Aspects of grassland management for pasture-based dairy farms with wet soils and fragmented farm area

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by

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Abstract

A long grazing season improves the profitability of pasture-based dairy farms. However, an increasing proportion of Irish milk is produced on farms where achieving a long grazing season is difficult. This study investigated how grassland management on farms with wet soils and fragmented farm area can be adapted to establish systems that maximise farm productivity and profitability.

An experiment with four grazing systems evaluated if soil moisture measurements can be an effective decision support to assess the risk of treading damage, impact on pasture productivity and dairy cow performance during wet soil conditions. The effect of grazing platform stocking rate (GPSR) on the productivity and profitability of fragmented pasture-based farms was evaluated in a second experiment with four grazing systems where a higher GPSR was supplemented with silage produced on non-GP parcels of the farm. Finally, it was investigated if accumulating herbage mass during autumn can lengthen the grazing season on pasture-based dairy farms.

Less time spent at pasture during wet soil conditions lowered treading damage but had no effect on annual herbage production. Milk solids production and profitability were higher when cows spent more time at pasture despite also incurring higher treading damage. Measuring soil moisture was a useful decision support for assessing the risk of treading damage when turning cows out to pasture. GPSR did not affect herbage production or milk production per cow albeit with a lower proportion of grazed herbage in the diet with higher GPSR. A greater extent of farm fragmentation lowered the profitability of pasture-based dairy production. The profitability of increasing GPSR was mainly determined by external factors. Higher milk prices, shorter distances and lower land rental price increased the optimum GPSR of fragmented systems. Accumulating herbage mass during autumn facilitated a longer grazing season while not impacting on milk production.

Declaration

This thesis has not previously been submitted for any degree at this or any other institution. Unless otherwise acknowledged, the work embodied in it is my own.

Friederike Fenger

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List of Abbreviations

AGL	above ground level
AHC	average herbage cover
CP	crude protein
DHA	daily herbage allowance
DM	dry matter
DMI	dry matter intake
FC	Field capacity
GP	grazing platform
GPSR	stocking rate on the grazing platform
GSMC	Gravimetric soil moisture content
HDMI	herbage dry matter intake
HM	herbage mass
NDF	neutral detergent fibre
OM	organic matter
OMD	organic matter digestibility
PGHM	pre-grazing herbage mass
SMC	soil moisture content
SMD	Soil moisture deficit
UFL	unité fourragère lait
VSMC	volumetric soil moisture content
WTD	Groundwater table depth

Chapter 1 Introduction

1.1. General Introduction

Researchers, producers and consumers show increasing interest in pasture-based dairy production. Compared to indoor systems the perceived benefits of pasture-based systems include: high resilience of production systems in times of price volatility (Ruelle et al., 2018), low requirement for capital investment in infrastructure (Roche et al., 2017), lower greenhouse gas emissions per unit of product (Cameron et al., 2018, Lorenz et al., 2018) higher animal welfare (Armbrecht et al., 2019) and superior product quality of grass-fed dairy products and associated health benefits of consumers (O'Callaghan et al., 2016, Faulkner et al., 2018). These factors contribute to a cleaner production image. Therefore, consumers that are concerned about production standards prefer pasture-based dairy products (Conner et al., 2008, Lobsiger et al., 2010, Gassler et al., 2018).

The abolition of the EU milk quota in 2015 led to an increase in milk output in many European countries but most substantially in Ireland relative to pre-quota production (Läpple and Sirr, 2019). Compared to 2014, Irish domestic milk production has increased by 47% in 2020 (CSO, 2021). This was mainly driven by an increase in cow numbers and dairy cow stocking rates on farms. Compared to milk production in other European countries, the Irish dairy sector benefits from lowest cost production with highest net margins (Shalloo et al., 2020). This allows Ireland to have a competitive advantage over high input indoor systems, which are predominant in Western Europe. Nationally, dairy farming is a major contributor to the Irish economy; hence, increasing dairy output is an important national objective (DAFM, 2021).

