tiller bases under the different defoliation regimes, which influence tiller initiation and appearance (Langer, 1963;

Mitchell, 1953). However, any effect of management practice on the sward can be masked by size/density compensation, also known as the ‘self-thinning rule’ law (Yoda *et al.*, 1963). Tiller size and density may have an inverse relationship (Langer, 1963). This means that, as HM increases, individual tillers are fewer but larger, while LAI and herbage accumulation remain constant (Matthew *et al.*, 1995). Peak tiller density seems to occur at 2 to 3 cm post-grazing residual height. Above this, tiller density changes following the self-thinning rule until it reaches an upper limit of 16 cm (Davies, 1988). This may help explain why grazing management did not affect herbage accumulation in the present study. Similarly, Grant *et al.* (1983) found that, with post-grazing residuals of 2.5 to 6 cm, any increase in growth rate was offset by increases in senescence, hence the net accumulation was similar between treatments.

The laxly-grazed treatment showed a slower increase in tiller numbers between the first two measurement dates (5 February and 17 June) in contrast to the other treatments (11 versus 25 tillers/day). There could have been an increase in death of vegetative tillers in the L treatment, due to failure of large tillers to supply assimilate to smaller tillers (Ong, 1978) or also due to flowering axis inhibiting the growth of tiller buds (Laidlaw and Berrie, 1974). These are important because both processes can potentially affect sward persistence (Tallowin, 1981). Net change in tiller density between the second and the third measurement dates, however, showed no differences between treatments. These findings agree with previous research (L'Huillier, 1987; Wade, 1979), reporting changes in tillering rates resulting from defoliation severity in spring but not in summer.

The reduction in non-PRG tiller ingression in the S sward as the grazing season progressed has been observed by both Korte *et al.* (1984) and Lee *et al.* (2008) and is related to the reduced opportunity for selective grazing offered to the S treatment animals. This is confirmed by the net change in numbers of non-PRG tillers, which were found to be significantly different from each other. Even though the composition of the base of the sward (below 3.5 cm) was quantified in this study, no significant sward composition differences were found and the main differences in leaf, stem and dead material content occurred in the grazing horizon. Similar to this study, both Michell and Fulkerson (1987) and Mayne *et al.* (1987) showed that HM increased at the sward base in the latter part of the season, due to stem and dead material accumulation.

The results of this study indicate that within the range of grazing severities investigated in this study, grazing management practice has an important impact on modern PRG swards for intensive grazing dairy production systems. While resulting in similar herbage accumulation above 3.5 cm, the results of this study indicate that increasing grazing severity to a consistent post-grazing residual height of 3.5 to 4 cm (similar to I and S swards in the current study) over the entire season can be an effective management strategy to increase the productivity of grass-based systems resulting in increased herbage utilisation, swards with higher concentrations of green leaf and digestible nutrients and less rejected herbage. While large differences in sward structure emerged during the grazing season, the results also suggest that future grazing research should consider the longer term and potentially cumulative effects of grazing management practice over multiple grazing seasons to fully quantify the effects of grazing management practice on the structure and productivity of PRG swards.

3.6 Conclusion

Milk quota abolition in Europe has revived interest in increasing SR to harvest more grass on dairy farms. From an agronomic perspective, increased SR coupled with an increase in grazing severity will result in similar net herbage and leaf accumulation and increased sward utilisation and quality. These findings endorse the concept of increased grazing severity as a method of retaining high-quality grass throughout the grazing season while reducing the build up of senescent material and proliferation of non-PRG grasses. This study demonstrated that, under the production environment of post-quotas dairy systems in Ireland, grazing management practice can have a major impact on characteristics and nutritive value of the sward.

Chapter 4: Herbage production and tiller density in Irish temperate grazing swards as affected by treading damage of dairy cows

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Accepted in Grass and Forage Science

4.1 Abstract

From March 2009 to October 2010, a perennial ryegrass-dominated sward on a well-drained soil (Experiment 1) and a creeping bent-dominated sward on a poorly-drained soil (Experiment 2) were subjected to four treading-damage treatments: control (C, no damage) light damage (L), moderate damage (M) or severe damage (S). In Experiment 1, treading damage was imposed on 17 March 2009. In Experiment 2, one third of the site was damaged on 20 October 2009, one third on 9 April 2010 and one third on both occasions. Both sites were grazed intermittently after treading damage. Pre-grazing herbage mass (HM) was estimated eight times in Experiment 1 and seven times in Experiment 2 on each plot. Tiller density was assessed four times at both sites. In Experiment 1, pre-grazing HM was reduced by 30% in S plots in the first cut after damage but cumulative HM was not different between treatments (12.7 tonnes dry matter/hectare). In Experiment 2, cumulative HM was reduced by between 14% and 51% depending on grazing frequency and season. Tiller density was not significantly affected by treatment in either experiment. A perennial ryegrass-dominated sward on a well-drained soil is resilient to heavy treading damage but a creeping bent-dominated sward on poorly-drained soil needs careful management to avoid significant losses in herbage production after treading damage.

Keywords: Poaching, pugging, herbage mass, temperate sward, free-draining soil, heavy soil.

4.2 Introduction

Worldwide there is rejuvenated interest in grazing systems as grazed grass remains the cheapest source of feed for dairy cows (Dillon *et al.*, 2008; Macdonald *et al.*, 2011a). In Ireland, the imminent abolition of milk quotas planned for 2015 challenges farmers to use their competitive advantage which is grass (Dillon, 2011). A powerful means to increasing the quantity of grass utilised by dairy cows is by extending the grazing season through earlier turnout to pasture in spring and/or by grazing swards longer into the autumn (Fox, 2000; Kennedy *et al.*, 2007b). A drawback of this is that grazing pastures early and late in the grazing season can increase the risk of treading damage, which will impinge on pasture growth and utilisation. In a survey conducted by Creighton *et al.* (2011) 60% of the sample population responded that soil conditions (and therefore the threat of treading damage) were the most limiting factor to extending the length of the grazing season in Ireland. This is a subject of growing concern, an example of this being grazing trials investigating the resistance of mixed perennial ryegrass (PRG)-white clover swards to trampling recently in Ireland (Phelan *et al.*, 2011).

Treading damage is complex and multi-factorial. It results from the integrated effects of animal, soil, plants and soil moisture content (Pande *et al.*, 2000). Treading damage can cause leaf burial in mud, crushing and bruising of the plants (Hamilton and Horne, 1988; Nie *et al.*, 2001), and reductions in both shoot and root growth (Cook *et al.*, 1996). In addition, treading increases roughness of the soil surface and may increase soil bulk density, which is a function of the level of compaction or, conversely, porosity (Betteridge *et al.*, 1999). Thus, losses in herbage growth can result from the direct effects of treading on the sward or, indirectly, from soil compaction and damage (Drewry *et al.*, 2001). In any case, decreased herbage growth rates after treading are often attributed to the reduction in grass tiller numbers (Pande *et al.*, 2000).

In a pasture-based system, quantifying the actual losses in pasture production is crucial. Treading damage has been shown to reduce herbage production by 20 to 40% (Horne, 1987; Ledgard *et al.*, 1996; Menneer *et al.*, 2005; Nie *et al.*, 2001). The effects, as reported in the review by Drewry *et al.* (2008), vary depending on length of the experiment, soil type, animal used and pasture species. For example, in a short-term experiment, conducted by Edmond (1958b), treading of sheep decreased grass accumulation up to 69%. Zegwaard *et al.* (2000), after treading with cattle, reported a 51% initial reduction in herbage production but full recovery of herbage growth after 98 days. In another experiment, severe damage effected a reduction in pasture production of 88% in a period of 100 days (Menneer *et al.*, 2001), although annual pasture production was reduced by 13 and 21%, with moderate poaching and by 34 and 45% with more severe poaching damage (Menneer *et al.*, 2001; Menneer *et al.*, 2005). It seems that initial reduction of herbage mass (HM) and overall annual reduction are to be considered separately when analysing the detrimental effects of treading damage.

Few studies have been performed in the Northern Hemisphere investigating the effects of treading damage on temperate pasture productivity, using field situations and measuring agronomic indicators such as tiller numbers. However, with the growing interest in grazing systems in European countries, the number of publications dealing with the effect of treading damage on the soil and on herbage parameters has been increasing (Herbin *et al.*, 2011; Kurz *et al.*, 2006; Phelan *et al.*, 2010; Piwowarczyk *et al.*, 2011; Tuñon *et al.*, 2010a), albeit most of the reported work on the subject comes from Australia and New Zealand, countries that have been focusing on intensive pasture-based systems for a long period of time. The objective of this study was to quantify the effect of treading damage in spring and autumn on herbage production and tiller density of grazing swards on two different soil types, a well-drained soil and a poorly-drained soil in Ireland.

4.3 Materials and methods

The study was undertaken at the Animal & Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland (52°7'N; 8°16'W; 46 m above sea level), during two consecutive grazing seasons (2009 and 2010). Two sets of plots were established on two differing grassland sites which were less than 5 km apart (experiments 1 and 2). The site for Experiment 1 had a two-year old PRG-dominated sward with some other grass and weed species, including annual meadow grass (*Poa annua* L.). No clover was present in the sward. The soil type was classified by Ryan *et al.* (2006) as a freely-draining acid-brown-earth, derived from mixed sandstone-limestone glacial till overlying a karstified-limestone bedrock-aquifer, this reflecting 2%

of the total land area of Ireland. The soil texture was sandy loam and the soil was typically up to 4.5-m deep with bedrock commonly occurring at 2.0 to 3.0 m below the ground surface (Gibbons *et al.*, 2005). In contrast, the Experiment 2 site had a creeping bent (*Agrostis stolonifera*)-dominated sward with a low proportion of PRG (less than 10%). No clover was present in the sward. The soil in Experiment 2 was a moderate to heavy brown-earth of sandy-loam texture with evidence of an iron pan. This area was classified by Gardiner and Radford (1980) as being 60% brown podzolic, 20%, acid-brown earths and 20% gleys; that is, a poorly-drained soil, representing 6% of the total land in Ireland. It is likely that the soils of the site are represented by the poorly-drained gley component of this soil association. Soil fertility status was similar and adequate (soil index 3 for phosphorus and potassium; soil pH 6.5) during the study for each grassland site, and recommended maintenance macro-nutrient applications were made during the grazing season (Hennessy *et al.*, 2008a). Table 4.1 summarises details of both experiments. Seasons are defined as follows: spring (15 February to 15 April); mid-season (16 April to 31 July) and autumn (1 August to 15 November). At each experimental site, treatment plots were part of a larger area that was fenced off, so treading treatments could be applied.

Table 4.1 Details of two experiments which tested the effects of four levels of treading damage: control (no damage), light damage, moderate damage and severe damage, at two contrasting grassland sites at different times and frequencies.

	Experiment	
	1	2
Treading dates	17 March 2009	20 October 2009/9 April 2010
Duration	35 weeks	50 weeks/26 weeks
Soil	well drained	poorly drained
Predominant pasture species	perennial ryegrass	creeping bent

4.3.1 Experiment and treatments

4.3.1.1 Experiment 1

In early spring (March) 2009, 24 plots (5 m × 11 m; 55 m^2) were established. The area was intermittently grazed by dairy cows on nine occasions during the preceding season.

Following rainfall, additional water was applied to the grassland site with a hose in order to achieve soil saturation, then four treading-damage treatments were applied (treading date 1; 17 March 2009): i) control (C, no damage), ii) light damage (L), iii) moderate damage (M) and iv) severe damage (S) (Figure 4.2; Figure 4.3), with six replicates per treatment. Forty five non-lactating dairy cows (average live weight; LWT 550 kg) were used to achieve the desired levels of damage. Residency times were 20, 40 and 120 minutes for L, M and S, respectively, with stocking rates (SR) of 0.7, 1.4 and 4.3 cows/hectare (ha), respectively. On treading date 1, C plots were defoliated mechanically to a residual height of 3.5 cm ±0.29 cm. The entire 24 plots were then intermittently grazed by dairy cows on seven occasions, until the end of the experiment (November 2010).

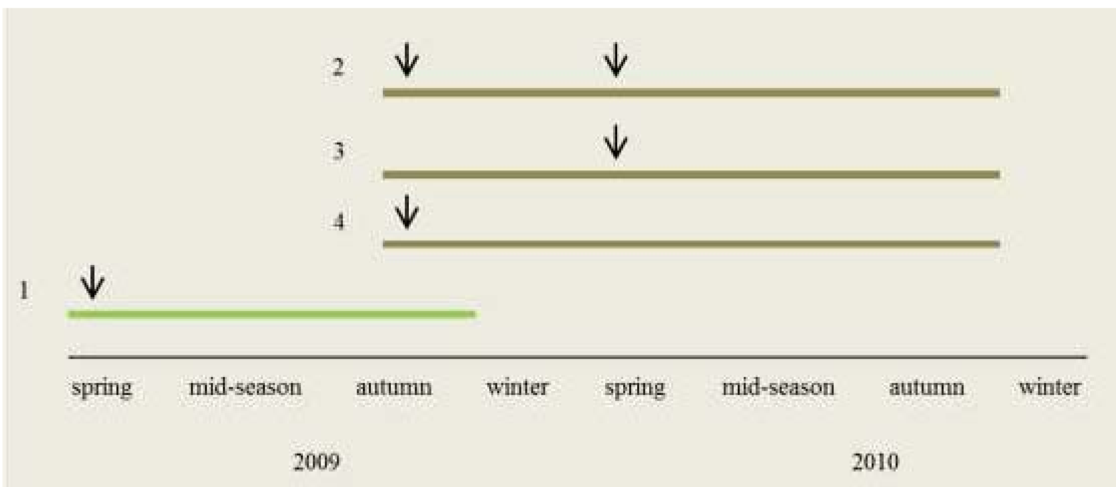

Figure 4.1 Time line of the experimental periods: 1) one treading damage event in spring 2009; 2) two treading damage events in autumn 2009 and spring 2012, 3) one treading damage event in spring 2010; and 4) one treading damage event in autumn 2009.

(a)

	Control	Light	Moderate	Severe
Hoof-print depth (cm)		3.6	4.8	5.8
Chain reduction		0.06	0.08	0.13

(b)

	Control	Light	Moderate	Severe
Hoof-print depth (cm)		3.3	7.3	10.6
Chain reduction		0.03	0.09	0.12

Figure 4.2 Experimental treatments (from left to right): control, light damage, moderate damage and severe damage imposed in (a) Experiment 1 (perennial ryegrass-dominated sward with a well-drained soil) and in (b) Experiment 2 (creeping bent-dominated sward with a poorly-drained soil).

4.3.1.2 Experiment 2

In autumn (October) 2009, 36 plots (5 m × 11 m; 55 m^2) were established. The objective was to examine the effects of treading damage in autumn 2009 only, compared to treading damage in spring 2010 only, and then to compare these to plots that were damaged in both autumn and spring (2009 and 2010, respectively). The area used was intermittently grazed by replacement heifers during the preceding season. Once the soil was sufficiently saturated for treading damage to occur, after heavy levels of rainfall, four treading-damage treatments were imposed. Thirty six heifers (average LWT 439 kg) were used to establish the treading damage. The treatments were similar to the ones described for Experiment 1, and were imposed on plots 1 to 24 (the autumn treading event, treading date 2). Residency times were approximately 50, 70 and 190 minutes for L, M and S plots, with SR of 1.4, 2.0 and 6.0 cows/ha, respectively.

In March 2010 (spring; treading date 3) plots 13 to 36 were subjected to treading damage following similar criteria and methodology to the damage on treading date 2. This resulted in plots 13 to 24 being damaged twice, while plots 25 to 36 were subjected to treading damage in the spring only. Residency times were approximately 45, 60 and 180 minutes for L, M and S plots, with SR of 1.3, 2.0 and 5.5 cows/ha, respectively. All treatments were replicated three times. On treading dates 2 and 3 (20 October 2009 and 9 April 2010, respectively), C plots were defoliated mechanically to a residual height of 2.5 ±0.80 and 3.4 ±0.34 cm, respectively. Once the first treading event was imposed, the site was intermittently grazed by heifers six times until the end of the experiment (November 2010). The experimental design was a split plot in both experiments. At both sites, swards were intermittently grazed to represent a paddock being grazed in a rotation, *i.e.*, the animals were not continuously present on the plots.

4.3.2 Measurements

4.3.2.1 Herbage production

Pre-grazing HM (above 4 cm) was estimated on each plot immediately before each grazing occasion, including once preceding treading date, by harvesting a strip of 10 m × 1.2 m, using a motor Agria mower (Etesia UK Ltd., Warwick, UK). Pre- and post-grazing sward heights (n = 10) were recorded before and after grazing each strip using a rising plate meter (diameter 355 mm and 3.2 kg/m^2; Jenquip, Fielding, New Zealand; Earle and McGowan, 1979). At each cut, the fresh weight of the harvested material was recorded and a sub-sample (100 g) was dried at 40ºC for 48 h to obtain DM proportion, to calculate pre-grazing HM (kg dry matter; DM/ha). The dried herbage was then ground-milled through a 1-mm screen (Tecator Cyclotec 1093 Mill) for subsequent chemical analyses. Cumulative HM for each treatment was calculated by summing the pre-grazing HM values. With a shovel and with minimum damage of plants, dung was removed from the plots after each grazing event to reduce the proportion of rejected area during subsequent grazing events due to presence of faeces (Figure 4.3). All plots were fertilised with 30 kg nitrogen (N)/ha in the form of calcium ammonium nitrate (CAN; 0.27 N) following each grazing. Grass growth rate (kg DM/day) and herbage production of the damaged treatments were also expressed as proportions of the undamaged control at each cut.

4.3.2.2 Tiller density

Three turves (10 cm × 10 cm) were selected randomly from each plot, cut to a depth of more than 3 cm and dissected (Figure 4.3). The species of each tiller was classified as PRG, creeping bent or weed grass and counted (Jewiss, 1993). Main and daughter tillers were both included. In Experiment 1, tiller density was assessed once before (26 February 2009) and on three occasions following treading date 1 (1 May, 28 May and 27 October 2009). In Experiment 2, tiller density was assessed once before (16 October 2009) and on three occasions following treading date 2 (4 April, 23 July and 21 October 2010).

4.3.2.3 Soil bulk density

In Experiment 2, soil bulk density was determined throughout the experimental area at treading dates 2 and 3, before and after the treading. Soil physical analyses were conducted on 10 soil cores (4.8-cm diameter) pre-trampling and 20 soil cores post-trampling. Half of the soil cores post-trampling were in the hoof marks and 10 outside the hoof marks. Soil cores were taken to a depth of 5 cm from each plot, using the cylinder method described by Blake and Hartge (1986). Briefly, soil samples were dried to obtain the DM of the soil, they were then sieved, and rocks or other material with dimensions greater than 2 mm were separated. The mass of all the material with dimensions greater than 2 mm was determined, and its volume was determined from the amount of water that it displaces.

4.3.2.4 Hoof print depth and surface roughness

After each treading event, hoof-print depth was measured with a plastic ruler on 20 random hoof marks in each plot (Figure 4.3). The ruler was placed in the deepest part of each hoof mark and the distance between the base of the imprint and the lip of the hoof depression, was measured. Before and after treatments were imposed, surface roughness was measured using a 7.6-m chain, which was placed on the soil surface to follow the contours of the damaged soil (Figure 4.3). The chain length reduction was an estimate of the roughness of the surface (Saleh, 1994). A quantitative description of the treatments in terms of these soil measurements is given in Table 4.2.

Table 4.2 Hoof-print depths and surface roughness (measured as proportion of chain reduction when placed on the soil surface) of plots allocated to light damage (L), moderate damage (M) and severe damage (S) in experiments 1 and 2.

		Treatment				Level of
	Date	L	M	S	s.e.m.	significance
Experiment 1						
TD 1 (spring 2009)						
Hoof-print depths (cm)	21 Mar 09	3.6^{a}	4.8^{b}	5.8^{c}	0.89	***
Surface roughness	19 Mar 09	0.06^{a}	0.08^{ab}	0.13^{b}	0.001	***
Experiment 2						
TD 2 (autumn 2009)						
Hoof-print depths (cm)	5 Nov 09	3.3^{a}	8.8^{b}	13.3^{c}	0.87	***
Surface roughness	5 Nov 09	0.02^{a}	0.10^{b}	0.14^{c}	0.002	***
TD 3 (spring 2010)						
Hoof-print depths (cm)	9 Apr 10	3.3^{a}	5.8^{b}	7.9^{c}	0.88	***
Surface roughness	9 Apr 10	0.04^{a}	0.07^{b}	0.10^{c}	0.002	***

Within rows means not showing a common superscript differ significantly ($P < 0.05$).
s.e.m. standard error of the mean.
TD = treading date.
***, $P < 0.001$.

4.3.3 Meteorological data

Weather data, including rainfall and average daily temperature, were recorded daily at a meteorological station that was within a radius of 5 km of both experimental sites (Table 4.3).

Table 4.3 Mean monthly temperatures and rainfall of the period 1950 to 2008, and for 2009 and 2010. Mean monthly rainfall for the period 1950 to 2008 and monthly rainfall values of 2009 and 2010.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean temp. (ºC)												
1950-2008	5	6	7	9	11	14	16	15	13	10	7	6
2009	5	5	7	9	11	15	15	15	13	12	8	3
2010	2	3	5	9	11	15	16	14	14	10	5	1
Mean monthly rainfall (mm)												
1950-2008	111	83	82	61	68	64	61	81	87	102	99	110
Monthly rainfall (mm)												
2009	194	16	56	107	89	52	154	117	41	127	260	83
2010	107	39	88	59	38	53	143	23	102	83	98	37

4.3.4 Statistical analysis

All sward measurements were analysed using SAS (Statistical Analysis System, version 9.2; SAS Institute Inc., Cary, NC, US). Analysis of variance for HM and comparative grass growth rate was performed using the MIXED procedure with a mixed model for repeated measures that included the fixed effects of treatment, cut and the interaction cut by treatment, and the random effect of plot to account for repeated cuts on the same plot. Analysis of variance for total tiller density was performed using a mixed model that included the fixed effects of treatment, season and the interaction treatment by season, and the random effect of plot to account for repeated measures on the same plot. Cumulative HM was analysed with a linear model that included the fixed effect of treatment. Analysis of variance for bulk density was performed with a mixed model that included the fixed effect of treatment and the random effect of plot. Least square means and their standard errors were obtained for each treatment and used for multiple comparisons using a t-test with a Bonferroni adjustment. Significant differences were declared when $P < 0.05$. Tiller density data were log transformed because of heterogeneity of the variance and then treatment means were back transformed with corresponding 0.95 confidence intervals.

(a)

(b)

(c)

(d)

(e)

(f)

Figure 4.3 (a) Tiller-density measurement; (b) surface-roughness measurement; (c) dung removal with shovel; (d) hoof-print-depth measurement; (e) severe treading damage and (f) moderate treading damage.

4.4 Results

4.4.1 Weather

Total annual rainfall during 2009 and 2010 was 1,293 and 869 mm, respectively (Table 4.3). The average for the preceding 58 years was 1,009 mm. The difference in 2009 was mainly due to very heavy rainfall events in January and November. In 2010, monthly rainfall exceeded the 58-year average in July and September. Very low mean temperatures were registered in winter 2009, in early spring 2010 and also at the end of 2010; otherwise rainfall was near of below the long term average.

4.4.2 Herbage production

Cut numbers start from the first cut after the treading event, excluding pre-experimental cuts, although the latter are used for cumulative HM.

4.4.2.1 Spring damage on a well-drained soil (Experiment 1)

At cut 1, pre-grazing HM on S treatments was 0.30 lower than the average of the other treatments (1,629 vs. mean 2,314 kg DM/ha, respectively; $P < 0.001$; Table 4.4). At the following cut, C plots yielded 168 kg DM/ha less than the average of the other three treatments. At cut 3, pre-grazing HM was highest in S plots, intermediate in M and lowest in L and C plots, with a difference of more than 150 kg DM/ha between S and the average of the other three treatments. Again, at the following cut, S plots yielded more, in this case 151 kg DM/ha, than the average of the other treatments. Cumulative HM was mean 12.7 t DM/ha and was not affected by treatment (Figure 4.4).

Table 4.4 Pre-grazing herbage mass (kg DM/ha >4 cm) of plots allocated to one of four treading-damage treatments: control (C, no damage), light damage (L), moderate damage (M) and severe damage (S) in the spring of 2009, on a perennial ryegrass-dominated grassland site with a well-drained soil.

		Treatment					Level of
Cut	Date	C	L	M	S	s.e.m	significance
Pre-exp.	9 Mar 09	1,008	911	917	846	59.6	†
TD 1 (spring)	17 Mar 09	--					
1	5 May 09	2,295[a]	2,404[a]	2,243[a]	1,629[b]	89.3	***
2	29 May 09	1,176[a]	1,320[b]	1,369[b]	1,342[b]	47.3	***
3	25 Jun 09	2,207[a]	2,331[a]	2,472[ab]	2,498[b]	82.1	***
4	22 Jul 09	1,498[a]	1,557[a]	1,587[a]	1,698[b]	57.3	***
5	28 Aug 09	2,035	1,984	2,156	2,148	80.1	NS
6	7 Oct 09	1,822	1,833	1,878	1,832	43.1	NS
7	10 Nov 09	454	466	527	493	20.6	NS

Within rows means not showing a common superscript differ significantly ($P < 0.05$).
s.e.m. standard error of the mean.
TD = treading date.
NS, not significant; †, $P < 0.10$. ***, $P < 0.001$.

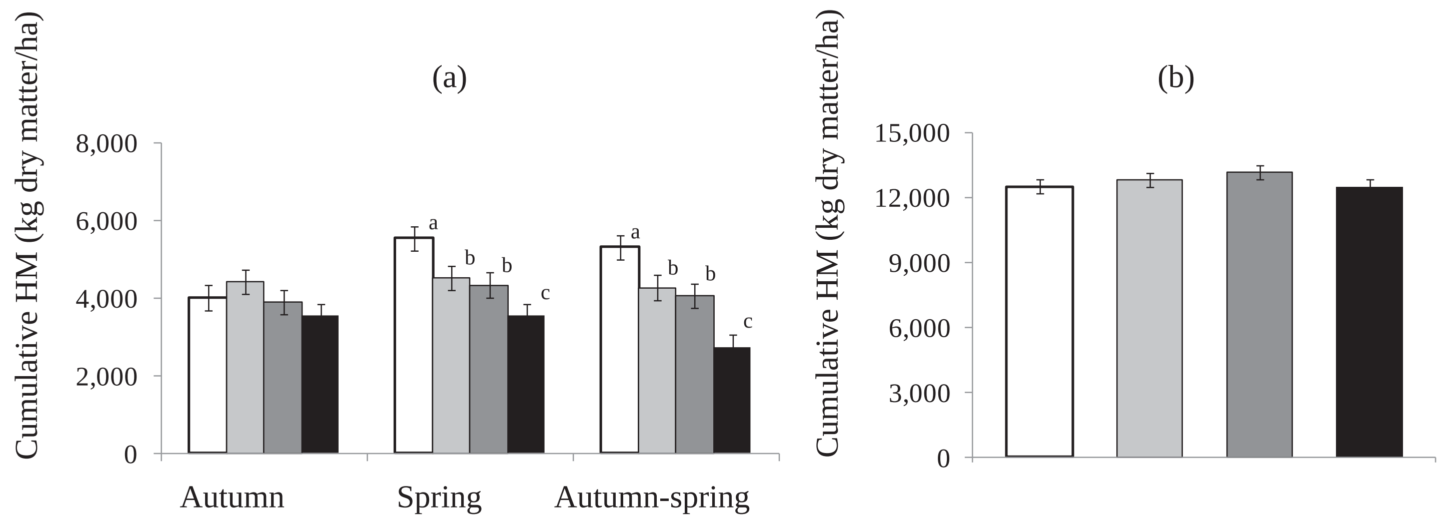

Figure 4.4 Cumulative herbage mass (HM) of plots that were allocated to four treading-damage treatments: control (no damage □), light damage (□), moderate damage (■) and severe damage (■) on (a) a creeping bent-dominated sward with a poorly-drained soil in autumn 2009, spring 2010 or on both occasions and on (b) a perennial ryegrass-dominated sward on a well-drained soil in spring 2009. a-c letters indicate differences between treatments at the 0.05 probability level; they refer to the means within a treatment allocation time.

4.4.2.2 Autumn damage on a poorly-drained soil (Experiment 2)

At cut 1 (early spring 2010), M and S treatments had similar pre-grazing HM (mean 23 kg DM/ha) but they had significantly lower yields than the C and L treatments (mean 300 kg DM/ha; $P < 0.001$; Table 4.5). At cut 2, mean pre-grazing HM on C, L and M treatments (555 kg DM/ha) was 471 kg higher than the S treatment ($P < 0.001$). At cut 3, pre-grazing HM was lowest for S plots, intermediate for M plots and greatest for the other treatments, differences between extremes being 173 kg DM/ha. Cumulative HM values were not different between treatments (mean 4.0 t DM/ha; Figure 4.4).

Table 4.5 Pre-grazing herbage mass (kg DM/ha >4 cm) of plots allocated to one of four treading-damage treatments: control (C, no damage), light damage (L), moderate damage (M) and severe damage (S) in the autumn of 2009 on a creeping bent-dominated sward with a poorly-drained soil.

		Treatment					Level of
Cut	Date	C	L	M	S	s.e.m.	significance
Pre-exp.	19 Oct 09	442	470	506	379	58.8	NS
TD 2 (autumn)	20 Oct 09	-----------------------------------					
1	7 Apr 10	319^{a}	280^{a}	44^{b}	1^{b}	51.5	*
2	5 May 10	485^{a}	752^{a}	428^{a}	84^{b}	116.9	*
3	27 May 10	470^{a}	405^{a}	344^{ab}	297^{b}	54.5	*
4	22 Jun 10	455	511	418	450	71.7	NS
5	22 Jul 10	548	585	635	749	155.1	NS
6	5 Oct 10	1,408	1,411	1,516	1,569	170.1	NS

Within rows means not showing a common superscript differ significantly ($P < 0.05$).
s.e.m. standard error of the mean.
TD = treading date.
NS, not significant; *, $P < 0.05$.

4.4.2.3 Spring damage on a poorly-drained soil (Experiment 2)

At the first and second cuts following treading date 3, all pre-grazing HM on all treatments were different from each other, values being lower with higher levels of damage ($P < 0.001$; Table 4.6). At cut 3, pre-grazing HM was highest on C plots and lowest on S plots. At cut 4, C, L and S plots (mean 645 kg DM/ha) had a significantly lower yield than the M plots (898 kg DM/ha; $P < 0.001$). Cumulative HM was lowest for S plots (3.5 t DM/ha), intermediate for M plots (4.3 t DM/ha) and highest for C and L plots (average 5.0 t DM/ha; $P < 0.05$; Figure 4.4).

Table 4.6 Pre-grazing herbage mass (kg DM/ha >4 cm) of plots allocated to one of four treading-damage treatments: control (C, no damage), light damage (L), moderate damage (M) and severe damage (S) in the spring of 2010 on a creeping bent-dominated sward with a poorly-drained soil.

		Treatment					Level of
Cut	Date	C	L	M	S	s.e.m.	significance
Pre-exp.	7 Apr 10	606	545	583	497	63.0	NS
TD 3 (spring)	9 Apr 10	--					
1	5 May 10	690^{a}	546^{b}	217^{c}	19^{d}	41.1	***
2	27 May 10	$1{,}007^{a}$	694^{b}	481^{c}	120^{d}	72.5	***
3	22 Jun 10	981^{a}	775^{ab}	778^{ab}	491^{b}	129.6	***
4	22 Jul 10	556^{a}	670^{a}	898^{b}	709^{a}	55.2	***
5	5 Oct 10	1,400	1,290	1,376	1,616	188.5	NS

Within rows means not showing a common superscript differ significantly ($P < 0.05$).
s.e.m. standard error of the mean.
TD = treading date.
NS, not significant; ***, $P < 0.001$.

4.4.2.4 Autumn and spring damage on a poorly-drained soil (Experiment 2)

Herbage mass measured in October differed significantly between treatments due to M having higher pre-grazing HM than the other three treatments (Table 4.7). At cut 1, pre-grazing HM was highest in the C treatment, intermediate for the L treatment and lowest for the M and S treatments ($P < 0.001$). At cut 2, after plots had been damaged for the second time, pre-grazing HM was similar for C and L treatments (mean 527 kg DM/ha), and was reduced by 437 kg in M and S treatments ($P < 0.001$). At cut 3, pre-grazing HM was similar on C, L and M treatments (mean 487 kg DM/ha) and 390 kg lower for the S treatments ($P < 0.001$). Cumulative HM was lowest for S plots (2.7 t DM/ha), intermediate for M and L plots (average 4.2 t DM/ha) and highest for C plots (average 5.3 t DM/ha; $P < 0.01$; Figure 4.4).

Table 4.7 Pre-grazing herbage mass (kg DM/ha >4 cm) of plots allocated to one of four treading-damage treatments: control (C, no damage), light damage (L), moderate damage (M) and severe damage (S) in the autumn of 2009 and spring of 2010, on a creeping bent-dominated sward with a poorly-drained soil.

		Treatment					Level of
Cut	Date	C	L	M	S	s.e.m.	significance
Pre-exp.	19 Oct 09	532^{ab}	543^{b}	680^{c}	418^{a}	38.3	***
TD 2 (autumn)	20 Oct 09	---------------------------------					
1	7 Apr 10	740^{a}	401^{b}	51^{c}	1^{c}	71.3	***
TD 3 (spring)	9 Apr 10	---------------------------------					
2	5 May 10	566^{a}	487^{a}	161^{b}	18^{b}	66.9	***
3	27 May 10	575^{a}	516^{a}	369^{a}	97^{b}	92.7	***
4	22 Jun 10	776	478	546	416	139.1	NS
5	22 Jul 10	716	625	723	581	67.9	NS
6	5 Oct 10	1,403	1,220	1,532	1,200	74.7	NS

Within rows means not showing a common superscript differ significantly ($P < 0.05$).
s.e.m. standard error of the mean.
TD = treading date.
NS, not significant; ***, $P < 0.001$.

4.4.2.5 Overall analysis of reduction in herbage production

Spring damage on a well-drained soil resulted in 30% initial pre-grazing HM reduction in S plots compared to the other treatments but no difference in cumulative HM was detected. Autumn damage on a poorly-drained soil resulted in reductions of 92% in pre-grazing HM at cut 1 (M and S compared to C and L) and 82% at cut 2 (S compared to all other treatments), but no reduction in cumulative HM in the subsequent grazing season. Spring damage on a poorly-drained soil resulted in pre-grazing HM reductions of 21, 69 and 97% at cut 1; 31, 52 and 88% at cut 2 (L, M and S, respectively, compared to C at both cuts); and 50% at cut 3 (S compared to the other treatments), and a reduction in cumulative HM of 14, 14 and 30% (L, M and S, respectively, compared to C). Finally, autumn and spring damage on a poorly-drained soil resulted in reductions of 46, 96 and 96% at cut 1 (L, M and S, respectively, compared to C); 83% at cut 2 (M and S compared to C and L) and 80% at cut 3 (S compared to the other treatments); and a reduction in cumulative HM of 22, 22 and 49% (L, M and S treatments, respectively, compared to C). Figure 4.5 b shows grass growth rates (kg DM/day) of the damaged treatments expressed as a proportion of the undamaged control at each cut for Experiment 2.

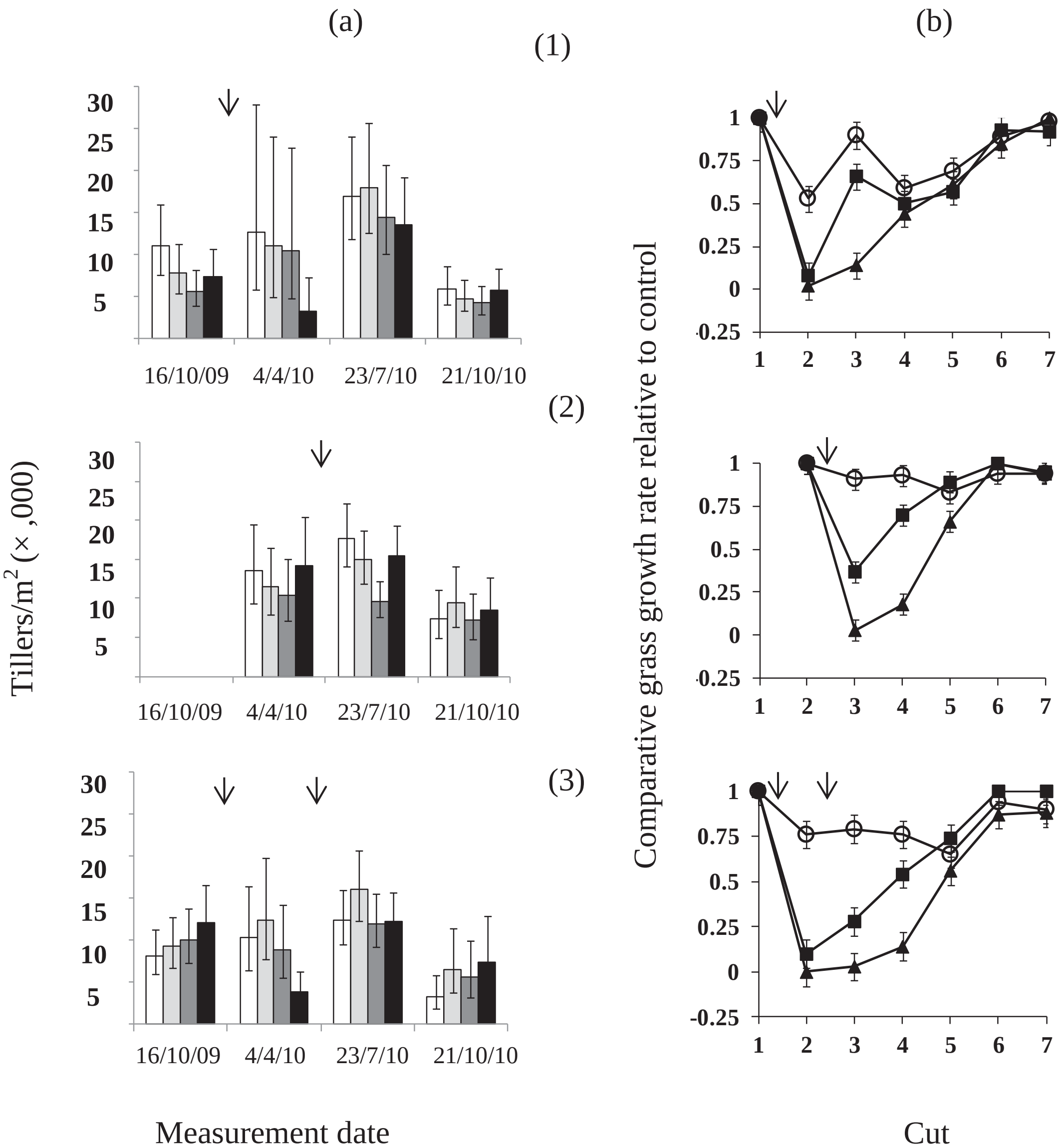

Figure 4.5 Total tiller density (a) and comparative grass growth rates in relation to control plots (b) in spring, mid-season and autumn of plots that were allocated to four treading-damage treatments: control (no damage □), light damage (□ left; ○ right), moderate damage (■ left; ■ right) and severe damage (■ left; ▲ right) on a creeping bent-dominated sward with a poorly-drained soil. Treading damage of 1/3 of the plots was imposed in autumn 2009 (1), 1/3 of the plots were damaged in spring 2010 (2), and 1/3 of the plots were damaged in autumn and spring (3). Arrows indicate treading dates (17 October 2009 and 9 April 2010).

4.4.3 Tiller density

In Experiment 1, PRG and non-PRG tiller densities were not significantly different between treatments in any of the four measurement periods. Means for each of the successive measurement date were 6,124, 8,104, 7,625 and 4,808 tillers/m^2 for PRG and 753, 1,377, 1,766 and 2,621 tillers/m^2 for non-PRG grasses. In Experiment 2, no significant difference in total tiller density was detected between treatments for any of the three imposed treading dates (Figure 4.5 a). Treatment means for each of the successive measurement dates were 12,072, 10,933, 9,017 and 8,175/m^2 for swards damaged once in autumn; 13,311, 12,333, 9,278 and 12,844/m^2 for swards damaged once in spring, and 9,192, 11,225, 10,167 and 12,333/m^2 for the swards that were damaged on both occasions.

4.4.4 Soil bulk density

On treading date 2 (October 2009), soil bulk density was similar between treatments before and after treading damage (both means 1.00 g/cm^3). Likewise, on treading date 3 (April 2010), no difference was found between treatments before and after treading damage (both means 1.00 g/cm^3, respectively). On each treading occasion, before and after damage, standard errors of the means were: 0.02, 0.03, 0.05 and 0.04, for C, L, M and S treatments, respectively.

4.4.5 Hoof-print depths and surface roughness

In spring 2009 (treading date 1; Experiment 1), hoof-print depths increased ($P < 0.001$; Table 4.2) with level of damage; S treatments had 2.2 and 1-cm deeper hoof prints than L and M treatments, respectively. Surface roughness followed a similar trend, being lowest for L (0.06), intermediate for M (0.08) and highest for S treatments (0.13; $P < 0.001$). In autumn 2009 (treading date 2; Experiment 2), hoof-print depths increased ($P < 0.001$) with level of damage; S treatments had 10.0 and 5.5 cm deeper hoof prints than L and M treatments, respectively. Surface roughness also increased with level of damage from 0.02 (L treatments) to 0.13 (S treatments; $P < 0.001$). In spring 2010 (treading date 3; Experiment 2), hoof-print depth increased ($P < 0.001$) with level of damage; S treatment had 4.6 and 2.5 cm deeper hoof prints than L and M treatments, respectively. Surface roughness also increased with level of damage compared to C treatment from 0.04 (L treatments) to 0.10 (S treatments; $P < 0.001$).

4.5 Discussion

The drive to increase the length of the grazing season in Irish systems to increase profitability (Kennedy *et al.*, 2007b; Läpple *et al.*, 2012) is associated with a trade-off between the benefits of early-spring turnout to grass and the damage vulnerability of wet soils. Treading damage is an associated risk of increasing the length of the grazing season, particularly during times of soil saturation which usually occur in early spring and autumn. The target areas of the post-quota dairy systems in Ireland cover different soils and different levels of sward renewal. The outcomes of this study provide an important insight into the effects of treading damage at different times and frequencies, on different soils and with different pasture species in Ireland. The ranges of SR simulated in these two experiments are set on a fixed date, for practical reasons. However, the majority of dairy herds in Ireland are spring calving, thus, by default, turnout is staggered, which means that grazing pressure can be lower during the earlier part of the season, until most of the herd has calved. On the other hand, during autumn, all cows are on grass. Both situations have been covered, again, as closely as possible to a real on-farm situation, within the context of a controlled study.

The level of damage achieved at each site was considered to be adequate for the objectives of the study. Betteridge *et al.* (2003), after treading with cattle, reported that some pasture damage occurred when hoof-print depths were 3 cm or more, provided that the level of moisture in the soil was high. Similarly, Nie *et al.* (2001) reported 2.0, 3.6 and 4.3 cm depths for plots that were subjected to light, medium and heavy treading damage, respectively. In the present trial, hoof-print depths in all treatments, at each of the treading dates, were deeper than 3 cm (Table 4.2). Values of surface roughness of 0.07, 0.12 and 0.15 for light, medium and heavy trampled treatments, respectively, were reported by Nie *et al.* (2001), which are slightly higher than the values reported here. A possible reason for the difference might be that Nie *et al.* (2001) measured surface roughness with a 1-m chain, whereas, in the present study, a 7.6-m chain was used. Nonetheless, it is clear that the level of damage in Experiment 1 and Experiment 2, achieved after different residency times in each of the treatments, was sufficient to create differences and adequately measure the impact of treading on herbage production and tiller density.

4.5.1 Herbage production and tiller density

In Experiment 1, a severe treading-damage event in spring caused a 30% reduction in pre-grazing HM at the next harvest, although cumulative HM was not affected. This initial pre-grazing HM reduction must not be underestimated. There is an opportunity cost for grass in early spring, when grass supply is in deficit. A reduction in the quantity of grass available for grazing can result in a need to feed supplements and, consequently, an increase in feed costs. In Experiment 2, there was a reduction in cumulative HM on plots that were damaged in spring and also on those plots damaged in both autumn and spring and, as it would have been expected, two treading-damage events were more detrimental for herbage production than only one. However, no significant difference in cumulative HM was detected on plots damaged in autumn only, even though there was a difference of 20% (875 kg DM/ha) between L and S plots in annual DM yield. The plots damaged in autumn only had more time than the other treatments to recover during the vegetative growth phase over the winter, *i.e.*, tillering and natural reseeding on the bare ground (Nie *et al.*, 2001), inasmuch as that the trampling action can bring dormant seeds to the surface. A situation that may have improved the recovery of the plots damaged in autumn could have been the colder than average winter of 2010 (Table 4.3). The 'freeze-thaw' action may have had positive effects on compacted soil, increasing permeability (Bowders and McClelland, 1994).

What causes the losses in pre-grazing HM when treading occurs is a subject that has not been widely discussed in the literature. The density of tillers and the size of plants make up the sward, therefore the reduction in pre-grazing HM could possibly be due to the loss of pasture plants through burial due to treading (Nie *et al.*, 2001). Not many studies report tiller density after treading damage, perhaps due to the difficulties of the measurement procedure. In the present study, no differences were found in tiller density, although Figure 4.5 a shows a trend in Experiment 2 towards lower tiller numbers for S plots as compared with the other treatments on most measurement dates. Pande (2002), after a number of experiments examining the effects of treading damage under different scenarios, concluded that the main effect of treading damage was a reduction in tiller populations. Nie *et al.* (2001) reported that total tiller density was reduced by 32 and 46% for medium and heavy treading damage, respectively. It remains unclear why there were no significant differences in tiller density in the present study, even when pre-grazing HM was affected by treatment in Experiment 2. Perhaps the difficulty of counting creeping bent in comparison with PRG made this result not as reliable. The standard error of the mean of tiller density was almost six times higher in Experiment 2 than in Experiment 1, which could help explain the lack of statistical differences between treatments. It is accepted that creeping bent-dominant sites, as was the case in Experiment 2, will give a larger variation in tiller and DM production.

Time for full recovery of herbage production, meaning the days that took for damaged plots to achieve similar yields as the control plots, ranged from 73 to 275 days, depending on the experiment and treatment in this study. Betteridge *et al*. (2003) reported that, after moderate treading damage, tiller density took 120 days to return to the level of the control. Ledgard *et al.* (1996) reported that recovery took 120 to 240 days. However, Nie *et al.* (2001) reported recovery 63 days after intensive treading on a heavy, poorly-drained soil. The differences in soil types of these studies may be accountable for the differing recovery times. Furthermore, it can be interpreted that differences between experiments in the present study are the result of a combination of soil types and sward species, which agrees with Climo and Richardson (1984).

Due to the complexity of the aforementioned processes involved in treading damage, comparing the reduction in HM of this study (ranging from 14 to 51% across all treatments in Experiment 2) with those from previous work is also difficult. For example, Nie *et al.* (2001) found 40 to 42% reduction in pasture yield on a clay-loam soil. Meneer *et al.* (2005), on a silt-loam soil, found reductions of 19 and 37% in plots with PRG swards after moderate and severe treading damage, respectively, and cumulative HM was reduced by 16 and 34%, respectively. Ledgard *et al.* (1996) found 20 to 80% reductions in pasture production after a single intensive cattle-treading event during winter, on a silt-loam soil, and reduced pasture growth lasted four to eight months. Nevertheless, it was clear that both experimental sites responded differently to treading damage. Fast recovery in Experiment 1 may be due to this sward being PRG-dominated, which seems to be the most resistant temperate grass species to treading damage. This supports what was reported by Edmond (1964).

Some level of treading damage seems to be beneficial to the sward. In Experiment 1, plots that were subjected to the L treatment had consistently higher pre-grazing HM than the control treatment (*i.e.* no treading damage). Some treading can create space for pasture growth, can increase soil bulk density in soils with low soil bulk density (ash, pumice, organic soils) and can also increase water retention when needed (Pande *et al.*, 2000). Edmond (1958b) found that artificial soil compaction after three weeks of treading damage resulted in increased herbage yields, which was probably due to breaking up the surface cap, leading to increased permeability and diffusion of air. On the other hand, soil contamination in treaded plots could have affected the samples, increasing the weight in the DM, and therefore underestimating the differences in herbage production.

4.5.2 Soil bulk density

Climo and Richardson (1984) and Betteridge *et al.* (1999) reported that treading by grazing animals compacts soil and reduces soil macroporosity and aeration. Edmond (1964) and Gradwell (1968) observed an increase in soil bulk density resulting from increased treading intensity. Bulk density was reported to be 21% greater on badly-damaged areas than on less-damaged areas (Mulholland and Fullen, 1991). In Experiment 2 of the present study, where the soil was a poorly-drained heavy soil, soil bulk density was shown to be not affected by treading damage. Bulk density may not be the best soil measurement for soil compaction. For instance, Gradwell (1968) reported that bulk density barely changed but macroporosity greatly changed in treading trials, therefore suggesting that macroporosity was a more useful measure of soil compaction.