With quota constraints gone the availability of land and particularly land accessible for grazing with dairy cows represents the next limiting factor for increasing milk production from pasture-based systems (Dillon et al., 2006, Läpple and Hennessy, 2012, Ramsbottom et al., 2015). However, the majority of Irish farms are fragmented to a greater or lesser extent, which limits grazing land around the milking parlour; i.e. the grazing platform (GP). Bradfield et al. (2020) reported that in a representative sample Irish dairy farms had on average six distinct parcels per farm (National Farm Survey data from 2014). A fragmented farm with a moderate overall farm stocking rate typically has a much higher stocking rate of dairy cows on the grazing platform (GPSR). Therefore, a key determinant of further increases in dairy cow numbers on farms is the size of the GP and the stocking rate that can be sustained on it.

Furthermore, about one third of the milk produced in Ireland originates from land characterised as heavy wet soil, where grazing with dairy cows can be problematic. In wet soil conditions grazing dairy cows can damage both the sward and upper soil layers, which can lower herbage production (Pietola et al., 2005, Drewry et al., 2008, Phelan et al., 2013c, Tuñon et al., 2013b). A survey showed that 60% of Irish farmers identified wet soil as the most important factor limiting early turnout to pasture and subsequent grassland management (Creighton et al., 2011). Improving the productivity of this land can increase dairy output on a national level.

Maximising production from limited land resources and balancing this with the requirements of intensified dairy systems is a major research question for the dairy sector. More intensive systems need adapted management strategies and tools to facilitate decision processes. Further expansion of Irish national dairy production requires an economic evaluation of intensive pasture-based dairy farms. This includes farms situated on wet soils and farms affected by farm area fragmentation. The length of the grazing season can be limited in both situations, wherefore management strategies to extend the grazing season need to be established.

1.2. Research Aims and Objectives

The overall objective of this thesis was to review various aspects of grassland management for pasture-based dairy farms, identify knowledge gaps and investigate the impacts of specific management on productivity and profitability of pasture-based dairy farms under following constraints:

i) Pasture-based dairy farms with wet soils (Chapter 3)

The objectives for this part of the thesis were:

a. to ascertain how soil moisture measured using a soil probe can be used to support the decision to (i) keep cows indoors, (ii) allow cows restricted access to pasture for a few hours per day or (iii) allow cows out to pasture for most of the day on days of the year when conditions are typically considered suboptimal for grazing.
b. to assess if lowering the risk of treading damage by using soil moisture measurements to steer grazing management can improve productivity and profitability of pasture-based dairy farms with wet soils

ii) Pasture-based dairy farms with fragmented farm area (Chapter 4)

The objectives for this part of the thesis were:

a. to determine how GPSR affects herbage production, the length of the grazing season and milk production where silage produced on non-GP parcels is incorporated into the diet of lactating dairy cows to fill feed deficits during the grazing season

b. to determine if a point exists where the benefits of higher milk output from the GP are counterbalanced by negative impacts and increased costs associated with farm fragmentation
c. to determine the optimum stocking rate on the grazing platform of fragmented pasture-based dairy farms within a system designed to maximise the utilization of home-produced feed

iii) Extending the length of the grazing season (Chapter 5)

The objectives for this part of the thesis were:

a. to analyse grassland management in autumn in order to identify strategies to extend the grazing season on pasture-based dairy farms
b. to examine the implications of accumulating herbage mass during autumn in terms of herbage production and nutritive value, milk production, the length of the grazing season and herbage mass in the following spring.

1.3. Thesis Layout

This thesis contains six chapters. Following this introduction, Chapter 2 reviews literature of pasture-based dairy production and grassland management for pasture-based farms in general and more specifically farms with wet soils and farms with fragmented farm area and the implications for productivity and profitability. Chapter 3 investigates the effects of varied access time to pasture under wet soil conditions on the productivity and profitability of pasture-based dairy farms. Chapter 4 investigates the effects of farm area fragmentation and GPSR on the productivity and profitability of pasture-based dairy farms. Chapter 5 evaluates grassland management during autumn to extend the grazing season. Finally, Chapter 6 includes a general discussion and synthesis of the findings of this thesis along with the overall conclusions, implications and recommendations for future work.