4.6 Practical implications

Given the weather conditions that prevail in spring and autumn in Ireland, soils are generally saturated in many parts of the country, making them more prone to treading damage. Expansion of milk production in Ireland will mean that operations will establish on soils with poor drainage and, consequently at high risk of treading damage. Treading damage can be minimised by reducing grazing pressure using management techniques such as ‘on-off’ grazing during periods of increased risk of treading damage (Kennedy *et al.* 2009). (2009) Restricting the access time of cows to pasture during periods of inclement weather reduces supplementary-feed requirement and minimises sward damage because of poor ground conditions, while not significantly affecting milk production. Grazing wet soils in Victoria, Australia, using on-off grazing periods of two hours in the morning and two hours in afternoon, reduced severity of treading damage (Ward *et al.*, 2003), this being attributed to a reduction in the decline in soil strength. A common spring grazing management practice, strip grazing, consists of confining animals to an area of grazing land to be grazed in a relatively short time, and varying the size of the paddock to allow access to a specific land area (Allen *et al.*, 2011). This can protect the treaded soils and avoid excessive damage. This could be the reason why no effects were found in this study on bulk density. Nevertheless, decreasing pressure on the soils by increasing the use of concentrates can lead to lower damage of soils towards the shoulders of the grazing season (O'Loughlin *et al.*, 2008).

Irish farms have the potential to produce between 12 and 16 tonnes of grass DM per ha per year (Brereton, 1995; Läpple *et al.*, 2012). A remarkable finding of this study was the three-fold greater annual production of pasture DM of Experiment 1 (PRG-dominated) compared with Experiment 2 (creeping bent-dominated). This highlights the scope for improvement that exists in grasslands in Ireland. Inclusion of PRG through reseeding can lead to improved herbage production and also improved resistance to treading damage. It has been reported that newly-sown swards dominated by PRG out-yielded creeping bent-dominated swards by average 30% (Sheldrick *et al.*, 1990). Reseeding levels on Irish farms are low (approximately 2.5% annually; Shalloo *et al.*, 2011) and soil fertility is also low with less than half of farmers soil testing when reseeding (Creighton *et al.*, 2011). This infers that the production scenario of Experiment 2 may well be representative of a large proportion the farms in Ireland. A reduction of pasture availability which occurs at times of relative pasture deficit would require an inclusion of supplements into the diet. For example: for the case of Experiment 1, a 30% reduction in pre-grazing HM on the S treatment in comparison to the other treatments was equivalent to a deficit of 685 kg DM/ha. So, assuming that a 550-kg cow needs to ingest approximately 17 kg DM of high-quality grass (12 megajoules of metabolisable energy per kg DM) to produce 1.6 kg MS per day (Holmes *et al.* 2002), then the feed for 43 cows was lost and other feeds would have been required. However, it seems clear from the analysis of this paper that grassland sites differ greatly, particularly in terms of pasture species and soil types. Hence, care must be taken before extrapolating the findings of this study to other grassland ecosystems.

4.7 Conclusions

These findings are highly relevant for the Irish dairy industry and for regions with a temperate climate because the sites investigated in these experiments are representative of a large proportion of dairy farms in Ireland. The detrimental effects of treading damage on subsequent grass growth and herbage production are dependent on frequency, severity of the damage, pasture species and also on soil type. A PRG-dominated sward with a well-drained soil was resilient to an intense treading event. Treading damage on a creeping bent-dominated sward with a poorly-drained soil, as exists in many farms in Ireland, resulted in a reduction of HM accumulation of 14 to 51%, the size of the reduction depending on severity of the damage, frequency and season of the year. Spring damage was more detrimental than autumn damage, but two treading events had large carryover effects. Grassland management focused on increasing the proportion of grass in the diet of the cow must be accompanied with knowledge of the interaction of the grazing animals, the sward and the soil to avoid HM losses by treading.

Chapter 5: Re-growth interval affected herbage accumulation and tissue turnover of a perennial ryegrass sward under a cutting regime in Ireland

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Submitted to Journal of Experimental Agriculture

5.1 Abstract

During a 24-week period in Ireland, a perennial ryegrass (PRG) sward was used to investigate the effects of re-growth interval (two, three or four weeks) on herbage mass (HM) accumulation, sward parameters and tissue turnover under a cutting regime. Pre-harvest HM above 4 cm and sward morphology were estimated at the end of the re-growth period. Tiller density was assessed every four weeks. At the beginning of each re-growth period, 20 PRG tillers were marked in each of 12 5m×3m plots. The length of each green leaf was measured weekly throughout the re-growth period. Leaf appearance rate and leaf extension rate (LER) were calculated for each period. The linear model used included the fixed effects of period and treatment, the interaction period by treatment, and the random effect of plot. Cumulative HM for 2-, 3- and 4-week re-growth interval plots were 6.7, 9.1 and 10.4 tonnes of dry matter/hectare. Tiller density of PRG was unaffected by treatment (average 7,459 tillers/m^2). Mean number of leaves per tiller emerged during the re-growth period were 1.1, 1.7 and 2.1 for 2-, 3- and 4-week re-growth interval treatments, respectively. Mean number of secondary tillers per tiller present at harvest was 0.21 for the 2-week re-growth treatment and 0.52 for the other two treatments. Week 1-to-week 2 LER in the tillers harvested every two weeks was 2.4 mm/day lower than in the other treatments, indicating a low energy status of the former. The findings of this study support previous literature and highlight the need to understand physiology of the plants for effective grazing management. Harvesting too often can jeopardise the plasticity of PRG swards and result in lower sward performance.

Keywords**:** leaf stage, perennial ryegrass, rotation.

5.2 Introduction

A renewed interest exists in grass-based milk production systems, as grazed grass, provided that is managed effectively, remains the cheapest source of feed for dairy cows (Macdonald *et al.*, 2011a; Peyraud and Delaby, 2005). In grass-based dairy systems, there is a compromise between harvesting efficiency and re-growth rate, and a need to maximise both (Chapman *et al.*, 2011). The two main critical management variables affecting these are time of grazing and residual leaf/mass. The management of grazing systems requires an understanding of the dynamics of grass growth to ensure the quality and persistency of the grass plant is maintained during successive rotations.

The basic unit of production of the perennial ryegrass (PRG) sward is the tiller. Within each tiller, leaf tissue turns over continuously, each leaf having a period of active extension growth, followed by maturity and death (Davies, 1977; Hodgson, 1990). As a new leaf appears, the next oldest leaf stops growing and a mature leaf senesces, all this occurring in step. At a deeper level, a synchrony exists between three consecutive nodes. When the oldest node stops cell division, the next younger undergoes ligule initiation and there is cell division in the leaf primordium at the next node (Skinner and Nelson, 1994). The result of this cycle is that each PRG tiller typically has three visible live leaves at a time, only one of which will be actively growing (Brereton *et al.*, 1985; Hennessy *et al.*, 2008a; Hodgson, 1990). Therefore, a tiller can usually be found to be at a 1-, 2- or 3-leaf stage, thereafter the number of leaves remaining relatively constant.

Defoliation disrupts plant energy supply and activates the mobilisation of carbohydrate reserves in the plant (Richards, 1993) so the timing of sward defoliation can have a great impact on sward production and quality. Traditionally, the timing of sward defoliation has been based on rotation length, sward height and/or pre-grazing herbage mass (HM; Mayne *et al.*, 2000). Donaghy and Fulkerson (1997) investigated the effect of defoliation frequency on levels of water-soluble carbohydrates (WSC) in the stubble of the PRG plant and found that WSC reserve levels and yields of leaves, tillers and roots were maximised when tillers were between the 2- and 3-leaf stage. Defoliating tillers repeatedly before two new leaves have appeared leads to depleted levels of energy reserves and decreased leaf extension (Fulkerson and Slack, 1995). Conversely, re-growth intervals on which the grass plant has passed three newly-appeared leaves result in reduced pasture quality due to an increased proportion of dead material in the sward and a decreased persistency resulting from reduced tiller density (Macdonald *et al.*, 2011b).

To survive an imposed management regime, plants use phenotypic plasticity (Hazard and Ghesquiere, 1995), which is a deviation of the natural growth pattern resulting from environmental changes (Schlichting, 1986). This means that management practices can cause PRG plants to adapt by changing its morphology in order to gain resources, this process being reversible (Skinner and Nelson, 1994). However, a sustained pressure can result in plants not adapting to it, therefore in a genetic shift, in this case being irreversible (Skinner and Nelson, 1994). Thus, genotypes in the heterogeneous population that can adapt to the environment will survive and constitute the dominant portion of the population (Hazard and Ghesquiere, 1995).

Therefore, for vegetative swards, the use of leaf stage to decide when to graze will result in optimum persistence, production, utilisation and quality of temperate swards (Donaghy *et al.*, 2008; Fulkerson and Donaghy, 2001). However, using modelling studies, Beukes *et al.* (2006) predicted greater profit for those systems in which the timing of grazing was based on decision rules, in contrast to systems that based their rotations on the leaf stage principle. Macdonald *et al.* (2010) attributes that to predetermined decision rules being more proactive than the leaf stage principle because the latter may not give the manager sufficient time to react. Nonetheless, Chapman *et al.* (2011) stated that there is a need for simple indicators (a trade-off between simplicity and accuracy) to avoid suboptimal decisions being made. In order to make grazing management decisions easier, the stage of leaf re-growth needs to be incorporated with effective decision-making rules such as rotation length. The present experiment investigated the effect of three re-growth intervals (two, three or four weeks) on HM accumulation, sward morphology, tiller density and tissue turnover in PRG swards under a cutting regime.

5.3 Materials and methods

5.3.1 Experiment and treatments

The experiment was undertaken at the Animal & Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland (52^{o}7'N; 8^{o}16'W; 46 m above sea level), between April and September 2009. The soil type was a free-draining acid-brown-earth soil with a sandy-loam-to-loam texture. A 3-year-old PRG-dominant sward was divided into 12 plots (3 m × 5 m; 15 m^2). There were three re-growth interval treatments: harvesting every two, three or four weeks, with four replicates per treatment. Plots received 30 kg phosphorus/ha after the first harvest and a total annual application of 290 kg nitrogen (N)/ha in the form of calcium ammonium nitrate (CAN; 0.27 N) and 248 kg potassium/ hectare (ha) divided according to the number of cuts.

5.3.2 Measurements

5.3.2.1 Herbage mass, tiller density and sward parameters

Pre-harvest HM (above 4 cm) was estimated on each plot at the end of the re-growth period by harvesting a strip the length of the plot and 1.2-m wide using a motor Agria (Etesia UK Ltd., Warwick, UK; Figure 5.1). The harvested material from each strip was collected, weighed and sampled. Dry matter (DM) content was estimated by drying a sub-sample (100 g) of the harvested material at 95°C for 15 hours. Pre-harvest HM (kg DM/ha >4 cm) was calculated using the following formula:

Herbage harvested HM (kg DM/ha >4 cm) = (fresh weight of cut × 10,000/length of cut × width of cut) × % DM.

Ten grass-height measurements were recorded pre- and post-cut on each cut strip using a rising plate meter (diameter 355 mm and 3.2 kg/m^2; Jenquip, Fielding, New Zealand; Earle and McGowan, 1979). Cumulative HM for each treatment was calculated by summing the HM from each harvest date. The morphological composition of the herbage was determined at each harvest. A sample of approximately 30 g was cut at random to ground level with a scissors before harvest (Figure 3.2). By securing the sample with an elastic band and placing it in a bag the vertical structure of the cut sward was preserved. The sample was later cut into two portions, above and below 4 cm.

Then, for each portion, individual layers were separated into leaf, stem (including true stem, pseudo-stem and flower head, if present) and dead material. Each constituent was dried overnight at 95°C for a minimum of 15 hours to determine morphological composition on a DM basis. Tiller density was assessed in each plot every four weeks, *i.e.*, six times in total. Three turves (0.10 m × 0.10 m) were selected randomly from each plot, cut to a depth of *c*.3 cm and dissected (Figure 3.2). The species of each tiller was identified and counted (Jewiss, 1993).

5.3.2.2 Tissue turnover

At the beginning of each re-growth period, 20 PRG tillers were marked with a ring of coloured-plastic-coated wire at 10-cm intervals along two 1-m transects in each plot (Hennessy *et al.*, 2008a). The length of each green leaf was measured weekly throughout the re-growth period using a plastic ruler (*e.g.* leaves in the 3-week re-growth interval treatment plots were measured three times, after one, two and three weeks of re-growth; Figure 5.1). The youngest leaf present on the tiller on the day of each weekly measurement was marked using Tipp-ex™ (Figure 5.1). The number of leaves produced during each week of re-growth was recorded. This information was used to determine leaf appearance rate (LAR). Leaves were identified by the order in which they appeared and their stage of development, *i.e.*, L0 was the expanding leaf at marking, L1 was the youngest/first fully-expanded leaf, L2 the second fully-expanded leaf and L3 was the third fully-expanded leaf at marking. Mean leaf extension rate (LER) was calculated as the mean daily increase in length (mm) of leaves expanding during the measurement period, including the length of new leaves appearing during the period. At each measurement day, secondary tillers were marked and measurements were carried out on each leaf, following same methodology as described for primary tillers. For primary and secondary tillers, extended tiller height (ETH) and extended sheath height (ESH) were measured on each marked tiller at the time of LER measurement, using a graduated ruler. Extended tiller height was measured from ground level to the highest point of the tiller and ESH was measured from ground level to the point of the highest ligule (longest leafed sheath). Free leaf lamina (FLL) was then calculated by subtracting the ESH from the ETH, as described by Gilliland *et al.* (2002). Rainfall and temperature were recorded daily at a meteorological station at Moorepark (Table 5.1).

(a) (b)

(c) (d)

Figure 5.1 (a) Pre-harvest height and herbage mass measurements; (b) collection and weight measurement of cut herbage; (c) tiller marked with colour-coated wire and (d) tiller with tips marked with Tipp-ex™.

Table 5.1 Mean daily temperature, soil temperature at 50 mm and monthly rainfall for 2009 as compared with previous 25-year average (1983-2008).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Daily temp.(°C)												
25-yr	6	6	7	8	11	14	16	15	13	10	8	6
2009	5	5	7	9	11	15	15	15	13	12	8	3
Soil temp.(°C)												
25-yr	5	5	7	9	13	16	17	17	14	11	8	6
2009	4	5	7	10	14	18	18	18	15	13	8	4
Rainfall (mm)												
25-yr	109	77	83	67	66	69	60	87	81	112	103	103
2009	194	16	56	163	89	141	154	117	41	127	260	83

5.3.3 Statistical analyses

Repeated measurements of pre-harvest HM, sward parameters and tissue turnover in the same plot were analysed using the MIXED procedure of SAS (Statistical Analysis System, version 9.2; SAS Institute Inc., Cary, NC, US). The linear model included the fixed effects of month and treatment, the interaction month by treatment and the random effect of plot. Figure 5.2 illustrates how tiller data were grouped for the analysis into months, averaging values in those cases in which there was more than one measurement. The relationship between the number of newly-appeared leaves and pre-harvest HM was estimated using all data with the REG procedure of SAS. .

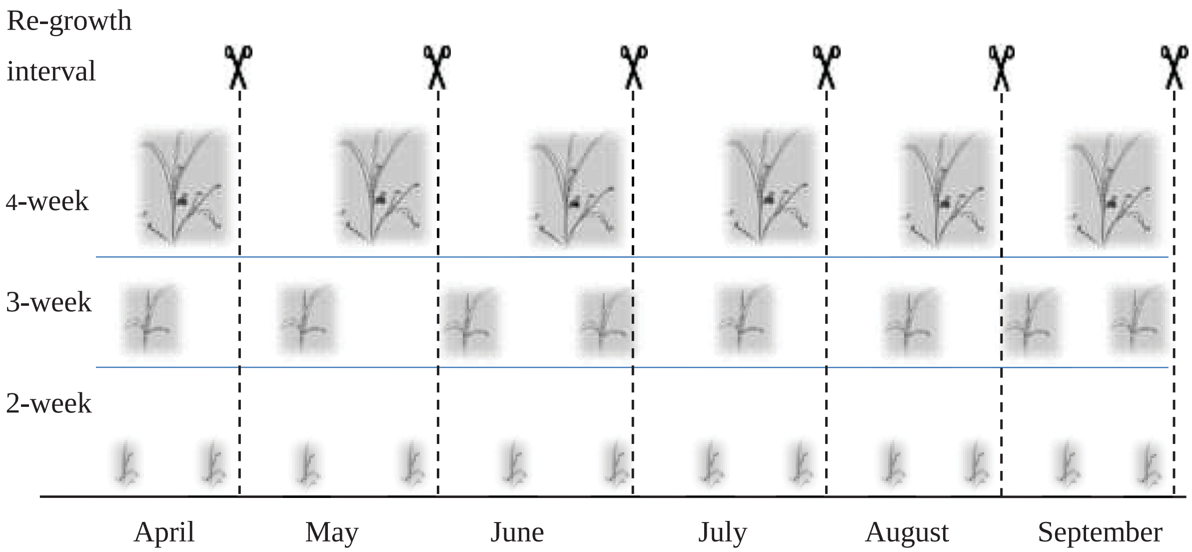

Figure 5.2 Time line of the experiment. The experimental period was divided into six periods of four weeks in order to compare the three treatments, harvested every four weeks (above), every three weeks (middle) or every two weeks (below).

5.4 Results

5.4.1 Weather

Compared to the 1983-2008 average, July, August and September 2009 were colder by 0.9, 0.5 and 0.2°C, respectively, while June was 0.8°C warmer (Table 5.1). Soil temperature was consistently higher for all of the experimental period in comparison to the 25-year average (average values 15.3 and 14.5°C, respectively). Rainfall in 2009 was much higher than the previous 25-year average in every month, except September. Cumulative values for the April-to-September period were 703.7 for 2009 and 428.5 mm for the 25-year average.

5.4.2 Herbage mass, tiller density and sward parameters

Pre-grazing HM was positively associated with the length of the re-growth period ($P < 0.001$; Table 5.2) and was greatest for all treatments in June and lowest in April ($P < 0.001$). Mean pre-harvest HM was different between treatments, with 2-week plots yielding 544 kg DM/ha less than 3-week plots, and these in turn yielding 625 kg DM/ha less than the 4-week plots. Cumulative HM, from April to September, was 6,735 kg DM/ha for the 2-week treatment, 9,103 kg DM/ha for the 3-week treatment and 10,378 kg DM/ha for the 4-week treatment. Pre-harvest sward height increased at a greater rate on the 4-week treatment in the April-to-May period than on the 2- and 3-week treatments, resulting in a significant interaction ($P < 0.001$) between treatment and month (Figure 5.3). Mean post-harvest sward height in the 2-week plots was 0.6 cm less than that from the other treatments. There was no treatment or month effect on PRG tiller density (average 7,459 tillers/m^2). Non-PRG tiller density was also not affected by treatment, however, there was a month effect, with values being highest in September (average 10,853 tillers/m^2).

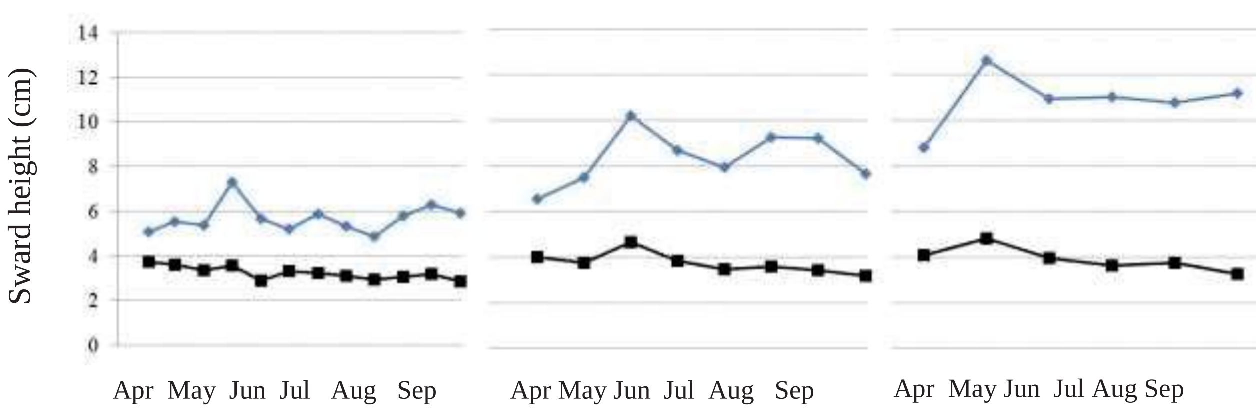

Figure 5.3 Mean pre- (◆) and post-cut heights (■) of plots that were harvested every two, three and four weeks (left, middle and right, respectively) from 4 April to 16 September 2009 in a perennial ryegrass sward.

Table 5.2 Mean pre-harvest herbage mass (above 4 cm), pre-harvest height and tiller density of 12 plots (5 m × 11 m) that were harvested at 2-, 3- or 4-week re-growth intervals (treatments) during six months (from 4 April to 16 September 2009) in a perennial ryegrass (PRG) sward.

		Month							Level of significance		
	Treatment	Apr	May	Jun	Jul	Aug	Sep	T mean	T	M	T×M
Pre-harvest herbage mass (kg dry matter/ha)	2 wk	444	526	735	537	577	550	561^{a} ±18.6			
	3 wk	939	975	1,299	1,066	1,176	1,174	$1,105^{b}$ ±29.7	***	***	NS
	4 wk	1,476	1,763	2,084	1,783	1,618	1,654	$1,730^{c}$ ±33.8			
	M mean	953^{w}	$1,088^{wx}$	$1,373^{y}$	$1,128^{x}$	$1,124^{x}$	$1,126^{x}$				
		±50.2	±50.2	±44.6	±50.2	±50.2	±44.2				
Pre-harvest height (cm)	2 wk	5.3	6.3	5.4	5.6	5.3	6.1	5.7^{a} ±0.04			
	3 wk	6.6	7.5	9.5	7.9	9.3	8.4	8.2^{b} ±0.13	***	***	**
	4 wk	8.8	12.6	10.9	11.0	10.8	11.1	10.9^{c} ±0.15			
	M mean	6.9^{w}	8.8^{x}	8.6^{x}	8.2^{x}	8.5^{x}	8.6^{x}				
		±0.26	±0.26	±0.23	±0.26	±0.26	±0.22				
Post-harvest height (cm)	2 wk	3.7	3.5	3.1	3.2	3.0	3.0	3.2^{a} ±0.08			
	3 wk	4.0	3.8	4.2	3.5	3.6	3.3	3.7^{b} ±0.09	***	***	**
	4 wk	4.1	4.8	4.0	3.6	3.8	3.3	3.9^{b} ±0.09			
	M mean	3.9^{w}	4.0^{w}	3.8^{wx}	3.4^{y}	3.5^{xy}	3.2^{yz}				
		±0.10	±0.10	±0.09	±0.10	±0.10	±0.09				

PRG tiller density (tlrs/m^2)	2 wk	6,254	6,325	6,934	7,717	6,817	6,375	6,737 ±426.0			
	3 wk	6,333	9,867	7,267	6,170	9,642	7,679	7,831 ±426.0	NS	NS	NS
	4 wk	8,525	8,192	8,350	6,925	8,075	6,823	7,815 ±439.8			
	M mean	7,037 ±497.0	8,128 ±541.0	7,517 ±541.0	6,947 ±541.0	8,178 ±541.0	6,959 ±499.2				
Non-PRG tiller density (tlrs/m^2)	2 wk	3,521	7,000	9,000	5,633	11,583	11,450	8,031 ±1,021.1			
	3 wk	2,475	4,150	4,484	2,742	4,408	8,012	4,378 ±1,021.1	NS	***	NS
	4 wk	1,145	5,100	3,467	1,956	2,711	13,097	4,579 ±1,196.2			
	M mean	2,380^{w} ±932.7	5,417^{xy} ±986.9	5,650^{xy} ±986.9	3,444^{wx} ±986.9	6,234^{xy} ±986.9	10,853^{z} ±945.4				

Within columns means not showing a common superscript (a,b,c) differ significantly ($P < 0.05$).
Within rows means not showing a common superscript (w, x, y, z) differ significantly ($P < 0.05$).
M, month; T, treatment.
±; standard error of the mean.
NS, not significant; **, $P < 0.01$; ***, $P < 0.001$.

Sward leaf proportion decreased from the start of the experiment until June, increasing thereafter until September ($P < 0.001$; Table 5.3) although no treatment effect was found for this variable. Stem proportion above 4 cm was highest in May and June and lowest in July, August and September ($P < 0.001$). Dead proportion above 4 cm was lower for the 4-week re-growth interval treatment than the other treatments by four percent units ($P < 0.05$). Stem proportion below 4 cm was affected by treatment with 2-week treatments being six percentage-units lower than the other treatments.

Table 5.3 Sward morphology above and below 4 cm of 12 plots (5 m × 11 m) that were harvested at 2-, 3- or 4-week re-growth intervals during 24 weeks (from 4 April to 16 September 2009) in a perennial ryegrass sward.