Chapter 2 Literature Review

2.1. Pasture-based dairy production

2.1.1. Principles of seasonal pasture-based dairying

In pasture-based systems, herbage grown on grasslands is primarily harvested directly by grazing dairy cows. Grazed herbage has been shown to offer the cheapest feed source in dairy systems in Ireland (Finneran et al., 2012a). To exploit this competitive advantage, grazed herbage must be maximized in the diet of dairy cows (Ramsbottom et al., 2015, Ruelle et al., 2018). Therefore, a key objective in pasture-based systems is to synchronise the feed demand of lactating dairy cows with the seasonal growth of herbage during the year (Roche et al., 2017). This is achieved by strategic seasonal spring calving and matching stocking rate to the amount of herbage produced in order to offer grazed herbage as the primary feed source during the main grazing season.

The main factors impacting milk production per unit land are herbage production and utilisation from grazed pastures, stocking rate (McCarthy et al., 2011) and cow breed (Coffey et al., 2018, Roche et al., 2018). Due to high seasonal variation of nutrient supply from pastures, grazing dairy cows may be insufficiently fed during the season and therefore do not always reach their full milk production potential (Jacobs, 2014). Factors improving milk production per cow have been extensively investigated, especially total dry matter intake (DMI) and herbage dry matter intake (HDMI) (O'Neill et al., 2013), feed type (Dillon et al., 2002, Kennedy et al., 2015) and amount of supplemental feeding (Bargo et al., 2002, Reid et al., 2015). During lactation concentrate supplementation is usually preferred over silage supplementation as it has a lower substitution rate to grazed herbage and a higher milk response (Stockdale, 1999, Reid et al., 2015).

Pasture-based dairy production is historically and presently primarily located on favourable sites with a high proportion of permanent grassland, where it is the most suitable system of milk production (Roche et al., 2017). In the European context this applies mainly to maritime north western regions, with Ireland having the greatest proportion of highly productive permanent grassland (Smit et al., 2008).

2.1.2. Economics of pasture-based dairy production

One of the key objectives of pasture-based dairy systems is to produce high value milk from low inputs. Ruelle et al. (2018) analysed the optimum strategy for Irish pasture-based dairy farms in whole farm models and concluded that systems built around matching the supply and demand of home-produced feed were most profitable and resilient across different input and output prices. The most profitable scenario was a stocking rate of 2.6 cows ha^{-1} with a concentrate supplementation of 600 kg of dry matter (DM) per cow. The factor with the greatest impact on profitability was variability of milk price.

Both Ramsbottom et al. (2015) and Hanrahan et al. (2018) analysed factors associated with profitability of pasture-based dairy farms and highlighted that more herbage mass utilised per ha was associated with higher net profitability. Ramsbottom et al. (2015) found that more herbage used per ha was associated with lower amounts of purchased supplemental feed. Hanrahan et al. (2018) further highlighted that a long grazing season improves the following aspects of profitability: (i) Grazed herbage offers the cheapest feed source for dairy cows and (ii) the management and cost intensive winter feeding and housing period is shorter (Finneran et al., 2012a, Läpple et al., 2012). Following an economic modelling of grazed and conserved feed systems Finneran et al. (2012b) concluded that the length of the winter feeding period had the greatest impact on annual cost of feed. Furthermore, a longer housing period has implications on housing costs and associated costs of slurry management (French et al., 2015). Moreover, a longer housing period may impact health and therefore production performance of dairy cows (Beukes et al., 2013). These costs, however, are difficult to quantify and the literature reports contrasting results. In a model study comparing alternative farming scenarios Beukes et al. (2013) assumed higher health costs when cows spend more time indoors due to increased risk of mastitis and lameness. French et al. (2015) on the other hand concluded in a review that the type of wintering system (outdoors or indoors) had minimal effect on dairy cow productivity. The only economic difference derived from costs of the type of wintering system. Consequently, management strategies to extend the grazing season should be evaluated in context of impacts on profitability. Furthermore, many studies investigating profitability on Irish dairy farms discussed above were conducted under the restrictions imposed by the EU milk quota. Phasing out of production limits and quota costs changes the relationships between production variables and profitability. More intensive production systems may be more profitable.

2.1.3. Irish Dairy Industry

The climate in Ireland is characterized as humid temperate oceanic with high rainfall, mild winters and mild summers with moderate temperatures. Annual rainfall varies from east to west with an average of 700 to 1400 mm in agricultural regions (McElarney et al., 2015) and exceeds actual evapotranspiration in all regions which is characteristic for a humid oceanic climate (Creamer and O'Sullivan, 2018). Combined with a high proportion of slow draining soils (see 2.3.1) the humid climate causes wet soil conditions in Ireland. As a result permanent grassland is often the most suitable alternative for land use as the climate offers ideal conditions for a long growing season (O'Sullivan et al., 2015). O'Donnell et al. (2008) reported in the results of a survey conducted in 2007 that there was underutilisation of land and resources on Irish farms and that there was a considerable potential to increase productivity by increasing specialisation in dairying and increasing stocking rate of dairy livestock. Currently, 17% of all Irish farms are specialised dairy farms which is the most profitable farming system in Ireland (Dillon et al., 2021).

The abolition of the EU milk quota in 2015 enabled the utilisation of growing potential in the dairy sector and led to an increase in milk output in many European countries. Relative to pre-quota the proportional increase was greatest in Ireland (Läpple and Hennessy, 2012, Läpple and Sirr, 2019). The Food Harvest 2020 (DAFM, 2021) had set a target of a 50% increase in dairy production by 2020 (using the average of the years 2007 to 2009 as a baseline). National dairy production has exceeded this target by far with a 68% increase in the designated timeframe (CSO, 2021). This increase is mainly due to an increase in the number of dairy cows and higher stocking rates on dairy farms (CSO, 2020b). Therefore, a key research objective for the national dairy sector is to develop management strategies and quantify economic potential of intensified pasture-based dairy systems with higher stocking rates.

2.2. Grassland management in pasture-based dairy systems

2.2.1. Grassland production under grazing

Grassland production for ruminant consumption is predominantly based on perennial ryegrass swards. Perennial ryegrass is most suitable for intensive management of cutting as well as grazing systems as it combines high DM yields with superior nutritive value (King et al., 2012, Hendricks et al., 2016). Parsons and Chapman (2000) described net tissue production of perennial ryegrass swards as the difference between gross photosynthesis and tissue death. As soon as the fourth leaf of a tiller emerges, the first leaf starts to die (Figure 2.1). The rate of gross photosynthesis is higher than the rate of senescence until a maximum is reached where the rate of senescence increases and comes equal to the rate of net production, also referred to as 'ceiling yield' or 'ceiling mass'. This results in an S-shaped grass growth curve with maximum growth rate at the inflection point of the curve. The ceiling mass is a state of dynamic equilibrium and not static. Perennial Ryegrass is therefore often referred to as a three-leaf plant with the constant production and senescence of leaf material termed tissue turnover (Fulkerson and Donaghy, 2001, Chapman, 2016). Leaf appearance rate and leaf elongation rate are regulated by environmental factors such as temperature, light and availability of moisture in the soil (Matthew et al., 2001, Gastal and Lemaire, 2015).