		Month							Level of significance		
	Treatment	Apr	May	Jun	Jul	Aug	Sep	T mean	T	M	T×M
Above 4 cm	2 wk	0.69	0.63	0.61	0.72	0.84	0.80	0.71 ±0.011			
Leaf proportion	3 wk	0.66	0.64	0.59	0.72	0.80	0.81	0.70 ±0.014	NS	***	NS
	4 wk	0.71	0.61	0.57	0.71	0.74	0.76	0.68 ±0.015			
	M mean	0.69^{w}	0.63^{x}	0.59^{x}	0.71^{w}	0.79^{y}	0.79^{y}				
		±0.019	±0.020	±0.017	±0.019	±0.019	±0.017				
Stem proportion	2 wk	0.16	0.24	0.23	0.09	0.07	0.10	0.15^{a} ±0.007			
	3 wk	0.23	0.23	0.25	0.12	0.11	0.11	0.17^{b} ±0.009	***	***	NS
	4 wk	0.20	0.33	0.34	0.19	0.16	0.13	0.23^{c} ±0.010			
	M mean	0.20^{w}	0.26^{x}	0.27^{x}	0.13^{y}	0.11^{y}	0.11^{y}				
		±0.012	±0.013	±0.011	±0.012	±0.012	±0.011				
Dead proportion	2 wk	0.16	0.13	0.16	0.17	0.10	0.11	0.14^{a} ±0.006			
	3 wk	0.11	0.14	0.16	0.16	0.10	0.09	0.12^{a} ±0.009	*	NS	NS
	4 wk	0.08	0.06	0.09	0.11	0.11	0.12	0.09^{b} ±0.001			
	M mean	0.12	0.11	0.14	0.14	0.10	0.10				
		±0.014	±0.015	±0.012	±0.014	±0.014	±0.012				

Below 4 cm	2 wk	0.03	0.04	0.06	0.05	0.10	0.07	0.06 ±0.011			
Leaf proportion	3 wk	0.02	0.05	0.03	0.03	0.03	0.06	0.04 ±0.011	NS	NS	*
	4 wk	0.05	0.02	0.01	0.02	0.03	0.03	0.02 ±0.012			
	M mean	0.03	0.04	0.03	0.03	0.05	0.05				
		±0.010	±0.010	±0.009	±0.010	±0.010	±0.009				
Stem proportion	2 wk	0.47	0.51	0.48	0.38	0.46	0.52	0.47^{a} ±0.007			
	3 wk	0.64	0.56	0.52	0.39	0.51	0.47	0.52^{b} ±0.011	**	***	†
	4 wk	0.56	0.59	0.53	0.48	0.55	0.45	0.53^{b} ±0.013			
	M mean	0.56^{w}	0.56^{w}	0.51^{wx}	0.42^{y}	0.50^{x}	0.48^{x}				
		±0.019	±0.021	±0.017	±0.019	±0.019	±0.017				
Dead proportion	2 wk	0.50	0.45	0.47	0.57	0.44	0.42	0.47 ±0.010			
	3 wk	0.34	0.38	0.45	0.58	0.46	0.47	0.47 ±0.013	NS	***	†
	4 wk	0.39	0.38	0.46	0.50	0.43	0.52	0.45 ±0.016			
	M mean	0.41^{w}	0.40^{w}	0.46^{wx}	0.55^{y}	0.45^{x}	0.47^{x}				
		±0.021	±0.022	±0.019	±0.021	±0.021	±0.018				

Within columns means not showing a common superscript (a,b,c) differ significantly ($P < 0.05$).
Within rows means not showing a common superscript (w, x, y, z) differ significantly ($P < 0.05$).
M, month; T, treatment.
±; standard error of the mean.
NS, not significant; † $P < 0.1$; * $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

A rapid increase in ESH on the 4-week treatment in June resulted in a significant treatment-by-month interaction ($P < 0.001$; Table 5.4). Re-growth interval had an effect ($P < 0.001$) on mean treatment ETH (134, 160 and 179 mm for the 2- 3- and 4-week treatments, respectively). Free leaf lamina increased on all treatments over time ($P < 0.001$) with the exception of the May-June period, in which values in 2- and 4-week re-growth treatments were lower. Free leaf lamina was similar for the 3- and 4-week treatments (127.0 mm) but was significantly less ($P < 0.001$) for the 2-week treatment (99.3 mm). In the secondary tillers, ESH was not affected by treatment, although it was affected by month ($P < 0.001$), April and May values being highest (average 27.4 mm), June, July and August being the lowest (average 21.8 mm), and September being intermediate (23.1 mm). Extended tiller height and FLL in secondary tillers were both affected by treatment ($P < 0.001$), being lowest for the 2-week treatment (74.9 and 53.5 mm, respectively), highest for the 4-week treatment (103.4 and 77.2 mm, respectively) and intermediate for the 3-week treatment (88.1 and 64.5 mm, respectively). Month did not have an effect on ETH and ESH of secondary tillers. There was a treatment effect on the number of secondary tillers produced (Table 5.5). There were an average of 0.21 secondary tillers per tiller at harvest for the 2-week plots and an average of 0.52 for the other two treatments ($P < 0.01$). The number of secondary tillers at harvest was greatest in August and lowest in May ($P < 0.001$).

Table 5.4 Sward structure of 240 marked primary tillers and secondary tillers in 12 plots (5 m × 11 m) that were harvested at 2-, 3- or 4-week re-growth intervals during six months (from 4 April to 16 September) in a perennial ryegrass sward.

		Month							Level of significance		
	Treatment	Apr	May	Jun	Jul	Aug	Sep	T mean	T	M	T×M
Primary tillers	2 wk	38.5	38.0	39.6	31.3	30.1	30.7	34.7^{a} ±1.42			
Extended sheath	3 wk	40.7	42.3	43.7	38.5	32.4	38.1	39.3^{a} ±1.53	**	***	*
height	4 wk	45.5	49.6	59.1	42.0	37.3	36.2	44.9^{b} ±1.58			
(mm)	M mean	41.6^{w}	43.3^{w}	47.5^{x}	37.3^{y}	33.3^{z}	35.0^{yz}				
		±1.46	±1.46	±1.34	±1.46	±1.46	±1.35				
Extended tiller	2 wk	134.7	131.6	132.7	129.6	137.1	136.2	133.7^{a} ±5.26			
height	3 wk	150.3	156.4	159.5	164.8	151.5	175.1	159.6^{b} ±5.53	***	NS	NS
(mm)	4 wk	179.0	170.7	190.0	176.4	174.7	180.9	178.6^{c} ±5.67			
	M mean	154.7	152.9	160.7	156.9	154.4	164.1				
		±4.71	±4.71	±4.40	±4.71	±4.71	±4.44				
Free leaf	2 wk	96.3	93.6	93.1	98.3	109.2	105.6	99.3^{a} ±4.14			
lamina	3 wk	109.7	114.1	115.8	126.4	119.1	137.0	120.3^{b} ±4.38	**	***	NS
(mm)	4 wk	133.5	121.1	131.0	134.5	137.4	144.7	133.7^{b} ±4.50			
	M mean	113.1^{wx}	109.6^{w}	113.3^{wx}	119.7^{xy}	121.9^{yz}	129.1^{z}				
		±3.84	±3.84	±3.57	±3.84	±3.84	±3.60				

Secondary tillers	2 wk	26.4	23.4	17.9	18.6	19.4	23.2	21.5 ±1.29			
Extended sheath	3 wk	27.0	28.6	21.4	24.7	20.2	22.2	24.0 ±1.40	NS	***	NS
height	4 wk	32.6	26.1	27.2	22.4	24.1	24.0	26.1 ±1.45			
(mm)	M mean	28.7[w]	26.0[w]	22.2[x]	21.9[x]	21.2[x]	23.1[wx]				
		±1.38	±1.49	±1.23	±1.34	±1.34	±1.28				
Extended tiller	2 wk	75.3	85.0	71.7	65.1	75.4	77.0	74.9[a] ±3.14			
height	3 wk	90.3	106.1	82.5	97.2	74.7	77.6	88.1[b] ±3.78	***	NS	NS
(mm)	4 wk	114.7	97.2	114.5	97.2	101.0	95.7	103.4[c] ±4.02			
	M mean	93.4	96.1	89.5	86.5	83.7	83.4				
		±4.78	±5.21	±4.17	±4.63	±4.63	±4.33				
Free leaf	2 wk	49.2	61.6	53.8	46.5	56.0	53.6	53.5[a] ±2.13			
lamina	3 wk	66.3	77.5	61.0	72.5	54.1	55.4	64.5[b] ±2.75	***	NS	NS
(mm)	4 wk	82.0	71.3	87.2	74.8	76.1	71.5	77.2[c] ±2.97			
	M mean	64.9	70.1	67.3	64.6	62.1	60.2				
		±3.86	±4.20	±3.34	±3.73	±3.73	±3.46				

Within columns means not showing a common superscript (a,b,c) differ significantly ($P < 0.05$).
Within rows means not showing a common superscript (w, x, y, z) differ significantly ($P < 0.05$).
M, month; T, treatment.
±; standard error of the mean.
NS, not significant; * $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

5.4.3 Tissue turnover

The increase in total leaf length at harvest over time was least on the 2-week treatment, resulting in a significant treatment-by-month interaction ($P < 0.01$; Table 5.5). Differences between LER for the 2-week treatment and the other two treatments were greater in the June-to-September period compared to the April-to-May period ($P < 0.001$), resulting in a significant interaction between month and treatment. The number of leaves emerging per tiller during the re-growth period was always least for the 2-week treatment ($P < 0.001$). There was a month effect ($P < 0.001$), with more leaves emerging per tiller during the second half (June to September) of the experiment. The number of live leaves was unaffected by treatment. Figure 5.4 shows the regression line of number of leaves appeared (NL) during the re-growth period on pre-harvest HM. The estimations of the regression coefficient are the following:

NL =	0.34103	+	0.00162 HM	–	0.00000004 HM^2
Standard error	0.12072		0.00022376		0.000000009
Significance	*		***		***
R^2 =	0.68				

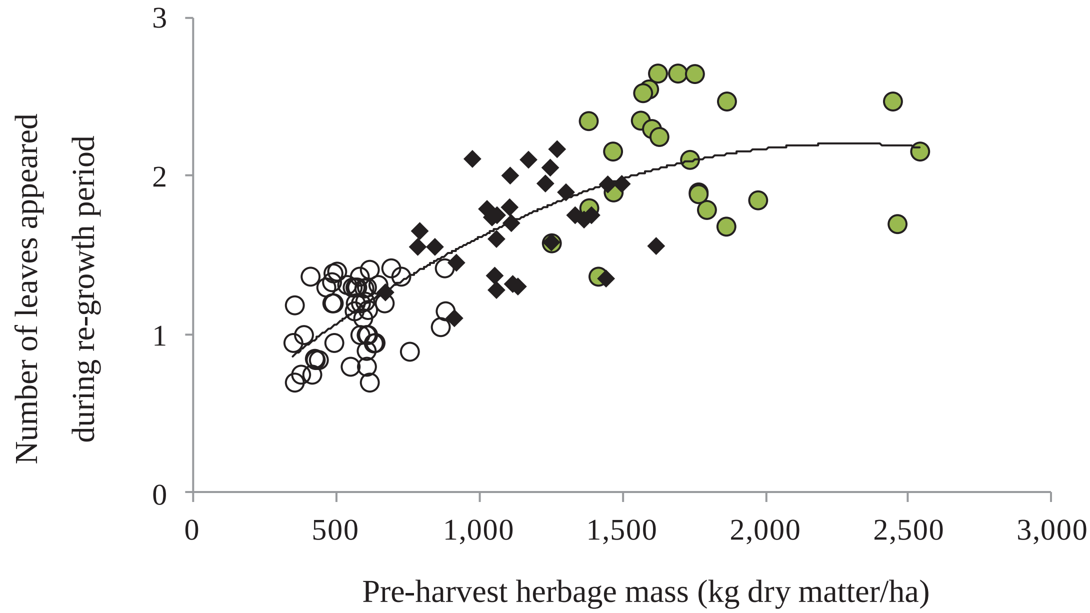

Figure 5.4 Pre-harvest herbage mass (kg dry matter per hectare) and leaves appeared per tiller during the re-growth period of 12 plots (5 m × 11 m) that were harvested every two (○), three (◆) or four (●) weeks for six months from 4 April to 16 September 2009 in a perennial ryegrass sward.

Table 5.5 Total leaf length per tiller at harvest, leaf extension rate (LER) from week 1 to week 2 of re-growth and number of leaves emerged during the re-growth period for each of the 240 marked tillers in 12 plots (5 m × 11 m) that were harvested at 2-, 3- and 4-week re-growth intervals during six months (from 4 April to 16 September 2009) in a perennial ryegrass sward.

		Month							Level of significance		
	Treatment	Apr	May	Jun	Jul	Aug	Sep	T mean	T	M	T×M
Total leaf length	2 wk	162.7	159.2	169.8	176.4	185.8	172.6	171.1[a] ±7.11			
at harvest	3 wk	190.1	199.8	219.5	259.3	252.8	273.0	232.4[b] ±7.69	***	***	**
(mm/tlr)	4 wk	254.1	258.6	293.1	282.0	335.4	299.1	287.0[c] ±8.07			
	M mean	202.3[w]	205.9[w]	227.5[x]	239.3[xy]	258.0[z]	248.2[yz]				
		±7.45	±7.87	±6.85	±7.45	±7.45	±6.85				
LER wk 1 to wk 2	2 wk	8.1	6.8	7.7	9.4	8.5	7.6	8.0[a] ±0.49			
(mm/tlr/day)	3 wk	7.3	9.4	9.5	13.0	10.1	13.5	10.5[b] ±0.55	*	***	**
	4 wk	7.5	7.5	12.5	12.6	11.5	10.3	10.3[b] ±0.58			
	M mean	7.6[w]	7.9[w]	9.9[x]	11.7[y]	10.0[x]	10.5[xy]				
		±0.59	±0.59	±0.53	±0.59	±0.59	±0.53				
Leaves emerged	2 wk	0.81	0.95	1.16	1.23	1.30	1.23	1.11[a] ±0.020			
during re-growth	3 wk	1.26	1.40	1.65	1.98	1.92	1.80	1.67[b] ±0.028	***	***	*
period	4 wk	1.61	1.93	1.98	2.33	2.60	2.34	2.13[b] ±0.032			
(n/tlr)	M mean	1.23[v]	1.43[w]	1.59[x]	1.85[yz]	1.94[y]	1.79[z]				
		±0.043	±0.046	±0.038	±0.043	±0.043	±0.038				

Secondary tillers	2 wk	0.09	0.16	0.24	0.29	0.28	0.18	0.21^{a} ±0.043			
at harvest	3 wk	0.50	0.11	0.31	0.63	0.86	0.45	0.48^{b} ±0.050	**	***	*
(n/tlr)	4 wk	0.25	0.24	0.63	0.71	1.01	0.50	0.56^{b} ±0.055			
	M mean	0.28^{wx}	0.17^{w}	0.39^{xy}	0.54^{y}	0.72^{z}	0.38^{wx}				
		±0.061	±0.065	±0.055	±0.061	±0.061	±0.055				

Within columns means not showing a common superscript (a,b,c) differ significantly ($P < 0.05$).
Within rows means not showing a common superscript (w, x, y, z) differ significantly ($P < 0.05$).
M, month; T, treatment.
±; standard error of the mean.
* $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

5.5 Discussion

This study investigated the effects of three re-growth intervals on sward production, sward characteristics and tissue turnover of a PRG sward in Ireland over a six-month period. This provides a comprehensive set of data on re-growth dynamics and the behaviour of tillers in response to defoliation.

Shorter intervals between defoliations resulted in lower levels of HM at harvest and decreased cumulative DM yields. The plots harvested every two weeks had 26 and 35% lower cumulative HM than the plots harvested every three and four weeks, respectively. Lower herbage production with faster rotations, and subsequent reduced levels of pre-harvest HM, were also found previously by Broughman (1959) and, more recently, by McEvoy *et al.* (2009), Wims *et al.* (2010) and Tuñon *et al.* (2011b). The amount of solar radiation intercepted by photosynthetic tissue will determine, to a large extent, the level of sward accumulation throughout the year (Hunt and Brougham, 1967). The level of pre-harvest HM in the 2- and 3-week treatments would have been insufficient for optimum re-growth. In a PRG sward, the maximum rate of increase in HM occurs when sufficient pre-harvest HM is present to intercept over 95% of the incident light (Brougham, 1956) and this seems to have occurred only in the 4-week treatment.

Low pre-harvest-HM swards are generally associated with increased tiller density, as tillers compensate for smaller size due to frequent grazing by increasing their number (Hernandez-Garay *et al.*, 1999; Hodgson, 1990). The increased reception of solar radiation at the base of the sward stimulates the appearance of secondary tillers (Grant *et al.*, 1981). Indeed, in a previous experiment at the same research station as the present study, pre-grazing HM that was managed to remain relatively low during mid-season (average 1,001 ±112 kg DM/ha) was associated with increased PRG tiller density in the autumn (Tuñon, accepted in Grass and Forage Science, Chapter 3). Those pre-grazing HM values are similar to the 3-week treatment; no increases in tiller density were observed in this experiment. The limit for phenotypic plasticity would have been reached for the sward defoliated every three weeks. In the case of the 2-week re-growth plots, by cutting them too often, the limit of phenotypic plasticity would have been passed, evidence of this being that the most frequently-defoliated treatment had 1,000 fewer tillers/m^2 than the other two treatments (numerical difference). These last apparent trends support Fulkerson and Slack (1995), who reported increased tiller density when swards are infrequently defoliated (at the 3-leaf stage) compared with frequent defoliation (at the 1-leaf stage) swards. The reason behind the contradictory results can be the WSC availability of the plant for re-growth, since tiller initiation is closely related to WSC reserves in the plant (Donaghy and Fulkerson, 1998). Only after two complete live leaves are originating during re-growth is when the first window for tiller development occurs (Skinner and Nelson, 1992). Donaghy and Fulkerson (1998) concluded that leaf re-growth was insensitive to WSC depletion and tiller initiation was, on the contrary, the most sensitive. Fulkerson and Donaghy (2001) proposed that PRG leaf growth is a top priority, even at the expense of roots, although this could result in root-system failure and plant death. The authors then established the 3-leaf stage as the maximum for optimum production, quality and persistence of the PRG tillers.

In contrast, high levels of pre-grazing HM are associated with a shading effect that, in turn, causes a loss of tillers (Colvill and Marshall, 1981). Tiller density was not found to be depressed in the least frequently-cut plots, perhaps due to the comparatively low pre-harvest HM values. Shading may occur with higher levels of pre-harvest HM than the values measured in this experiment. There could have been a ‘year’ effect, 2009 was wetter than the average (Table 5.1) and colder in the July-September period, this being translated into pre-harvest-HM values that hardly surpassed 2,000 kg DM/ha, and so swards may not have been susceptible to shading. Nevertheless, with PRG tiller densities over 7,000/m^2, the negative impact of losing tillers from shading when HM values get close to 2,000 kg DM/ha may be offset by the relative high density of tillers that is found in young swards such as the ones in the present experiment.

As the experiment progressed, total leaf length per tiller at harvest increased in the autumn for the 3-week treatment, while it decreased for the other two treatments. An explanation for this is the better energy status of the 3-week re-growth interval treatment in comparison with the 2-week treatment, although it remains unclear why this did not occur in the 4-week treatment, since the tillers in these plots had optimum number of emerged leaves, meaning that the energy levels would have been optimal (Fulkerson and Donaghy, 2001) and also higher residual ESH, which is associated with increased LER (Grant *et al.*, 1981). Based on that the 2-week plots had only 1.1 leaves appearing in each re-growth interval, their energy status is assumed to have been consistently low across the experiment. The appearance of secondary tillers was lower in 2-week re-growth interval plots than in the other two treatments. Based on previously mentioned research (Fulkerson and Donaghy, 2001), the leaf stage was suboptimum for the 2- and 3-week treatments throughout all the experimental period, and even for the 4-week re-growth treatment during the first half of the experiment. Only in the second half of the experiment did the 4-week re-growth-interval plots achieved optimum leaf stage, *i.e.*, between two and three leaves appeared during the re-growth period (Figure 5.4). A conclusion that can be drawn from this is that in such conditions, the optimum re-growth interval for the sward of the experiment would have been four weeks most of the season.

Although the motor Agria was set to a cutting height of 4 cm, this could not be always achieved, the most-frequently-harvested plots having a 0.6-cm lower post-cut height than the other two treatments, leaving a very soft post-cut residual. This was evidenced by the 0.6 lower stem proportion (below 4 cm) in the 2-week treatments compared with the other two treatments. The PRG tillers defoliated every two weeks seemed to have adapted to lower post-cut heights, which agrees with Chapman *et al.* (2011), who discussed that PRG tillers consistently defoliated at very low levels seem to adapt in order to be able to regrow as fast as possible after defoliation, and that this is an important feature of PRG. The numerical difference detected in leaf proportion below 4 cm, with the 2-week treatment being three times greater than the 4-week treatment, can be interpreted as an adaptation of the most-frequently-harvested plots to this intensive regime. This agrees with Brock *et al.* (1996) who observed that, to survive the frequent defoliation of continuous defoliation under set stocking, the PRG plant adopts a more prostate growth habit than the usual. Rhodes (1971) examined how PRG varieties of prostate or erect growth habits responded to frequent defoliations and found that the former adapted well due to a higher leaf area index, this an example of phenotypic plasticity.

The number of live leaves per tiller was unaffected by treatment and month, with an average value of 2.89, in agreement with Davies (1977). Chapman *et al.* (2011) also reported that the number of live leaves per tiller showed a seasonal pattern, the maximum number achieved during reproductive growth in late spring. However, this did not seem to occur in the present study. It must be pointed out that FLL is evidencing that the leaf length was shorter with more frequent defoliations, with 2-week plots being 27.7 mm shorter than the mean value of the other two treatments. Leaf growth is the priority after defoliation, at the expense of tillering, this is because the plant needs to ensure it captures light for photosynthesis. The leaf growth zone is rarely carbohydrate deficient (Schnyder and Nelson, 1989). However, this competition for light can lead to an increased mortality rate (Hazard *et al.*, 2001). Days for a new leaf to appear from week 0 to week 1 of the re-growth cycle (15.2, 17.9 and 16.2) and from week 1 to week 2 of the re-growth cycle (12.8, 14.8 and 13.1, for 2-, 3- and 4-week treatments, respectively) were not affected by treatment. Tillers produce leaves, even at negative energy balance, in order to survive in the competition for light (Davies and Thomas, 1983). This can be to the detriment to persistency and production.

5.6 Implications for grazing management

If the conditions present in the current study were applied on farm, grass DM intake would have been jeopardised for those cows that were grazing at the pre-grazing sward heights of the 2- and 3-week plots. When pre-grazing sward height is lower than 9 - 10 cm, grass DM intake is at risk of decreasing due to smaller bite size, for which cows increase their bite rate to compensate for the smaller bite sizes (Hodgson, 1990), as was reported by Tuñon *et al.* (2011b). In addition, the production losses in the more frequently-defoliated plots would mean the need to fill that gap with supplementary feeds. With the weather conditions in 2009, optimum re-growth interval would have been close to four weeks for most of the season, probably with the exception of June, in which signs of stem elongation were detected, *i.e.*, higher proportion of leaf above 4 cm and higher ETH in contrast with the other two treatments. This could have led to declining levels of sward digestibility.

Grass management is a compromise between having sufficient leaf tissue to intercept light, but also trying to have young tissue, because the photosynthetic activity of the leaves decreases with age (Woledge, 1971). Thus, on the one hand, it is required that rotation is fast enough so as to avoid leaves growing older but, on the other hand, a fast rotation means there is a risk of pre-harvest HM being not sufficiently high and light interception not adequate. There seems to be an optimum defoliation window (Fulkerson and Donaghy, 2001), between what Michalk and Kemp (1993) called boundaries, which results in maximum growth and utilisation of pasture, and also persistence and quality. Parsons *et al.* (1988) concluded that the optimum time for defoliation would be at the time of maximum average growth rate but just before the ceiling yield. The authors also stated that effective grazing management must couple severe defoliation with relatively short re-growth periods in order to avoid stem accumulation, and the authors considered there was little danger of too short durations of re-growth intervals. This study, however, highlights the danger of too frequent defoliations and the importance of understanding the ecosystem in which individual tillers are growing. Further research can help define the boundaries for combinations of PRG varieties.

5.7 Conclusions

Harvesting too frequently (<3 weeks) damages the growth potential of the pasture. Harvesting every two weeks during the main grazing season went beyond the limits of plant phenotypic plasticity. A re-growth interval that allows each tiller to produce between two and three leaves will result in optimum sward structure, morphology and herbage accumulation. This study supports recommendations for grass-based dairy production (Chapman *et al.*, 2011; Fulkerson and Donaghy, 2001; Macdonald *et al.*, 2010) of defoliation of PRG swards when tillers have achieved between two and three emerged leaves. Decisions of when to defoliate that do not take into account the physiology of the tiller during re-growth can lead to depressed sward production.

Chapter 6: Effects of herbage mass on characteristics and tissue turnover of a perennial ryegrass sward under grazing with dairy cows

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6.1 Abstract

As a part of a grazing trial investigating the effects of three pre-grazing herbage mass (HM) levels on sward and animal performances, the present study focused on the effects of level of pre-grazing HM on sward characteristics and tissue turnover over 24 weeks in Ireland. In each of nine selected plots, within 20% of the area used for the larger farmlet trial, 40 perennial ryegrass (PRG) tillers were marked with coloured-coated-plastic wire. Treatments were low (L), medium (M) or high (H) pre-grazing HM (targets 900, 1,500 and 2,200 kg dry matter (DM)/hectare (ha), respectively). Three groups of 15 dairy cows were used. At the beginning of each re-growth period, another set of tillers was marked in each base plot. The length of each green leaf was measured weekly throughout the re-growth period. Leaf appearance and extension rates were calculated for each period. Herbage mass above 4 cm was estimated every time measurements were performed. Leaf, stem and dead proportions were estimated weekly where cows were about to graze, this including the larger farmlet area. Tiller density was assessed five times during the experimental period (5 March, 10 April, 4 June, 1 August and 5 October) in the base plots. The linear model used included the fixed effects of period and treatment, the interaction period by treatment and the random effect of plot. The average grazing intervals of the L, M or H pre-grazing HM plots were 14.0, 21.9 and 28.7 days, corresponding to pre-grazing HM values of 945, 1,623 and 2,360 kg DM/ha >4 cm, respectively. The mean number of leaves per tiller emerged during the re-growth period was 1.0, 1.9 and 2.4 for L, M or H pre-grazing HM treatments, respectively. Mean number of secondary tillers present at harvest was 0.17, 0.36 and 0.62 for L, M and H pre-grazing HM treatments, respectively. The findings of this study add to the scientific knowledge of grassland systems and highlight the need to understand physiology of the plants for effective grazing management. Harvesting too often, at low levels of HM, can result in decreased sward production and individual grass DM intakes.

***Keywords*:** leaf stage, grazing, perennial ryegrass, rotation.

6.2 Introduction

Large quantities of high-quality grass throughout a relatively long grazing season can be grown in Ireland. This is paramount for Ireland because grass remains the cheapest source feed for dairy production systems (Dillon *et al.*, 2007; Macdonald *et al.*, 2011a; Peyraud and Delaby, 2005). This competitive advantage has been forcing Irish dairy farmers towards a grass-based dairy system and away from systems based on high levels of supplementation. Maximum grass utilisation requires increased stocking rates (SR; McMeekan, 1961) coupled with an extended grazing season (Hennessy and Kennedy, 2010). To achieve this successfully the farmer must understand the interaction between the animal and the sward to meet the requirements of both.

A major decision in grassland management is the choice of when to graze a paddock. Restricted intakes and severe defoliation must be coupled with re-growth intervals that are sufficiently long to allow optimum grass growth but not too long so as to avoid substantial increases in the proportion of stem in the sward (Parsons and Penning, 1988). Criteria to determine the time of grazing has up to now predominantly been based on rotation length, pre-grazing herbage mass (HM) and sward height (Mayne *et al.*, 2000; Sheath and Clark, 1996). However, the timing of defoliation in relation to plant development can have a huge impact on the sward (Donaghy and Fulkerson, 1998). Fulkerson and Donaghy (2001) established that the optimal time for defoliation is between the 2- and the 3-leaf stage, for optimum production, quality and persistence of the perennial ryegrass (PRG) tillers in vegetative swards. This was supported recently (Chapman *et al.*, 2011; Macdonald *et al.*, 2010; Tuñon *et al.*, 2011a).

Previous experiments, in which swards were defoliated by mechanisms other than grazing (Fulkerson and Slack, 1995; Tuñon *et al.*, 2011a; Turner *et al.*, 2006), have reported the effects of varying defoliation intervals on PRG swards. A more difficult approach for investigating performance at the individual tiller level is to incorporate the animal factor. Not many studies reported measurements of tissue turnover of marked tillers in a grazing regime for a long period such as the present study (24 weeks; Chapman *et al*, 1983). This experiment was designed as a continuation of previous study under a cutting regime (Tuñon *et al.*, 2011a). The objective of the present study was to investigate the effects of three levels of pre-grazing HM on sward characteristics and tissue turnover under grazing of dairy cows during the main grazing season in Ireland.

6.3 Materials and methods

The study was undertaken at the Animal & Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland (52°7’N; 8°16’W; 46 m above sea level) from 17 April to 7 October 2010. This study was undertaken within a larger farmlet trial (16.5 hectare; ha) investigating the effects of three target levels of pre-grazing HM on cow and sward performance: low (L; 900 ±100 kg dry matter; DM/ha), medium (M; 1,500 ±200 kg DM/ha) and high (H; 2,200 ±300 kg DM/ha). Nine 0.36-ha plots, hereafter referred to as base plots, were used in this study. The soil type was a free-draining acid-brown-earth soil with a sandy-loam-to-loam texture. The grassland site was under permanent pasture with a predominately PRG sward that was, on average, eight years old. No clover was present in the sward. The present study focused on the effects of pre-grazing HM on tissue turnover, sward structure, sward morphology and tiller density in a PRG sward.

6.3.1 Animals

Prior to the experiment 45 Holstein-Friesian dairy cows (15 primiparous and 30 multiparous) were selected and blocked using records of daily milk yield, lactation number, body condition score and live weight. From calving until the start of the experiment, animals were grazing as a single herd. Animals were randomly assigned to the three pre-grazing HM treatments on 27 April (32 days in milk) and remained in their assigned treatment groups until the end of the experiment. Animal performance data is reported in Tuñon *et al.* (2011b).

6.3.2 Grazing management

The grassland site used for the larger farmlet trial comprised 24 paddocks. Each herd was assigned eight paddocks which were intermittently grazed for the duration of the experiment, with grazing interval determined by the treatment assigned to a paddock. Overall grazing SR was 2.7 cows/ha. The nine base plots were grazed following the rotations of the larger farmlet trial. Before the large farmlet trial commenced, the entire experimental area was grazed to a similar post-grazing sward height (4 cm; target for the three treatments for the rest of the experiment); the target pre-grazing HMs were created by varying the interval (days) between pre-experimental grazing and the first experimental grazing. Thus, the H paddocks were grazed initially, followed by the M pasture and finally the L paddocks, thereby creating different re-growth intervals. Throughout the experiment, cows were offered fresh grass daily after morning milking. Pasture allocation was 17 kg DM/cow/day (above 4 cm). The grassland site received 30 kg phosphorous/ha after the first grazing, a total annual application of 250 kg nitrogen (N)/ha in the form of calcium ammonium nitrate (CAN; 0.27 N) and 248 kg potassium/ha, both divided according to the number of grazings.

6.3.3 Measurements

6.3.3.1 Herbage mass, sward morphology and tiller density

To make sure that each herd was grazing as close as possible to the target pre-grazing HM, HM was assessed daily in the base plots using the quadrat technique. This consisted in placing a 0.5m×0.5m quadrat in an area that was representative of the paddock. The grass within the quadrat was cut to between 3.5 and 4 cm with a Gardena hand shear. The grass obtained in the sample was placed in a bag a subsequently weighed with a small scale. To calculate the DM yield in the plot, the following equation was used:

Weight of grass (kg) × DM% × 40,000 = kg DM/ha in the paddock

Cumulative HM was calculated adding the mean pre-grazing HM of each treatment. Grass-height measurements were recorded daily pre- and post-grazing using a rising plate meter (diameter 355 mm and 3.2 kg/m^2; Jenquip, Fielding, New Zealand; Earle and McGowan, 1979) across the diagonal of each plot.

6.3.3.2 Tissue turnover and tiller structure

In each base plot, at the beginning of each re-growth period, a new set of 40 PRG tillers were marked with a ring of coloured-plastic-coated wire (Figure 5.1) at 10-cm intervals along two 1-m transects (Hennessy *et al.*, 2008a). The marked tillers were fenced using two pigtail posts and a 2-m power line rope attached to them (Figure 6.1). This was sufficient to stop animals trampling, defecating or urinating over the marked tillers.

However, it did not stop them from grazing under the fence effectively. The length of each green leaf was measured weekly using a plastic ruler throughout the re-growth period. The youngest leaf present on the tiller on the day of each measurement was marked using Tipp-ex™. The number of leaves produced during each week of re-growth was recorded. This information was used to determine leaf appearance rate (LAR). Leaves were identified by the order in which they appeared and their stage of development, *i.e.* L0 was the expanding leaf at marking, L1 was the youngest/first fully-expanded leaf, L2 the second fully-expanded leaf and L3 was the third fully-expanded leaf at marking. Mean leaf extension rate (LER; mm/tiller/day) was calculated as the mean daily increase in length (mm) of leaves expanding during the measurement period, including the length of new leaves appearing during the period. Extended tiller height (ETH) and extended sheath height (ESH) were measured on each marked tiller at the time of LER measurement, using a graduated ruler. Extended tiller height was measured from ground level to the highest point of the tiller. Extended sheath height was measured from ground level to the point of the highest ligule (longest leafed sheath). Free leaf lamina (FLL) was then calculated by subtracting the ESH from the ETH, as described by Gilliland *et al.* (2002). Rainfall and temperature were recorded daily at a meteorological station less than 1 km away from the experimental site (Table 6.1).

(a) (b)

Figure 6.1 (a) Marked tillers fenced using two pigtail posts and a 2-m power line rope attached to them in a high-herbage-mass base plot and (b) a cow grazing under the fence in a medium-herbage-mass plot.

Table 6.1 Mean daily temperature and monthly rainfall for 2010 as compared with previous 10-year average (1999-2009).

	Apr	May	Jun	Jul	Aug	Sep	Oct
Mean temperatures 2010 (°C)	9	11	15	16	14	14	10
Mean temperatures 1999-2009 (°C)	9	12	14	16	16	14	11
Monthly rainfall 2010 (mm)	59	39	53	143	23	102	83
Mean monthly rainfall 1999-2009 (mm)	66	75	68	70	86	90	117

6.3.3.3 Sward morphology and tiller density

The morphological composition of the herbage was determined weekly in each of the paddocks where each herd was about to graze, this included all the paddocks of the large farmlet. A sample of approximately 30 g was cut at random to ground level with a scissors before harvest. By securing the sample with an elastic band and placing it in a bag, the vertical structure of the cut sward was preserved. The sample was later cut into two portions, above and below 4 cm. Then, for each portion, individual layers were separated into leaf, stem (including true stem, pseudo-stem and flower head, if present) and dead material. Each constituent was dried overnight at 95^{o}C for a minimum of 15 hours to determine morphological composition on a DM basis. Tiller density was assessed in each of the base plots five times (5 March, 10 April, 4 June, 1 August and 5 October). Six turves (0.10 m × 0.10 m) were selected randomly from each plot, cut to a depth of *c*.3 cm and dissected. The species of each tiller was identified and counted (Jewiss, 1993).

6.3.4 Statistical analysis

All statistical analyses were carried out using the MIXED procedure of SAS (Statistical Analysis System, version 9.2; SAS Institute Inc., Cary, NC, US). Repeated measures on the same plot of pre-grazing HM, pre- and post-grazing sward height, grazing interval, grass growth rate and tissue turnover and structure from the marked tillers were analysed with a mixed model that included the fixed effects of treatment, month and the interaction treatment by month, and the random effect of plot. Sward morphology variables were analysed with a linear model that included the fixed effects of treatment, month and the interaction treatment by month. Tiller density was analysed with a mixed model that included the fixed effect of treatment, time and the interaction treatment by time, and the random effect of plot. Using the Akaike's information criterion, a compound symmetry error structure was determined as the most appropriate residual covariance structure for repeated measures over month or time within plot. For this study seasons are defined as spring (from the start of the experiment until 15 April), mid-season (16 April until 1 August) and autumn (2 August until the end of the experiment). The relationship between the number of newly-appeared leaves and pre-harvest HM was estimated using all data with the REG procedure of SAS.

6.4 Results

6.4.1 Weather

Compared with the previous 10-year average, mean temperature during the experimental period (2010) was lower in April, May, August, September and October, and only higher in June and July. Cumulative rainfall during the experimental period was 69 mm lower in 2010 in contrast with previous 10-year average. Highest rainfall was recorded in July and lowest in April.

6.4.2 Herbage mass, grazing interval and sward height

Treatment had significant effects on pre-grazing HM, grazing interval and sward height (Table 6.2; Figure 6.2). The levels of pre-grazing HM were all different from each other ($P < 0.001$), with differences of 678 kg DM/ha between L and M pre-grazing HM, and 737 kg DM/ha between M and H treatments. These pre-grazing HM values were achieved after different grazing intervals ($P < 0.001$). Average grass growth rate across the experimental period was lowest for L (71.9 kg DM/day), highest for H (84.0 kg DM/day) and intermediate for the M treatment (78.3 kg DM/day; $P < 0.001$). Pre-grazing sward heights were 6.4, 9.4 and 11.5 cm for L, M and H treatments, respectively, and were all different from each other ($P < 0.001$; Figure 6.2). Post-grazing sward height was 3.9 cm in L plots and this value was significantly lower than M and H treatments, 4.1 and 4.2 cm, respectively ($P < 0.001$; Figure 6.2). There was a treatment-by-month interaction in May with high pre-grazing-HM plots showing a higher increase in pre- and post-grazing sward height compared to the other treatments.

Table 6.2 Pre-grazing herbage mass (above 4 cm) and grazing interval of swards grazed by dairy cows at low, medium or high pre-grazing herbage mass (targets 900, 1,500 or 2,200 kg DM/ha, respectively) in a perennial ryegrass sward.

		Month							Level of significance		
	Treatment	Apr	May	Jun	Jul	Aug	Sep	T mean	T	M	T×M
Pre-grazing	Low	883	975	898	966	891	1,058	945^{a} ±19.9			
herbage mass	Med	1,513	1,652	1,721	1,591	1,560	1,701	$1,623^{b}$ ±28.9	***	***	***
(kg DM/ha)	High	2,334	2,975	2,486	2,838	1,591	1,935	$2,360^{c}$ ±33.2			
	M mean	$1,577^{w}$	$1,867^{x}$	$1,702^{y}$	$1,799^{yz}$	$1,347^{z}$	$1,565^{w}$				
		±48.4	±44.2	±49.0	±43.3	±50.8	±54.9				
Grazing interval	Low	11.9	13.8	11.4	11.4	19.2	16.0	14.0^{a} ±0.45			
(days)	Med	20.7	18.7	22.3	14.7	31.0	24.0	21.9^{b} ±0.55	***	***	***
	High	22.3	29.0	33.7	27.0	31.0	29.3	28.7^{c} ±0.60			
	M mean	18.3^{w}	20.5^{x}	22.5^{x}	17.7^{w}	27.1^{y}	23.1^{x}				
		±0.75	±0.69	±0.76	±0.68	±0.79	±0.85				

Within columns means not showing a common superscript (a,b,c) differ significantly (P < 0.05).
Within rows means not showing a common superscript (w, x, y, z) differ significantly (P < 0.05).
M, month; T, treatment.
±; standard error of the mean.
***, P < 0.001.

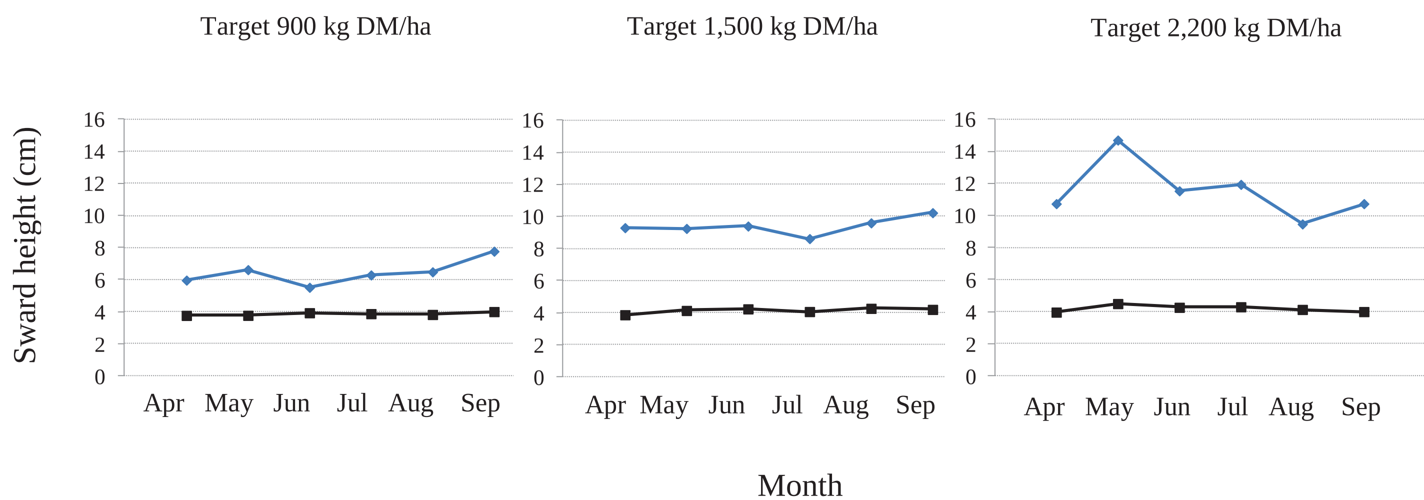

Figure 6.2 Pre- (◆) and post-grazing sward heights (■) of perennial ryegrass swards that were grazed at three targets of pre-grazing herbage mass.

6.4.3 Structure and tissue turnover

Total leaf length at harvest was positively associated with pre-grazing HM. The differences between L and M and between M and H treatments, were 56 mm in both cases (*P* < 0.001; Table 6.3). A significant treatment-by-month interaction was evident in July with the high pre-grazing-HM treatment increasing up to almost 300 mm while M and L treatments did not achieve 200 mm of total leaf length in those months (*P* < 0.001; Figure 6.3, 1). The number of leaves emerged during re-growth was different between treatments (*P* < 0.001). The marked tillers that were grazed at low pre-grazing HM had always less than two new leaves appeared during re-growth. The tillers grazed at medium pre-grazing HM only achieved the 2-leaf stage in August and September. The tillers grazed at high pre-grazing HM achieved always the 2-leaf stage, with the exception of the first month of the experiment (Figure 6.3, 2). Leaf extension rate of the tillers grazed at low pre-grazing HM tillers was 0.7 mm lower than the average of the other two treatments (*P* < 0.05; Figure 6.3, 3).

The number of secondary tillers at grazing was different between treatments (*P* < 0.001). The tillers grazed at lowest pre-grazing HM achieved one secondary tiller for every five tillers and the tillers grazed at medium pre-grazing HM had one secondary tiller for every three tillers at grazing. The tillers that were grazed at high pre-grazing HM had more than one secondary tiller for every two tillers (*P* < 0.001; Figure 6.3, 4). A significant interaction was evident in June and July, with the tillers grazed at high pre-grazing HM having a very pronounced increase in production of secondary tillers compared to the other two treatments (*P* < 0.001). The total number of leaves per tiller at grazing was affected by treatment (*P* < 0.001) with tillers marked in the L treatment having less than the other two treatments (2.8 and 3.1 leaves/tiller, respectively).

Table 6.3 Total leaf length per tiller at grazing, leaves emerged during the re-growth period, secondary tillers at grazing and leaf extension rate of 360 marked tillers were grazed by dairy cows at low, medium or high pre-grazing herbage mass (targets 900, 1,500 or 2,200 kg DM/ha, respectively) in a perennial ryegrass sward.

		Month							Level of significance		
	Treatment	Apr	May	Jun	Jul	Aug	Sep	T mean	T	M	T×M
Total leaf length	Low	157.2	154.1	111.5	147.5	96.6	129.4	132.7^{a} ±4.84			
at grazing	Medium	202.5	180.6	219.0	187.4	163.1	183.3	189.3^{b} ±5.63	***	***	***
(mm/tlr)	High	238.7	236.9	283.3	299.0	234.9	179.4	245.3^{c} ±6.21			
	M mean	199.5^{w}	190.5^{w}	204.6^{w}	211.2^{w}	164.9^{x}	164.0^{x}				
		±6.99	±6.66	±7.06	±6.11	±8.79	±6.08				
Leaves emerged	Low	0.87	1.21	0.94	1.04	0.63	1.73	1.01^{a} ±0.04			
during re-growth	Medium	1.65	1.55	1.93	1.43	2.52	2.16	1.87^{b} ±0.05	***	***	***
period	High	1.73	2.55	2.75	2.58	2.60	2.26	2.41^{c} ±0.05			
(n/tlr)	M mean	1.41^{w}	1.77^{xy}	1.87^{xy}	1.68^{x}	1.92^{yz}	2.05^{z}				
		±0.07	±0.06	±0.07	±0.06	±0.09	±0.06				
Secondary tillers	Low	0.25	0.18	0.10	0.19	0.02	0.28	0.17^{a} ±0.04			
at grazing	Medium	0.61	0.19	0.50	0.10	0.34	0.45	0.36^{b} ±0.05	***	***	***
(n/tlr)	High	0.42	0.18	1.30	0.87	0.44	0.53	0.62^{c} ±0.05			
	M mean	0.43^{wz}	0.18^{x}	0.63^{y}	0.39^{w}	0.26^{wx}	0.42^{z}				
		±0.05	±0.05	±0.05	±0.04	±0.06	±0.04				

Leaf extension rate	Low	7.48	10.08	5.92	10.17	4.17	4.64	7.08^{a} ±0.076			
at grazing	Medium	6.65	7.02	9.67	12.19	3.74	6.14	7.57^{b} ±0.178	*	***	***
(mm/day/tlr)	High	8.33	8.15	7.64	10.53	7.23	5.59	7.91^{b} ±0.232			
	M mean	7.49^{w}	8.42^{w}	7.74^{w}	10.97^{x}	5.05^{y}	5.46^{y}				
		0.365	0.342	0.354	0.305	0.459	0.304				

Within columns means not showing a common superscript (a,b,c) differ significantly ($P < 0.05$).
Within rows means not showing a common superscript (w, x, y, z) differ significantly ($P < 0.05$).
M, month; T, treatment.
±; standard error of the mean.
* $P < 0.05$; ***, $P < 0.001$.

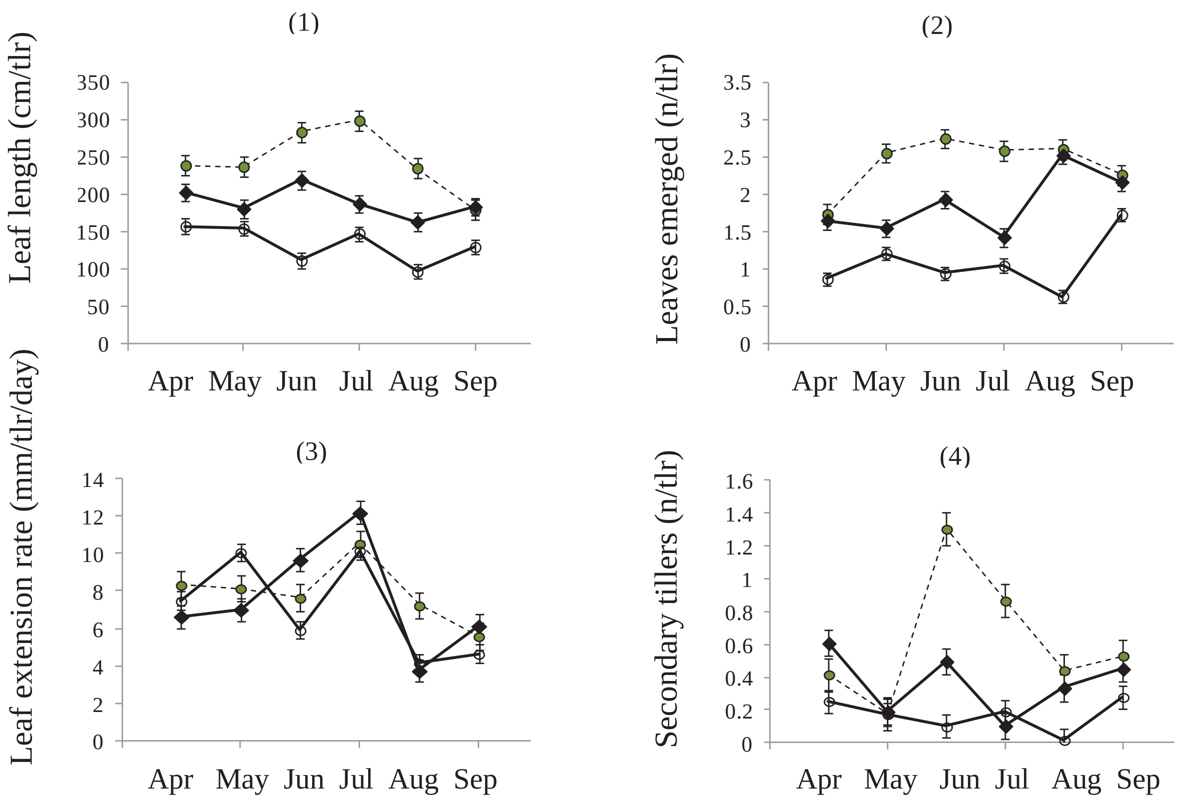

Figure 6.3 (1) Leaf length at grazing; (2) leaves emerged during re-growth period; (3) leaf extension rate per tiller and (4) number of secondary tillers at grazing from marked tillers that were defoliated at low (○), medium (◆) or high (●) pre-grazing herbage mass during the main grazing season.

Extended sheath heights were positively associated with level of pre-grazing HM ($P < 0.05$; Table 6.4). The difference between H and L treatments was 12.2 mm. Month had a significant effect on ESH, being highest in May and June, lowest in August and September and intermediate in April and July ($P < 0.001$). Tillers in the M treatment had 27.3-mm greater ETH than the tillers grazed at low pre-grazing HM, while the tillers grazed at high pre-grazing HM had 26.6-mm higher ETH than the tillers grazed at medium pre-grazing HM ($P < 0.001$), all different from each other. Free leaf lamina was affected by treatment, with differences of 22 mm between H and M treatments, and of 20.1 mm between M and L treatments ($P < 0.001$). Figure 6.4 shows the regression line of number of leaves appeared (NL) during the re-growth period on pre-grazing HM. The estimations of the regression coefficient are the following:

NL =	-0.17125	+ 0.00159 HM	– 2.18420000000 HM^2
Standard error	0.29105	0.00036167	0.000000010
Significance	NS	***	*
R^2 =	0.62		

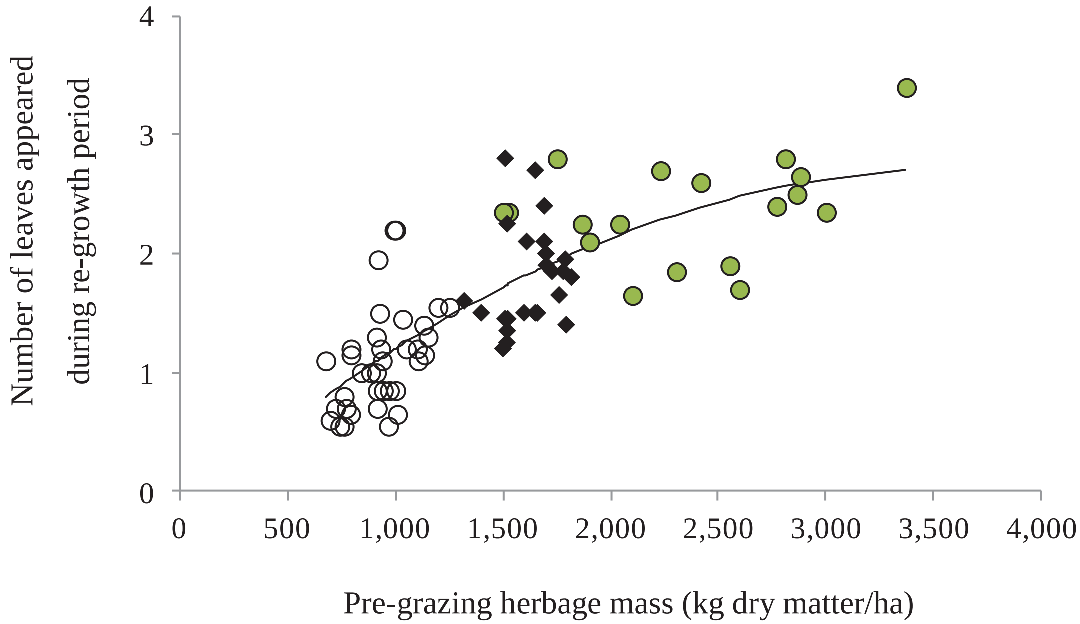

Figure 6.4 Pre-grazing herbage mass (kg dry matter per hectare) and leaves appeared per tiller during the re-growth period of nine plots (0.36 ha) that were grazed at low (○), medium (◆) or high (●) pre-grazing herbage mass for 24 weeks in a perennial ryegrass sward.

Table 6.4 Sward structure of marked tillers grazed by dairy cows at low, medium or high pre-grazing herbage mass (targets 900, 1,500 or 2,200 kg DM/ha, respectively) in a perennial ryegrass sward.

	Treatment	Month						T mean	Level of significance		
		Apr	May	Jun	Jul	Aug	Sep		T	M	T×M
Extended sheath	Low	35.1	42.7	34.6	29.5	26.6	26.8	32.5[a] ±2.13			
height	Medium	37.1	44.5	48.1	37.4	29.0	33.9	38.3[ab] ±2.24	*	***	*
(mm)	High	43.9	60.8	51.1	46.3	35.4	30.7	44.7[b] ±2.34			
	M mean	38.7[w]	49.3[x]	44.6[x]	37.7[w]	30.3[y]	30.5[y]				
		±2.00	±1.93	±2.03	±1.81	±2.41	±1.82				
Extended tiller	Low	118.7	121.6	96.3	115.4	89.1	101.4	107.1[a] ±5.02			
height	Medium	128.4	132.8	154.0	146.5	115.9	128.8	134.4[b] ±5.21	***	***	***
(mm)	High	156.0	161.0	170.6	193.0	161.1	124.4	161.0[c] ±5.37			
	M mean	134.4[w]	138.4[w]	140.3[w]	151.7[x]	122.1[y]	118.2[y]				
		±4.25	±4.13	±4.31	±3.92	±5.01	±3.91				
Free leaf	Low	83.6	78.2	60.4	85.9	62.0	74.5	74.1[a] ±2.88			
lamina	Medium	91.3	88.1	106.1	109.1	86.6	95.1	96.1[b] ±3.06	***	***	***
(mm)	High	112.1	100.2	118.8	146.8	125.7	93.8	116.2[c] ±3.20			
	M mean	95.7[w]	88.8[x]	95.1[w]	113.9[y]	91.4[wx]	87.8[x]				
		±2.82	±2.72	±2.86	±2.55	±3.42	±2.55				

Within columns means not showing a common superscript (a,b,c) differ significantly ($P < 0.05$).
Within rows means not showing a common superscript (w, x, y, z) differ significantly ($P < 0.05$).
M, month; T, treatment.
±; standard error of the mean.
* $P < 0.05$; ***, $P < 0.001$.

6.4.4 Sward morphology and tiller density

Pre-grazing HM had a significant effect on the proportions of leaf and stem above 4 cm. The H sward had nine-percentage-unit lower leaf proportion and seven-percentage-unit higher stem proportion than the other treatments ($P < 0.001$; Table 6.5). No differences were detected in dead proportion above the 4-cm horizon. Below 4 cm, leaf proportion of the L treatment was two-fold higher than the other two treatments ($P < 0.001$). Stem proportion below 4 cm tended to decrease with time, while dead proportion increased during the experimental period ($P < 0.05$). Mean density of PRG tillers in L plots was higher by 935 tillers/m^2, compared to the other two treatments ($P < 0.01$; Table 6.6). Non-PRG tiller density was not affected by treatment (average 2,891 tillers/m^2), although April and October values were higher than the other months ($P < 0.001$).

Table 6.5 Sward morphology above and below 3.5 cm of plots that were grazed by dairy cows at low, medium or high pre-grazing herbage mass (targets 900, 1,500 or 2,200 kg DM/ha, respectively) in a perennial ryegrass sward.

		Month							Level of significance		
	Treatment	Apr	May	Jun	Jul	Aug	Sep	T mean	T	M	T×M
Above 4 cm	Low	0.72	0.66	0.61	0.72	0.73	0.76	0.70^{a} ±0.015			
Leaf proportion	Med	0.63	0.59	0.64	0.68	0.75	0.72	0.67^{a} ±0.015	***	***	NS
	High	0.59	0.50	0.52	0.67	0.66	0.68	0.60^{b} ±0.015			
	M mean	0.65^{w}	0.58^{x}	0.59^{x}	0.69^{wy}	0.71^{y}	0.72^{y}				
		±0.019	±0.023	±0.022	±0.022	±0.023	±0.022				
Stem proportion	Low	0.08	0.22	0.21	0.16	0.12	0.12	0.17^{a} ±0.007			
	Med	0.24	0.26	0.17	0.15	0.16	0.14	0.19^{a} ±0.009	***	***	NS
	High	0.28	0.40	0.34	0.19	0.20	0.17	0.26^{b} ±0.010			
	M mean	0.24^{w}	0.29^{x}	0.24^{x}	0.17^{y}	0.16^{y}	0.14^{y}				
		±0.018	±0.021	±0.020	±0.020	±0.021	±0.020				
	Low	0.10	0.12	0.19	0.12	0.16	0.12	0.13 ±0.010			
Dead proportion	Med	0.13	0.15	0.19	0.18	0.10	0.14	0.15 ±0.010	NS	NS	NS
	High	0.12	0.11	0.14	0.14	0.15	0.15	0.13 ±0.010			
	M mean	0.12	0.12	0.17	0.15	0.13	0.14				
		±0.013	±0.015	±0.014	±0.014	±0.015	±0.014				

Below 4 cm	Low	0.07	0.04	0.03	0.03	0.05	0.02	0.04^{a} ±0.004			
Leaf proportion	Med	0.03	0.02	0.02	0.02	0.02	0.02	0.02^{b} ±0.004	***	**	NS
	High	0.02	0.02	0.01	0.01	0.01	0.02	0.01^{b} ±0.004			
	M mean	0.04^{w}	0.03^{x}	0.02^{x}	0.02^{x}	0.03^{x}	0.02^{x}				
		±0.005	±0.006	±0.006	±0.006	±0.006	±0.006				
	Low	0.46	0.49	0.41	0.40	0.38	0.37	0.42 ±0.021			
Stem proportion	Med	0.42	0.46	0.35	0.39	0.44	0.36	0.40 ±0.021	NS	†	NS
	High	0.49	0.45	0.51	0.48	0.33	0.31	0.43 ±0.021			
	M mean	0.46	0.47	0.42	0.42	0.38	0.35				
		±0.027	±0.031	±0.030	±0.030	±0.031	±0.030				
	Low	0.46	0.47	0.57	0.57	0.57	0.61	0.54 ±0.020			
Dead proportion	Med	0.55	0.53	0.63	0.59	0.54	0.62	0.58 ±0.021	NS	*	NS
	High	0.48	0.53	0.49	0.51	0.66	0.68	0.56 ±0.020			
	M mean	0.50^{w}	0.51^{w}	0.56^{wx}	0.56^{wx}	0.59^{x}	0.64^{x}				
		±0.026	±0.030	±0.029	±0.029	±0.030	±0.029				

Within columns means not showing a common superscript (a,b,c) differ significantly ($P < 0.05$).
Within rows means not showing a common superscript (w, x, y, z) differ significantly ($P < 0.05$).
M, month; T, treatment.
±; standard error of the mean.
NS, not significant; † $P < 0.1$; **, $P < 0.01$; ***, $P < 0.001$.

Table 6.6 Tiller density of plots that were grazed by dairy cows at low, medium or high pre-grazing herbage mass (targets 900, 1,500 or 2,200 kg DM/ha, respectively) during 24 weeks in a perennial ryegrass (PRG) sward.

		Month						Level of significance		
	Treatment	Mar	Apr	Jun	Aug	Oct	T mean	T	M	T×M
PRG tiller density	Low	4,855	8,455	10,389	7,867	10,950	8,503^{a} ±167.5			
(tlrs/m^2)	Med	4,906	8,111	8,572	7,394	8,344	7,465^{b} ±167.5	**	***	NS
	High	4,500	8,933	8,628	7,417	8,878	7,671^{b} ±167.5			
	M mean	4,754^{w}	8,500^{xy}	9,196^{x}	7,559^{y}	9,391^{x}				
		±401.2	±401.2	±401.2	±401.2	±401.2				
Non-PRG tiller	Low	928	3,683	1,672	4,117	939.0	2,268 ±821.6			
density	Med	1,711	5,567	2,372	4,656	1,017	3,065 ±821.6	NS	***	NS
(tlrs/m^2)	High	3,217	4,789	2,744	4,639	1,317	3,341 ±821.6			
	M mean	1,953^{w}	4,680^{x}	2,263^{w}	4,470^{x}	1,091^{w}				
		±674.4	±674.4	±674.4	±674.4	±674.4				

Within columns means not showing a common superscript (a,b,c) differ significantly ($P < 0.05$).
Within rows means not showing a common superscript (w, x, y, z) differ significantly ($P < 0.05$).
M, month; T, treatment.
±; standard error of the mean.
NS, not significant; **, $P < 0.01$; ***, $P < 0.001$.

6.5 Discussion

The effects of three levels of pre-grazing HM on production and characteristics of a PRG sward were investigated over the main grazing season in Ireland. Within the context of a renewed interest in intensive grazing systems, it becomes crucial to explore the fundamentals of grazing management under a production scenario. The study included measurements on tiller dynamics in response to actual grazing. It has long been recognised that the effect of a defoliation regime of a grazed pasture cannot be reproduced satisfactorily by a cutting treatment (Watkin and Clements, 1978). Animals defoliate, graze selectively and trample, deposit dung and urine and also disperse seeds within a grass sward (Sears, 1956).

The targets for low, medium and high pre-grazing HM were achieved through effective manipulation of the intervals between grazings. Faster grazing rotations were associated with increased proportions of leaf and decreased stem proportions in the swards, which would lead to increased sward quality (Holmes *et al.*, 1992). However, cumulative DM yield of the L plots (11.1 t DM/ha), was 16 and 27% lower than the cumulative DM yields achieved in M and H plots (13.0 and 14.2 t DM/ha, respectively). These findings agree with previous work at Moorepark (McEvoy *et al.*, 2010; Wims *et al.*, 2010) reporting lower grass-growth rates in association with lower levels of pre-grazing HM. Similarly, Fulkerson and Michell (1987) reported that increasing defoliation interval from 14 to 28 days resulted in a 37% increase in pasture production. Immediately after defoliation there is a lag phase in which rate of growth is slow, thereafter increasing exponentially until a constant rate is attained (Brougham, 1957). A severe defoliation regime, as was the case of this study (between 3.9 and 4.2 cm post-grazing sward height), coupled with relatively short re-growth intervals is associated with insufficient time for the plants to achieve the phase of rapid growth (Brougham, 1957) and therefore can result in decreased sward production.

Parsons and Chapman (1998) pointed out that maximum yields would be the result of severe defoliation coupled with relatively long re-growth intervals. The authors also stated that harvesting must occur at the time of maximum average growth, this happening after the time of the maximum instantaneous growth but before the ceiling yield. There is a positive relationship between the amount of light intercepted by the sward and grass growth (Gay, 1993). Effective use of light for photosynthesis and growth occurs when 0.95 of the incident light is intercepted by the sward (Lemaire and Chapman, 1996), thus grazing a sward before 95% light interception reduces DM yields. Water-soluble-carbohydrate (WSC) reserves are vital for the plant to regrow as these are utilised during the lag phase (White, 1973). Therefore, reduced grass growth after frequent defoliation might be also due to a lack of ability of tillers to fully replenish the necessary WSC reserves for optimal leaf, root and new tiller growth (Fulkerson and Slack, 1995).

As previously discussed, the energy status of the plant is affected by leaf stage. If the 2-leaf stage is not achieved, *i.e.*, there are less than two newly-appeared leaves during the re-growth period, and defoliation occurs again, there is a possibility of reduction in grass growth (Fulkerson and Donaghy, 2001). Fulkerson and Slack (1995) reported a reduction of 25% in grass re-growth after repeatedly defoliating at 1-leaf stage. The low pre-grazing-HM treatment had a 14-day mean grazing interval, this associated with pre-grazing HM of 945 kg DM/ha, and tillers never achieving two newly appeared leaves during the re-growth period. Evidence of a possible lower energy status of the plants that were grazed at low pre-grazing HM could have been the reduced number of secondary tillers per tiller at grazing and the lower LER compared with the other treatments.

Plants use compensatory mechanisms to adapt to the constraints imposed by management (Chapman *et al.*, 2011; Hodgson, 1989). For example, increased tiller density may result from increased defoliation frequency, albeit tillers being of reduced size (Korte *et al.*, 1984; Matthew *et al.*, 1996). The increased amount of light hitting the base of the tillers is associated with greater tillering (Valentine and Matthew, 2000). The higher tiller density of the L plots implies there was tiller density/size compensation (Hernandez-Garay *et al.*, 1999) as an adaptation to the frequent grazing regime. This is an example of phenotypic plasticity that tillers have in order to intercept light and survive such a regime.

Another mechanism observed in the tillers grazed in the L treatment was the more prostrate growth habit compared to the other two treatments. This is deduced from the post-grazing data which shows that the low pre-grazing-HM swards had 0.3-cm lower post-grazing sward height than the other two treatments, plus a higher proportion of leaf below the 4-cm horizon. However, ESH of these tillers was not statistically different to ESH in the medium pre-grazing HM treatment. This means that, even though the plate meter was pushing the soft material by its weight, the pseudo-stem height did not differ between L and M treatments.

In contrast to the low pre-grazing-HM treatment, the tillers on the high pre-grazing-HM treatment consistently achieved and surpassed the 2-leaf stage (2,360 kg DM/ha and 28.7-day re-growth intervals). However, on the negative side, the ESH and ETH data, and stem proportion, suggest that there was some stem elongation in H plots. Even though the number of secondary tillers per tiller was four times greater in this treatment compared with the low pre-grazing HM treatment, this was not translated into a higher tiller density. A possible explanation of this is that shading in the highest pre-grazing HM treatment resulted in tiller death. When shade is imposed artificially or is the result of an increase in leaf area, this leads to the production of fewer tillers (Colvill and Marshall, 1981; Ong, 1978). The tillers grazed at medium pre-grazing HM (1,623 kg DM/ha) achieved the 2-leaf stage in June, August and September, but were at sub-optimum leaf stage in April, May and July (21.9-day re-growth interval). The regression line fitted with a polynomial of order 2 to predict the appearance of leaves in relation to level of pre-grazing HM is shown in Figure 6.4.

6.6 Implications for grazing management

A system based on consistently grazing low levels of pre-grazing HM would have reduced surplus grass to be harvested for reserves. This, particularly when SR is high, leads to the need for more imported feeds. Low HM systems are difficult to manage. The herd in such a system rotates at a faster speed than would be the case in a system with higher pre-grazing HM. The area per cow per day may also become too large to meet the required daily herbage allowance. In addition, lower-than-9-cm pre-grazing sward heights are not recommended because bite size decreases (Hodgson, 1990) hence reducing herbage intake per bite. The L plots, with mean pre-grazing HM of 945 kg DM/ha, had always lower-than-8-cm pre-grazing heights. This creates the need for the animals to increase bite rate in order to compensate for the smaller bite size (Tuñon *et al.*, 2011b) to meet their nutritional demands. The animals are therefore at risk of decreasing grass DM intake due to insufficient grazing time to graze. The M and H swards, with sward heights above 9 cm and pre-grazing HM of 1,623 and 2,360 kg DM/ha, respectively, would not force animals to compensate for small bites with increased bite rate. However, as it was previously discussed, increased stem, as was the case of H swards, could also impair grass DM intake and put animals at risk of depressed intakes.

6.7 Conclusions

Plots grazed at 970 kg DM/ha pre-grazing HM during the main grazing season resulted in 16 and 27% less grass production than plots grazed at pre-grazing HM of 1,623 and 2,360 kg DM/ha, respectively. The leaf stage of the plots grazed at low or medium pre-grazing HM was suboptimum, leading to swards that were underperforming. Intensive grazing regimes need defoliation intervals that allow the sward to be at an adequate leaf stage for optimum production, quality and persistency.

Chapter 7: Effect of pre-grazing herbage mass on grazing behaviour, grass dry matter intake and milk production of dairy cows

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Published in the New Zealand Society of Animal Production 70: 28-32

7.1 Abstract

Identifying the optimum level of pre-grazing herbage mass (HM) across the grazing season is critical to maximise dry matter (DM) intake and milk production from dairy cows. From 27 April to 17 October 2010, 45 Holstein-Friesian dairy cows (mean calving date 23 March 2010) were randomly assigned to low, medium or high pre-grazing HM treatments (targets 900, 1,500 or 2,200 kg DM/ha, above 4 cm, respectively) using perennial ryegrass-based pastures. Pre-grazing HM was determined twice weekly. Grazing behaviour was measured once and herbage DM intake twice. Milk production was recorded daily. The experiment was divided into period 1 (mid-season; 27 April to 25 July) and period 2 (autumn; 26 July to 17 October). In the autumn, cows on low pre-grazing-HM swards grazed for 90 minutes more and had 18% more grazing bites on a daily basis than did the cows on the other treatments. Cows grazing medium pre-grazing HM swards tended to have highest DM intake (low-15.2, medium-16.5, high-15.7 kg DM/cow/day), while cows grazing high pre-grazing HM swards tended to have lowest milksolids (MS) yields (low-1.43, medium-1.43, high-1.31 kg MS/cow/day). Pre-grazing HM levels of 2,200 kg DM/ha >4 cm may impair DM intake and MS production per cow, most likely due to decreased sward quality, *i.e.*, lower leaf proportion and greater stem proportion.

Key words: pre-grazing; grazing behaviour; herbage mass; dry matter intake; milk solids.

7.2 Introduction

Milk production costs are increasing worldwide, yet grass remains the cheapest source of feed for dairy cows. In Ireland, Dillon *et al.* (2005) showed a reduction of about NZ$ 0.60 in the cost to produce 1 kg of milksolids (MS) when the proportion of pasture harvested by the cows was increased by 10%. Achieving maximum daily intake of highly digestible pasture to produce high milk yields per cow and per hectare (ha) is the objective of pasture-based systems (Holmes *et al.*, 2002; Mayne *et al.*, 1987). The intake of pasture by cows is the product of the time spent grazing, the rate of biting during grazing and the weight of pasture per bite (Hodgson, 1990). Pre-grazing herbage mass (HM) influences bite weight and, therefore, the efficacy and profitability of pasture-based dairy systems (Combellas and Hodgson, 1979; Peyraud *et al.*, 1996).

A balance between optimum sward production and quality must dictate the level of pre-grazing HM. A relatively high pre-grazing HM allows for an increased rotation length (McEvoy *et al.*, 2009) but also results in increased accumulation of stem and dead material, leading to a reduction of overall quality of the pasture available (Hoogendoorn and Holmes, 1992). In contrast, a lower pre-grazing HM may lead to shorter rotation length but increased sward quality, as dead material and stem do not accumulate in the sward. These characteristics, which are inherent of rotational grazing systems, influence the interaction between plant and animal factors, having an impact on milk production (Combellas and Hodgson, 1979). Even at a common pasture allowance, milk yield per cow will be depressed with high pre-grazing HM swards (Holmes *et al.*, 1992). The objective of this experiment was to identify the optimum pre-grazing HM across the main grazing season by assessing the effects of pre-grazing HM on grazing behaviour, dry matter (DM) intake and MS production.

7.3 Materials and methods

The experiment was conducted at the Animal & Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland (52^{o}7’N; 8^{o}16’W; 46 m above sea level). The soil type was a free-draining acid-brown-earth soil with a sandy-loam-to-loam texture. The area used was under permanent pasture with a predominately perennial ryegrass (PRG) sward. The swards were, on average, eight years old. Rainfall and temperature were recorded daily at a meteorological station less than 1 km away from the experimental site (Table 7.1).

7.3.1 Treatments and experiment

The experiment was conducted from 27 April to 17 October 2010, and investigated the effect of three levels of pre-grazing HM (targets above 4 cm): low (L; 900 ±100 kg DM/ha), medium (M; 1,500 ±200 kg DM/ha) or high (H; 2,200 ±300 kg DM/ha) on grazing behaviour, herbage DM intake, and MS production of dairy cows in a randomised block design. For a better understanding of the findings, the experiment was split into two periods: period 1 (mid-season; 27 April to 25 July) and period 2 (autumn; 26 July to 17 October).

7.3.1.1 Animals

Prior to the experiment 45 Holstein-Friesian dairy cows (15 primiparous and 30 multiparous) were selected and blocked using records of daily milk yield, lactation number, body condition score and live weight. From calving until the start of the experiment, animals were grazing as a single herd. Animals were randomly assigned to the three pre-grazing HM treatments on 27 April (32 days in milk) and remained in their assigned treatment groups until the end of the experiment.

7.3.1.2 Grazing management

The experimental grazing area comprised 16.5 ha, divided into 24 paddocks; each herd was assigned eight paddocks which were intermittently grazed for the duration of the experiment. Overall grazing stocking rate (SR) was 2.7 cows/ha. Before the trial commenced, the entire experimental area was grazed to a similar post-grazing sward height (4 cm); the target pre-grazing HMs were created by varying the interval (days) between pre-experimental grazing and the first experimental grazing. Thus, the high pre-grazing-HM paddocks were grazed initially, followed by the medium pre-grazing-HM pasture, thereby creating different re-growth intervals. Cows were offered fresh grass daily after morning milking. Pasture allocation was 17 kg DM/cow/day (above 4 cm). Total nitrogen (N) applied was approximately 250 kg N/ha between mid January to mid September as in the form of calcium ammonium nitrate (CAN; 0.27 N).

7.3.1.3 Pasture measurements

Pre-grazing HM (above 4 cm) was calculated twice weekly by cutting four strips (1.2 m × 10 m) with a motor Agria (Etesia UK Ltd., Warwick, UK) for the duration of the experiment. Pre- and post-grazing sward heights were measured using a rising plate mater (diameter 355 mm and 3.2 kg/m; Jenquip, Fielding, New Zealand; Earle and McGowan, 1979), before and immediately after grazing, for each of the three individual treatments.

7.3.1.4 Grazing behaviour

Six animals from each grazing treatment were fitted with IGER (Institute of Grassland and Environmental Research) behaviour recorders (Rutter *et al.*, 1997). Behaviour measurements were taken on two 24-h periods from each cow (Figure 7.1) within the 14-day period of 23 June to 9 July. Following recording, jaw movements were analysed using Graze analysis software (Rutter, 2000).

7.3.1.5 Herbage dry matter intake and sample analysis

Individual grass DM intake was measured in two periods, 14 to 19 June (mid-season) and 13 to 18 August (autumn) using the n-alkane technique described by Mayes *et al.* (1986), as modified by Dillon and Stakelum (1989). All cows were dosed twice daily for 12 days before morning (7 am) and afternoon milking (4 pm) with a pellet containing 500 mg of dotriacontane (C_{32}-alkane; Carl Roth, GMbH and Co, KG, Karlesruhe, Germany; Figure 7.1). Faecal grab samples were collected morning and evening from each cow (after milking) in the last six days of n-alkane dosage, and stored at -20°C. For each cow, the faecal grab samples of the six-day period were thawed and bulked (10 g of each collected sample) and dried for 48 h in a 60°C oven. Samples were then milled through a 1-mm screen and stored for chemical analysis. During the period of faeces collection, the diet of the animals was also sampled. Herbage samples were manually collected with a Gardena hand shears (Accu 60, Gardena International GmbH, Ulm, Germany) following close observation of the treatments previous defoliation height to collect a representative sample of the herbage grazed. Herbage samples were frozen at -20°C following collection. Herbage samples were then bowl-chopped, freeze-dried and milled through a 1-mm screen prior to chemical analysis. The ratio of herbage C_{33} to dosed C_{32} was used to estimate intake. The n-alkane concentration of the dosed pellets, faeces and herbage were determined as described by Dillon (1993). Bite weight was calculated by dividing the estimated daily intake by the number of bites.

7.3.1.6 Milk yield and composition

Individual milk yields were recorded at each milking (Dairymaster, Causeway, Co. Kerry, Ireland). Milk fat, protein and lactose concentrations were calculated weekly from one successive evening and morning milking sample for each animal. A Milkoscan 203 (Foss Electric DK, 3400 Hillerød, Denmark) was used to determine the concentrations of these constituents in the milk. Cumulative milk production performance was calculated from daily milk yields and weekly constituent concentrations. Protein and fat yields were added to estimate MS yields.

(a) (b)

Figure 7.1 (a) Dosing alkane for intake measurement and (b) cow fitted with a grazing behaviour recorder.

7.3.2 Statistical analysis

All statistical analyses were carried out using the MIXED procedure of SAS (Statistical Analysis System, version 9.2; SAS Institute Inc., Cary, NC, US). Repeated measures on the same cow for DM intake, fat, protein and MS yields as well as grazing behaviour variables were analysed with a mixed linear model that included the fixed effect of treatment, week of lactation and their interaction, and the random effect of cow. Using the Akaike's information criterion, a compound symmetry error structure was determined as the most appropriate residual covariance structure for repeated measures over time within cow. Pre-experimental milk yield was included as a covariable. Least squares means and their standard errors were obtained for each treatment for each week in lactation.

7.4 Results

Table 7.1 shows mean daily temperature and monthly rainfall for the experimental period and for the 10-year average 1999-2009.

Table 7.1 Mean temperature and rainfall for the period of April to October 2010 compared with the 10-year average 1999-2009.

	Apr	May	Jun	Jul	Aug	Sep	Oct
Mean temperature 2010 (°C)	9	11	16	16	14	14	10
Mean temperature 1999-2009 (°C)	9	12	14	16	16	14	11
Monthly rainfall 2010 (mm)	59	38	53	143	23	102	83
Mean monthly rainfall 1999-2009 (mm)	66	75	68	70	86	90	117

7.4.1 Grass and grazing management

Ten grazing rotations were completed by the L herd, eight by the M herd and five by the H herd. The mean rotation lengths were 14.5, 20.3 and 29.0 days for the L, M and H treatments, respectively. Mean pre-grazing HM was 978, 1,521 and 2,330 kg DM/ha for L, M and H treatments, respectively, values being different from each other ($P < 0.001$). Areas of pasture allocated were 176, 113 and 74 m^2/cow/day for L, M or H treatments, respectively ($P < 0.001$). Mean post-grazing sward heights were 4.0, 4.2 and 4.3 cm for the L, M or H treatments, respectively, and were not significantly different ($P < 0.096$). Total surplus grass, which was removed as silage throughout the experiment was 2.7 (L), 3.3 (M) and 3.7 t DM/ha (H).

7.4.2 Grazing behaviour

Grazing time was 90 min longer for the cows grazing low pre-grazing HM swards compared to the other two groups ($P < 0.001$, Table 7.2). Rumination time was 90 min longer for the cows grazing H swards compared to the other two groups ($P < 0.05$). The number of bites per day was greater for cows grazing L swards by 6,286 bites per day ($P < 0.05$) compared to the other two treatments.

7.4.3 Grass dry matter intake

Mean DM intake was 16.03 kg DM/cow/day for the whole experimental period. Dry matter intake did not differ between treatments in period 1 (14 June, 16.03 kg DM/cow/day) but there was a tendency ($P = 0.09$) in period 2 (13 August) for cows on M swards to have a higher DM intake than the other groups (+1.05 kg DM/cow/day, Table 7.2).

Table 7.2 Grazing behaviour for period 1 (27 April to 25 July) and herbage dry matter (DM) intake and daily milksolids (MS) yield for period 2 (26 July to 17 October 2010) for the low (L), medium (M) or high (HM) pre-grazing herbage mass treatments (978, 1,521 and 2,330 kg DM/ha, respectively).

		Treatment				Level of
	Time	L	M	H	s.e.d	significance
Grazing time (h/day)	2/7	10.8[a]	9.3[b]	9.3[b]	0.7	**
Rumination time (h/day)	2/7	8.4[a]	9.0[b]	9.9[c]	0.8	*
Bites (n/day)	2/7	42,148[a]	36,180[b]	35,543[b]	3,614	*
DM intake (kg/cow/day)	15/8	15.2	16.5	15.7	0.5	†
MS yield (kg/cow/day)	26/7-17/10	1.42	1.43	1.31	0.06	NS

Within rows means not showing a common superscript differ significantly ($P < 0.05$).
s.e.d., standard error of the difference
NS, not significant; †, $P < 0.10$; *, $P < 0.05$; **, $P < 0.01$.

7.4.4 Milksolids yield

Mean MS production per day was 1.66 kg MS/cow for the three treatments. Milksolids production was similar across treatments in period 1 (1.94 kg MS/cow/day) and in period 2 (1.39 kg MS/cow/day; Table 7.2). There was a treatment-by-week interaction in period 2 with cows on the M treatment having greater daily MS yields than the other treatments from around week 26 onwards ($P < 0.05$; Figure 7.2).

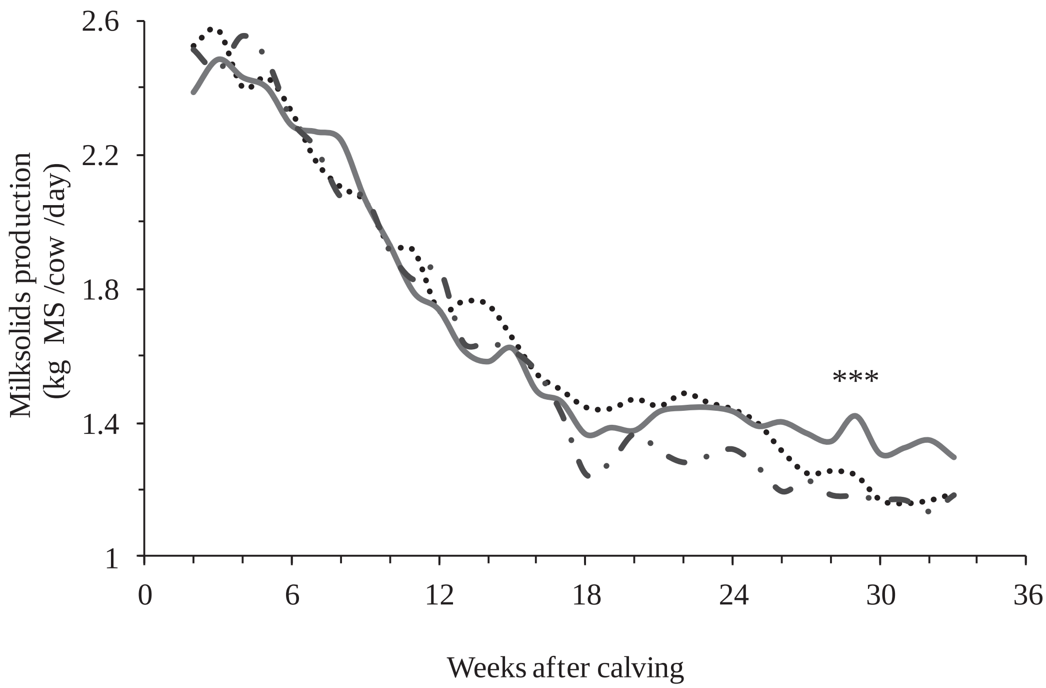

Figure 7.2 Mean weekly milksolids (MS) production of cows during each week of the trial while grazing low (......), medium (——) or high (–·–) mean pre-grazing herbage masses (means 978, 1,521 and 2,330 kg dry matter per hectare, respectively, measured at 4 cm above ground level) *** corresponding to treatment-by-week interaction, ($P < 0.001$).

7.5 Discussion

Identifying the optimum level of pre-grazing HM across the grazing season is critical to maximise the DM intake and MS production of spring-calving dairy cows in any pastoral environment. How pre-grazing HM is expressed differs between countries. This study was carried out in Ireland, where pre-grazing HM is determined as DM above 4 cm from ground level. In contrast, New Zealand pre-grazing HM values are expressed as DM from ground level. Hence, the treatments of the present study could be expressed as ground level values provided they are added to pre-grazing HM values below 4 cm. However, pre-grazing HM below 4 cm can be very variable. Tuñon *et al.* (Accepted in Grass and Forage Science; Chapter 3), working with Irish PRG swards during a year, estimated a mean of 2,376 kg DM/ha for pre-grazing HM below 3.5 cm, ranging from 1,618 to 3,134 kg DM/ha. Likewise, other experiments in Ireland and France, also using pure PRG swards, reported 2,200 to 3,700 kg DM/ha <4-5 cm (Delagarde *et al.*, 1997; Kennedy *et al.*, 2007c; Ribeiro *et al.*, 2005). Therefore, the L, M or H treatments of the present study (978, 1,521 and 2,330 kg DM/ha >4 cm, respectively), if added to a standard value of 2,200 kg DM/ha for below-4cm pre-grazing HM, could be converted into pre-grazing HM values of more or less 3,200, 3,700 and 4,500 kg DM/ha from ground level, respectively. In New Zealand, Macdonald *et al.* (2008) reported pre-grazing HM of 2,500, 4,000 and 3,000 kg DM/ha (measured to ground level) for spring, summer and autumn, respectively. Nonetheless, although it appears that the low pre-grazing-HM treatment is the most comparable to the New Zealand scenario, it also remains difficult to compare the treatments used by Macdonald *et al.* (2008) with the present study, perhaps due to the variability found in the below-4 cm pre-grazing HM. Any extrapolation should be made with care.

Grazing time and number of bites were greatest (+90 min and +18%, respectively) for the cows grazing low pre-grazing-HM swards although they tended to have lowest DM intake. Bite weight was lower for the cows on the L treatment compared to the other treatments (0.36 and 0.45 g, respectively). Sward height could have had an influence on bite weight. Pre-grazing sward heights were 6.9, 8.8 and 11.8 cm for the L, M or H treatments, respectively (data not reported). Hodgson (1990) stated that the level of pasture height from which DM intake begins to be limited is between 9 and 10 cm. Thus, it seems that cows on the L treatment (978 kg DM/ha) were at risk of significantly decreasing their DM intake due to failure of compensatory mechanisms of grazing behaviour (Hodgson, 1990) as cows' ability to graze is affected by pre-grazing HM.

The cows grazing the medium pre-grazing HM swards tended to eat more (+1.05 kg DM/cow/day; P = 0.09) when compared with the other treatments in the autumn. This is supported by previous work which reported that grass DM intake decreased when pre-grazing HM was high (Hodgson and Wilkinson, 1968; Jamieson, 1975; Stakelum and Dillon, 1990). When pre-grazing HM increases, the proportion of stem in the sward also increases (Hoogendoorn and Holmes, 1992) creating a barrier effect to intake (Laredo and Minson, 1975 ; Wade, 1991). In contrast, lower pre-grazing-HM swards contain higher proportions of grass leaf and lower proportions of stem and dead material (as is the case of the medium pre-grazing-HM treatment in the present study; data not reported); this, in turn, results in higher DM-digestibility values and, consequently, increased DM intake (Holmes *et al.*, 1992; Hoogendoorn and Holmes, 1992; O'Donovan and Delaby, 2008; Stakelum and Dillon, 2007). However, Peyraud *et al.* (1996) and Wales *et al.* (1999) found that DM intake actually increased with higher pre-grazing HM because cows were able to harvest greater amounts of material before they needed to graze the deeper and stemmier horizons. Pre-grazing HM must be sufficiently high to allow effective grazing but not too high so as to impair grazing and sacrifice quality too. It remains to be clarified where pre-grazing HM starts to be too low and where too high under current management practices in Ireland.

Recent studies performed in Ireland, also measured the effect of pre-grazing HM on DM intake. In contrast with the present study, Curran *et al.* (2010) did not find a difference in DM intake between grazing pre-grazing HMs of 1,600 or 2,400 kg DM/ha (above 4 cm) during the main grazing season (mid-season and autumn). However, Wims *et al.* (2010) reported that cows on swards with 1,000 kg DM/ha pre-grazing HM achieved higher grass DM intake than cows grazing 2,200 kg DM/ha pre-grazing HM swards in summer, which supports the trend towards higher DM intake for cows grazing the medium pre-grazing HM swards in this experiment.

The trend towards decreased MS yield and the increased rumination time of the cows on the high pre-grazing HM treatment during autumn suggests that the high pre-grazing HM was of lower feeding value than the pre-grazing HM in the L and M treatments. Organic-matter digestibility in the leaf fraction is higher than in live stem and dead material (Tilley and Terry, 1963). Leaf proportion was, in effect, lowest for the H, intermediate for the M and highest for the L swards in the present experiment (data not reported). Contrasting results were found by Wales *et al.* (1999) who reported that cows grazing swards with low pre-grazing HM (3,100 kg DM/ha; from ground level) produced less milk than cows grazing swards with high pre-grazing HM (4,900 kg DM/ha). In that study, pre-grazing sward height of the low and high treatments were 6.3 and 12.9 cm, respectively. Hence, comparing to the pre-grazing sward heights of the present study (6.9, 8.8 and 11.8 cm), it appears that cows on the lower pre-grazing HM could not compensate for smaller bites and decreased DM intake and MS. Conversely, Curran *et al.* (2010) and McEvoy *et al.* (2009) reported higher milk production from lower pre-grazing HM swards, particularly in the second half of the grazing season, and they concluded this was due to enhanced grass quality. These two last experiments agree with the findings of the present study because what they called low was comparable to the medium pre-grazing-HM treatment. The increased per-cow milksolid production of the herd grazing the medium HM sward, evidenced in the interaction shown in Figure 7.2, can be assumed to result from cows grazing, not only a sward at an optimum level of pre-grazing height but also a sward of a higher quality than the sward in the high HM treatment. The lack of increase in MS production in the cows grazing the low HM treatment seems to support the trend of lower DM intakes in this group.

In summary, if pre-grazing HM is too high, DM intake, sward quality and milk production are reduced. However, if pre-grazing HM is too low, sward quality will be high, DM intake may be affected, even after compensatory grazing behaviour, and milk production may be sacrificed. Even so, besides the afore-mentioned DM-yield reduction associated with consistently defoliating at low pre-grazing HM, there does not seem to be a reason to discourage grazing low pre-grazing HM swards (to the level of the present study). However, if grazing time needs to be restricted due to potential treading damage (Kennedy *et al.*, 2009), conditions for heat stress (Blackshaw and Blackshaw, 1994) or due to the aim to minimise N leaching from urine deposition in the paddock (Christensen *et al.*, 2010), the cows grazing low pre-grazing HM will not be able to compensate for smaller bites and will reduce their grass DM intake. Furthermore, less surplus grass in the low pre-grazing HM system (-0.6 and -1 t DM/ha when compared to the medium or high pre-grazing HM systems, respectively) means that there are potential feed deficits if SR is increased or less grass available for conservation.

7.6 Conclusions

Cows grazing medium pre-grazing HM swards (1,521 kg DM/ha; estimated from 4 cm above ground level) tended to have greatest grass DM intake in the autumn (+1.05 kg DM/cow). Cows on the high pre-grazing-HM swards (2,330 kg DM/ha) tended to produce less MS in the autumn, this was associated with an apparent decrease in sward quality. Cows on the low pre-grazing-HM swards (978 kg DM/ha) spent 90 extra minutes per day grazing but their DM intake tended to be lower than the other treatments. The results of this study show that a balance must be achieved in offering the correct pre-grazing HM to lactating dairy cows. This balance is dictated by achieving high output per cow and per ha, whilst offering high-quality pasture which can allow animals to graze to consistent residuals. These objectives were achieved within the medium pre-grazing-HM treatment. The optimum level of pre-grazing HM seems to be between 1,300 and 1,700 kg DM/ha (above 4 cm).

Chapter 8: General discussion

8.1 Overview and thesis objectives

Low-cost grazing systems based on efficient use of grass will be more profitable in the post-European Union (EU) quota production environment in contrast to those systems that are based on high levels of supplementation (O'Donnell *et al.*, 2008). As previously discussed, extending the length of the grazing season through an earlier turnout of cows to pasture and later closing date, associated with increased stocking rates (SR), are practices influencing positively the amount of grass harvested by the dairy herd. However, as grass-based systems become more intensive, there are effects on the sward and the animals that must be considered. The thesis had five major objectives: i) to investigate the effects of post-grazing sward height on sward structure, morphology and production, on tiller density and on grass utilisation in a dairy grazing study; ii) to quantify the effects of cow treading damage on temperate swards under different soils, seasons, frequencies, grass species and levels of damage; iii) to study the effects of 2-, 3- and 4-week re-growth intervals on dry matter (DM) yield, sward morphology, tiller density and tissue turnover in perennial ryegrass (PRG) swards under a cutting regime, during the main grazing season; iv) to test the effects of different levels of pre-grazing herbage mass (HM) on tissue turnover and sward performance under dairy grazing conditions during the main grazing season; and v) to quantify the impact of three levels of pre-grazing HM on milksolids (MS) production, grass DM intake and grazing behaviour of dairy cows during the main grazing season. The treatments imposed in each of the experiments resemble as close as experimentally possible the modern grazing management practices that are being used on many grass-based dairy farms in Ireland.

8.2 Main findings and implications

A main objective of grassland farming is to achieve higher levels of herbage DM yields while maintaining the quality. Chapter 3 demonstrated that under current grazing management practices, a 1.5-cm difference between the lax and severe grazing regimes (4.9 and 3.6-cm post-grazing sward heights, respectively) was sufficient to effect significant changes in the structure, morphology and tiller density of a PRG sward. But sward herbage accumulated and harvested were not affected by the grazing regime. The findings encourage the use of increased grazing severity through relatively high SR in order to maintain sward quality, increase PRG tiller density and reduce grazing rejected areas. Chapter 4 showed that a grassland site on a well-drained soil and dominated by PRG was resilient to treading damage, with the severe damage causing an initial reduction of 30%, but no differences in cumulative DM yields being found between treatments. On a creeping bent-dominant sward on a poorly-drained soil, treading damage imposed in autumn resulted in reductions in herbage accumulation, while seasonal production was not affected by treading damage. Treading damage in spring and treading damage in autumn and again spring, were both more detrimental (overall DM reductions ranging from 14 to 51%) than treading damage in the autumn. Some losses are unavoidable when cows graze on pastures. Nevertheless, before grazing swards that are at risk of excessive treading damage, losses can be minimised by considering soil characteristics, predominant grass species, soil water content, frequency of the treading events and duration of treading events. Lastly, the long term productive capacity of the pastures could have been compromised as a result of the treatments imposed. This is due to the creation of opportunities (gaps) for weed species to establish in damaged swards, leading to deterioration of pasture botanical composition. However, it remains a weakness of the study that pasture composition was not measured. As reviewed earlier in this thesis, lower tiller density can result in decreased DM yields (Brougham, 1960; Edmond, 1958a). The speed at which the sward recovers from treading damage is influenced by residual leaf tissue, carbohydrate reserves and meristematic activity of the surviving tillers, and also on nutrient status and water uptake ability of the soil (Pande, 2002). This highlights the importance of an adequate management of grazing severity after treading damage. The use of management strategies to minimise treading were discussed in Chapter 4.

Chapter 5 demonstrated that tillers that were mechanically-defoliated every two and three weeks during a 24-week period were always at a suboptimal leaf stage during the main grazing season. The optimum leaf stage, as was explained previously, *i.e.*, between two and three newly-appeared leaves during re-growth, for defoliation was only achieved after 28-day re-growth intervals from the second half of the main grazing season. This was translated into differences in herbage accumulation between treatments, with the most-frequently-defoliated treatment having 14 and 35% lower herbage production than the 3- and the 4-week re-growth treatments, respectively. Chapter 6 found that a lower pre-grazing HM was associated with lower grass growth rates. Low pre-grazing HM swards were always at sub-optimum leaf stage throughout the grazing season. Low pre-grazing HM swards had 16 and 27% lower grass accumulation than the medium and high pre-grazing HM treatments, respectively. In the medium pre-grazing HM swards, optimum leaf stage was only achieved in June, August and September. High pre-grazing HM swards had optimum number of leaves appearing during re-growth throughout the grazing season but also showed evidence of stem elongation, which had a negative influence on sward nutritive value, as discussed previously. These two experiments showed, under cutting and under grazing, that repeatedly defoliating swards when less than two leaves have appeared after defoliation results in decreased production. This occurred despite the compensatory mechanisms used by the plants to survive such intensive regimes, such as tiller size/density, prostrate growth habit and increased leaf proportion below 3.5 cm (Chapter 3, 5 and 6). Care must be taken, on the other hand, to avoid increased proportions of stem due to tillers becoming reproductive, which leads to decreased nutritive value of the sward. Parsons *et al.* (1988) discussed that there was an infinite number of combinations of the variables of grassland management, but, in general terms, defoliation should be infrequent and severe. As frequency of defoliation increases, herbage accumulation tends to decrease (Brougham, 1961; Holliday and Willman, 1965; Reid, 1986). This makes the length of the re-growth interval a better predictor of pre-grazing HM than grazing residuals (Cosgrove, 1992).

A key finding of the experiment in Chapter 5 was that the cumulative DM yield from April to September across the three treatments differed substantially: 6.7, 9.1 and 10.4 t DM/ha for the 2-, 3- and 4-week treatments, respectively. The 4-week treatment resulted in 55% greater herbage accumulation than the 2-week treatment. Does the difference come from changes in leaf appearance rate, leaf size, tillering/tiller density, or combinations of these? Taking the data for the mean number of leaves that emerged during the re-growth period in Table 5.5, which was 1.11, 1.67 and 2.13 leaves, respectively for the 2-week, 3-week and 4-week treatments, leaf appearance interval (LA_{int}) was calculated as follows: 12.6, 12.6 and 13.1 days per leaf respectively. Therefore, leaf appearance rate did not appear to differ among treatments. The tillers would have produced the same number of leaves during the experiment. This implies that the differences in cumulative DM yield are therefore not due to leaf emergence but due to leaf size. Since the 2-week treatment produced on average only one leaf between defoliation events (mean 1.1 in Table 5.5), while the 4-week treatment produced about two leaves (mean 2.13), these treatments give us a comparison between the 1-leaf (L1) and 2-leaf (L1 + L2) stages of regrowth. Mean pre-grazing HM was 561 kg DM/ha for the 2-week and 1,730 kg DM/ha for the 4-week. Thus, if it was assumed that L1 contributed with the same mass in both treatments, then the contribution of L2 to yield in the 4-week treatment must be about 1,730-561, or about 1,170 kg DM/ha. Although this is only using means, it does show that leaf mass differs between treatments. Hence, it is mass we need to use to explain the yield differences. In these terms, the second leaf to emerge after defoliation is 100% heavier than the first leaf to emerge after defoliation.

Thus, cumulative yield was greater in 4-week than 2-week because the 4-week treatment regularly produced two leaves per tiller before defoliation (and, therefore, before yield was measured again) whereas the 2-week treatment generally only produced on leaf per tiller before defoliation. The second leaf to emerge after defoliation was heavier than the first. Cumulative yield in the 2-week treatment came almost exclusively from L1 leaves, while in the 4-week treatment lots of (heavier) L2 leaves contributed to yield. This phenomenon is embedded in the sigmoid regrowth curve and has very important implications for understanding the effect of grazing frequency on regrowth dynamics and yield. It is important to note here that there was also an effect of treatment on tillering. Factoring this in reduces the apparent difference in relative mass of L1 compared with L2 proposed above. The 4-week treatment had 307 kg DM more than the 4-week treatment; this means that there was a 60% increase in DM weight from the 1-leaf to the 2-leaf stage. However, when the secondary tillers are included, this difference is 102 kg DM, meaning a 24% increase from L+1 to L+2.

Table 8.1 Tissue turnover and yield of plots harvested every 2, 3 or 4 weeks or re-growth.

	Re-growth interval			
	2-week	3-week	4-week	Difference
Leaf extension rate (mm per day)	8	10.5	10.3	
Leaves emerged (n)	1.11	1.67	2.13	
Leaf length (mm)	7.21	6.29	4.84	
Leaf appearance interval (days)	12.6	12.6	13.2	
Pre-harvest yield (kg DM/ha)	561	1,105	1,730	
Leaf weight (kg DM)	505	662	812	307 kg DM
New leaves (including 2nd tillers)	1.34	2.43	3.32	
Kg DM per leaf (including 2nd tillers)	419	455	521	102 kg DM

Cumulative yield of the three treatments of Chapter 6 was 11.3, 13.1 and 14.2 t DM/ha for the L, M and H treatments, respectively. Therefore, in this case, H resulted in 25% higher cumulative yield compared to L, as opposed to 55% higher cumulative yield for the 4-week treatment compared to the 2-week treatment in Chapter 5, under cutting. There is quite a discrepancy here in the size of the difference. A question that arises now is if defoliation method or year effect are to explain the discrepancy?

Mean LA_{int} was 13.9, 11.8 and 12.0 days per leaf for L, M and H, respectively. Thus, the longest interval (slowest leaf appearance rate) was in the low HM / frequent defoliation treatment, whereas in the cutting experiment (Chapter 5) it was in the high HM / infrequent treatment. It remains unclear why the apparent difference. Using the same approach for further analysis of data in Chapter 5, the difference between L2 and L1 in leaf mass under grazing was estimated to be about 5%, quite a lot less than in the cutting experiment, and less than the 25% difference in cumulative yield. So, does this indicate more complete adaptation of plants in the L treatment for defoliation when defoliation is via animals than via cutting? And, where is the source of the difference in cumulative yield (the extra 2.9 t DM/ha grown in H compared to L under grazing)?

Table 8.2 Tissue turnover and yield of plots harvested at low, medium or high herbage mass.

	Herbage mass			
	Low	Medium	High	Difference
Grazing interval (days)	14	22	29	
Leaves emerged (n)	1.01	1.87	2.41	
Leaf appearance interval (days)	13.9	11.8	12.0	
Pre-harvest yield (kg DM/ha)	945	1,623	2,360	
Leaf weight (kg DM)	936	868	979	43 kg DM
New leaves (including 2^{nd} tillers)	1.18	2.54	3.90	
Kg DM per leaf (including 2^{nd} tillers)	801	639	605	196 kg DM

The difference of 196 kg DM in the weight of each leaf in this case is in favour of the lowest HM, most frequently harvested, treatment. This is 32% difference for the lower mass treatment in comparison with the higher mass treatment.

Chapter 7 showed that the optimum level of pre-grazing HM for sward production, grass DM intake and herbage quality was on average 1,571 kg DM/ha. Low pre-grazing HM (mean 970 kg DM/ha) resulted in cows requiring increased grazing time (extra 90 min) to achieve the level of intake of the other two treatments. High pre-grazing HM (mean 2,300 kg DM/ha) leads to a decrease in leaf proportion, an increase in stem and dead proportions and an overall increase in herbage accumulated over the grazing season. Low pre-grazing covers are difficult to manage because, in order to maintain a desired daily herbage allowance, the daily area allocated to the herd can be too large. Furthermore, besides the aforementioned suppressed growth of low swards, there is a risk of decreased individual grass DM intake due to more and smaller bites. In situations in which grazing time must be shortened, such as the case of on-off grazing, a low HM sward would certainly result in lower grass DM intake and the need to supplement the daily ration, which means increased costs.

The regression lines of number of newly-appeared leaves on pre-harvest or pre-grazing HM (Figure 5.4 and Figure 6.4, respectively) were put together in Figure 8.1. These lines predict the level of HM necessary for a PRG sward to achieve adequate number of newly-appeared leaves. As explained in previous chapters, only when two new leaves have appeared in tillers during the re-growth period, the sward is at optimum for production, quality and persistence, provided that the accumulation of dead and stem components are controlled by not going beyond three newly-appeared leaves. Figure 8.1 shows that a higher level of pre-grazing HM (close to 1,800 kg DM/ha) was needed in the “grazing” study to achieve the 2-leaf stage, compared to the “cutting” experiment, in which a lower level of pre-harvest HM (close to 1,500 kg DM/ha). However, it must be pointed out that, during the “grazing” experiment, the marked tillers that were grazed under the fence (Figure 6.1) did not receive urine and dung, and were not subjected to trampling. This situation would have led to the herbage cover under the fence being slightly lower than the rest of the paddock. That is the reason why a more conservative figure of 1,600 kg DM/ha is used as an estimate instead of the 1,800 kg DM/ha arising from the prediction. Nevertheless, care must be taken when comparing the findings of both studies, as they were carried out in different grassland sites and in different seasons.

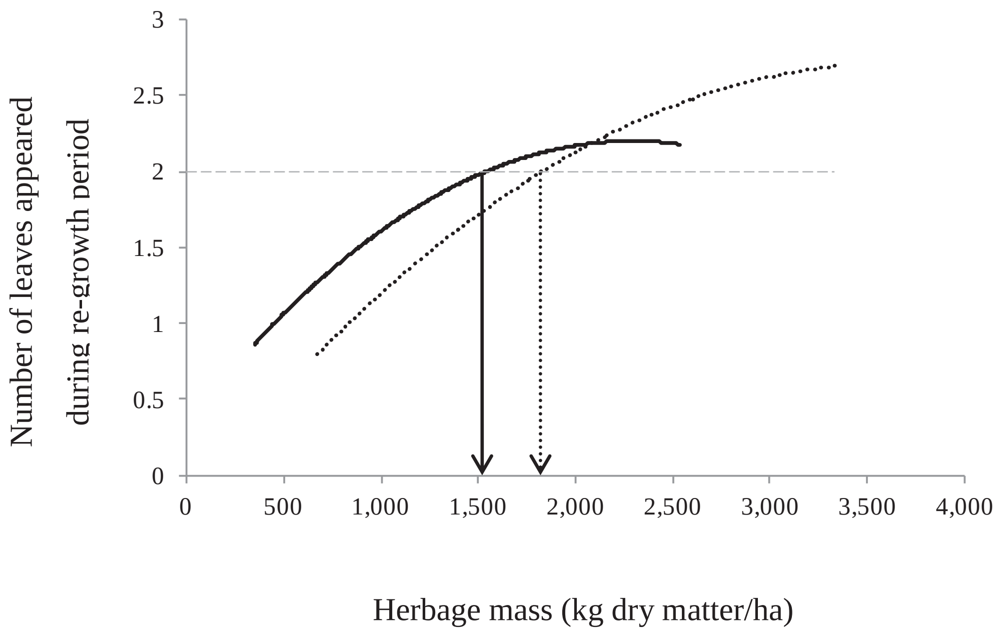

Figure 8.1 Predicted values for number of leaves emerged and pre-grazing herbage mass under cutting (___) and under grazing (.....).

8.2.1 The management boundaries

Post-grazing sward height, treading damage, re-growth interval and pre-grazing HM are four critical factors of grazing management that were investigated in this thesis. This is applicable to Irish conditions, where the experiments were carried out, but the principles can be applied to other temperate areas with similar production conditions. Managing a successful grass-based dairy system requires strict monitoring of the processes. The use of grassland management technologies such as HM measurement and budgeting have been developed (O'Donovan *et al.*, 2002a). These technologies must be used frequently by the manager to make effective decisions. Good grassland managers make quick subjective accurate decisions, however to provide a solid link between research and practice, skills must be gained by people that are starting into grassland management (Dillon, 2011; Hodgson, 1989).

The information from this thesis provides management premises for how to attain high-quality, productive and persistent PRG swards, with particular focus on the Irish production environment. Following these guidelines can help Irish farmers achieve optimum animal performance from grass. However, as was mentioned in Chapter 2, the grass-based dairy farm is a complex biological eco-system in which soil-plant-animal interactions take place. Because of that, as Brougham (1959) stated, making a broad appraisal of the grass-based systems is inappropriate. There is no single answer in grassland management. To explain this concept, Spain *et al.* (1985), and later Kemp (1991), developed the 'pasture management envelope'. There are ranges for the different management factors such as post-grazing sward height. A sward that is managed outside the critical range will re-adapt and develop a new state but this time outside the 'envelope'. This will need a strong intervention to return to a state which is associated with optimum grazing management. Figure 8.2 illustrates three hypothetical situations A, B and C, identified in relation to the envelope. In situation A pre-grazing HM is above the optimum recommended therefore cows are at risk of decreased grass DM intake due to high stem proportion, the sward may go beyond optimum leaf stage and there is a risk of leaving a post-grazing residual height of more than 5 cm. Situation C is also outside the envelope with too low pre-grazing HM, also risk of lower grass DM intake due to longer grazing time, too low post-grazing sward height and suboptimal leaf stage. Situation B represents a scenario of optimum pre-grazing HM, post-grazing sward height, grass DM intake and adequate leaf stage for sustainability, production and quality of the sward and animal performance.

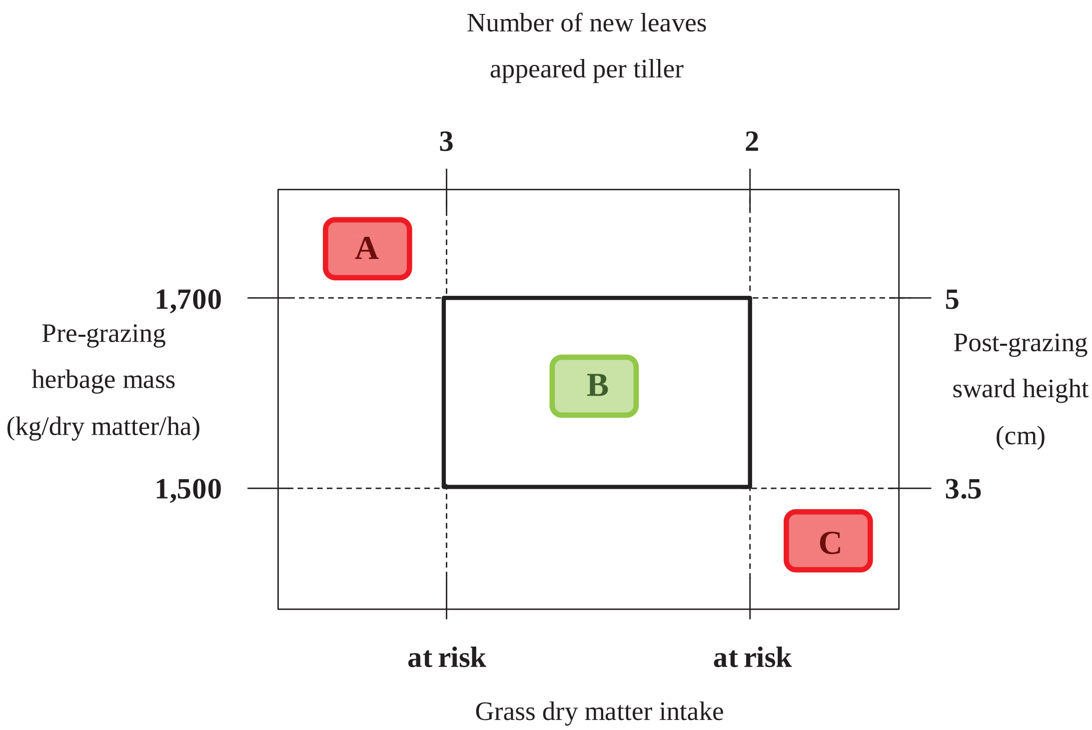

Figure 8.2 The pasture management envelope (developed after Spain *et al.*, 1985).

This thesis supports recommendations for grass-based dairy production (Chapman *et al.*, 2011; Fulkerson and Donaghy, 2001; Macdonald *et al.*, 2010) of defoliation of PRG swards when tillers have achieved between two and three emerged leaves. Decisions of when to defoliate that do not take into account the physiology of the tiller during re-growth can lead to depressed sward production. Chapman *et al.* (2011) estimated that managing the sward for the growth of the third leaf would result in a 10 to 15% increase in productivity. The authors, however, emphasise the need to seek for the balance between HM and feed availability across the system, grass growth rates, sward quality and total feed demand. In other words, as it was mentioned above, the system is complex and must be managed to achieve a successful compromise between the factors and, ultimately, profitability and sustainability for the dairy business.

8.3 Further work

An experiment investigating the interaction between grazing severity and frequency, coupled with measurements of leaf stage at the time of defoliation can provide very valuable information as a continuation to the field and plot trials performed in this work. Second, due to the complexity of the factors involved in grassland management for profitability, simulation models that provide guidelines for management under differing scenarios can be very useful. High-quality data from field experiments can feed those systems. For example, the treading data from this thesis can contribute to data from other experiments to simulate on-farm scenarios and predict economic losses. Economic parameters could be added to a model to analyse the feasibility of investing on potential solutions such as stand-off pads.

Third, different plant genotypes may react differently to the constraints of grazing management. For example, Simons *et al.* (1972) reported that, when defoliation height was lowered, those PRG plants which had genotypes for rapid leaf appearance rate were favoured over PRG plants with a slower leaf appearance rate. Fulkerson *et al.* (1994), working with two Lolium genotypes (L. *multiforum* and L. *perenne*), observed a marked defoliation-by-cultivar interaction on re-growth. This confirms the need to consider defoliation responses in any evaluation of cultivars. The behaviour of different varieties of PRG in response to defoliation regime could be included into a selection index that would measure performance data to determine the economic merit of that grass cultivar, such as is being carried out in Ireland (McEvoy *et al.*, 2011). The theory behind the leaf stage principle is attractive because it is simple and elegant. Finally, work is needed towards finding a tool that could be simple and effective for measuring leaf stage on farm.

8.4 Main conclusions

This thesis demonstrated that:

1. A 1.5-cm range between the lax and the severe treatments in a grazing trial was sufficient to effect significant changes in the sward, but did not affect herbage production.

2. Perennial ryegrass plants showed some degree of adaptation to the constraints imposed by the treatments in each of the experiments.
3. Severe treading did not cause reduced grass production on a well-drained soil but, on a poorly-drained soil, grass production reductions ranged from 14 to 51%.
4. On a plot study, the optimum number of appeared leaves was only achieved at 28-day re-growth intervals from the second half of the main grazing season. Leaf appearance interval did not differ between treatments and the difference in cumulative DM yields was considered to result from leaf size.
5. Under a grazing regime, only the sward maintained at a high level of pre-grazing HM (higher than 2,300 kg DM/ha >4 cm) had optimum number of leaves appeared during re-growth interval, this translated into 27% more grass DM production. On both the cutting and the grazing experiments longer rotations had better results than shorter rotations.
6. Low pre-grazing HM (970 kg DM/ha >4 cm) was difficult to manage, required extra grazing time (+90 min) to achieve the level of intake of the other two treatments. Pre-grazing HM had a direct influence on grazing behaviour.

Post-grazing sward height, treading damage, re-growth interval and pre-grazing HM can have a significant impact on sward and on animal performance. The imposition of best practice grazing management leads to effective management of these factors. This will allow Irish farmers to convert more grass into milk. Ultimately, effective grazing management for improved use of PRG swards must involve an understanding of the physiology of the plants and how they respond to defoliation, the impact of treading damage on the sward and soil, and the balanced interaction between the animals and the sward.

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Appendix 1

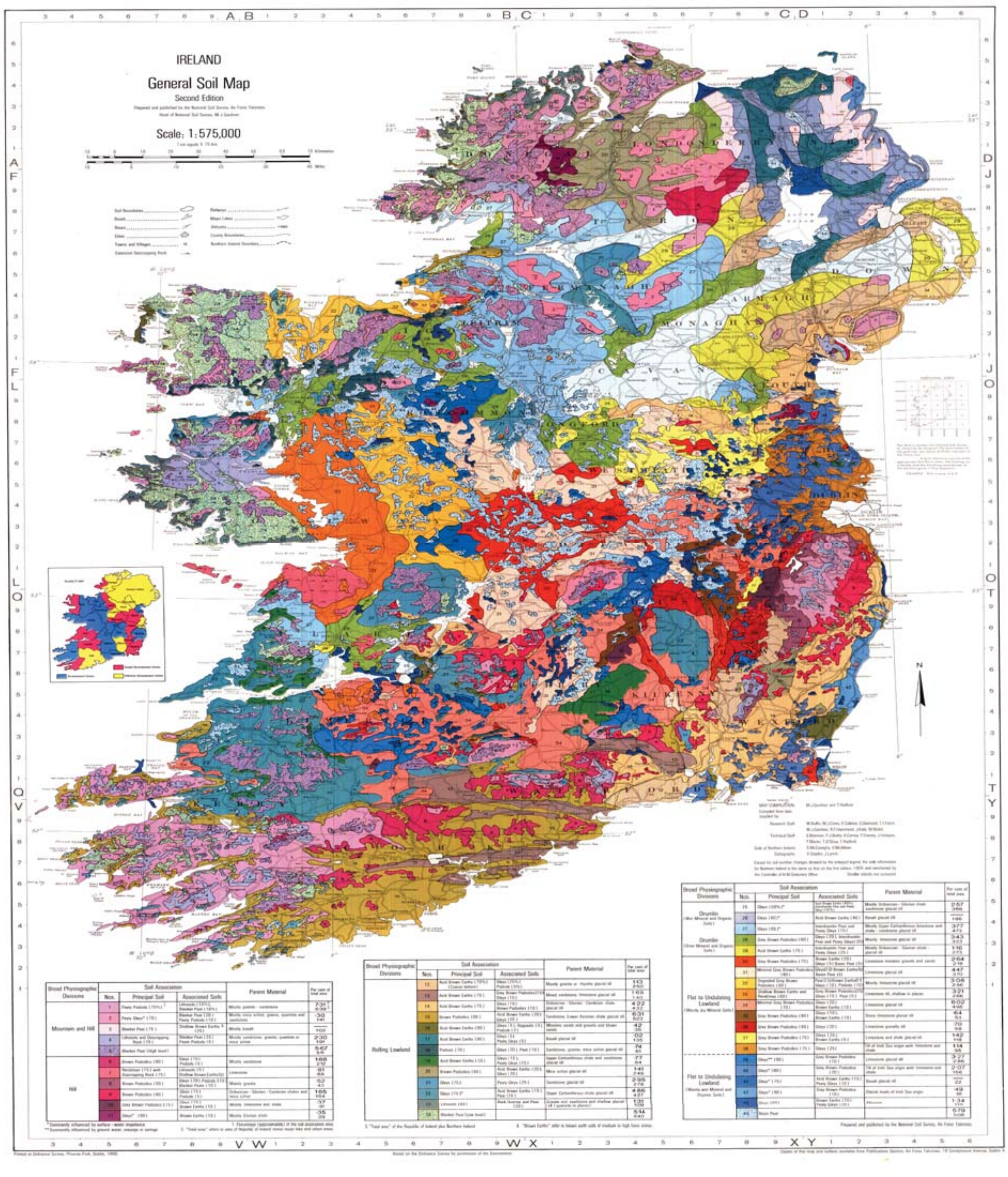

Figure 10.1 General soil map of Ireland (adapted from Gardiner and Radford, 1980).

Appendix 2

At the end of the farm walk the paddocks are ranked from highest to lowest according to the estimated quantity of grass. The pre-grazing herbage mass (HM) is calculated multiplying stocking rate (SR), allocation per cow and rotation length, and this added to the target post-grazing HM. The result is the pre-grazing HM. For example:

> 4 cows/hectare (ha) × 16 kg dry matter (DM)/cow/day × 20 days + 100 kg DM/ha (residual) = 1,380 kg DM/ha
>
> Target pre-grazing HM is 1,380 kg DM/ha

To create the grass wedge, the target pre-grazing HM is marked in the first column on the left and the target post-grazing residual is marked in the last column on the right. **¡Error! No se encuentra el origen de la referencia.** shows three examples of grass wedges. The example A is a farm with surplus grass. In this situation, pre-grazing HM and residuals are too high. In the example B there is a surplus in the first three paddocks although there is a deficit coming in the next few paddocks. Therefore, there is sufficient grass in the farm. Finally, the example C shows a farm with a serious deficit. Pre-grazing yields are too low.

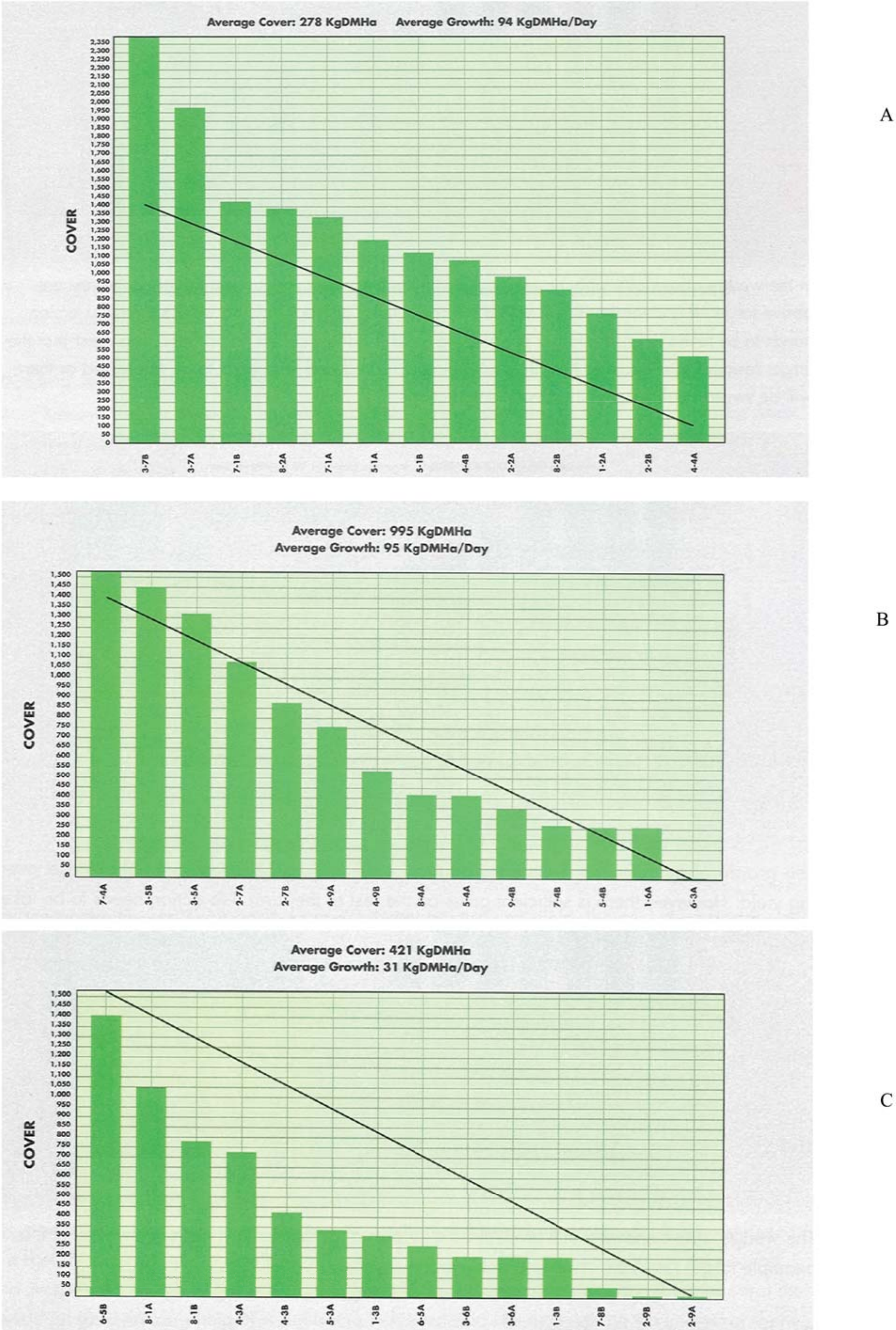

Figure 11.1 Examples of grass wedges.