The vernalisation process in winter triggers reproductive growth of perennial ryegrass in the following spring. If a perennial ryegrass sward is defoliated in the reproductive stage, the meristematic tissue is removed and the main tiller is not able to produce new leaves and will eventually die. Regrowth now depends on activation of axillary buds to form daughter tillers (Matthew et al., 2001).Consequently, a sward where all reproductive

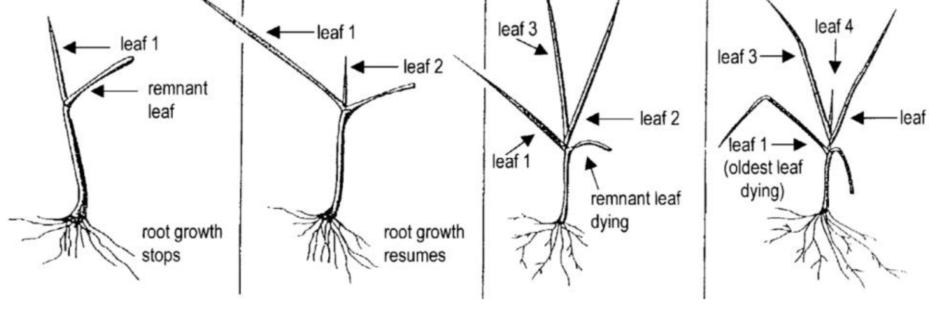

Figure 2.1: Development of leaf stages of a perennial ryegrass tiller (Fulkerson and Donaghy, 2001)

tillers have been defoliated will commence vegetative growth and only develop leaf material. This usually occurs in late summer so that autumn swards consist only of vegetative plant material.

The characteristic growth curve of perennial ryegrass (Figure 2.2) swards reflects the growing environment. Mild winters with rare frost and snow events allow growth almost all year round in Ireland. A high peak in spring is the result of highly productive growth of reproductive tillers. The following decrease in growth rate after the peak is a combined effect of tiller turnover, the replacement of reproductive tillers by vegetative tillers, and restricted moisture availability during summer months.

The physiological principals described above have implication on grassland management. Many studies suggested that matching the timing and interval of defoliation in a grazing system to the physiology of perennial ryegrass improves herbage production and persistence (Fulkerson and Donaghy, 2001, Chapman, 2016).

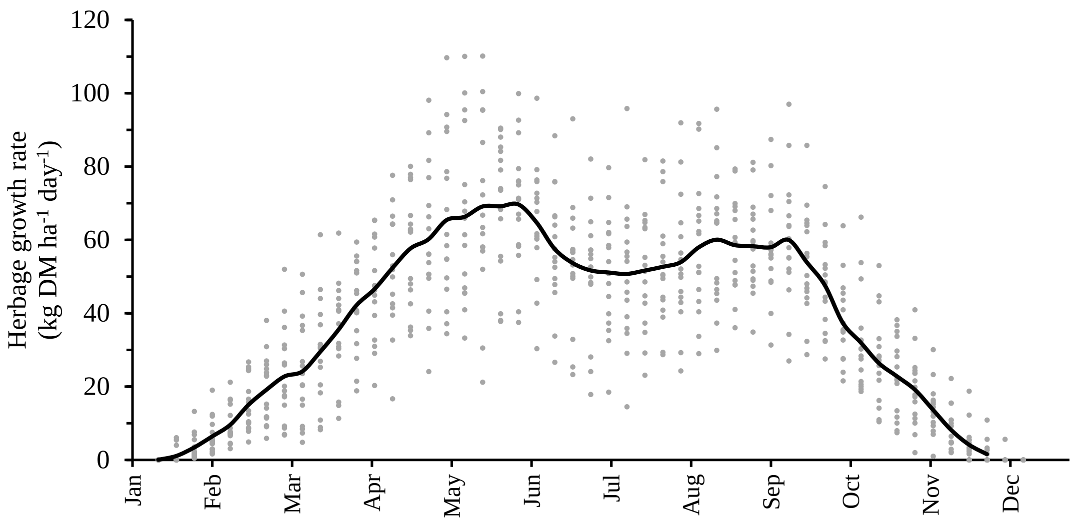

Figure 2.2: Daily herbage growth rate in Solohead Research Farm; three-week rolling average of individual years from 2000 to 2019 (●) and the mean of all years (—).

2.2.2. Nutritive value of grazed swards

Grazed perennial ryegrass swards have high nutritive value for ruminant feeding. Within the grass plant leaf tissue has the highest organic matter digestibility (OMD) and energy content (Beecher et al., 2015). Supplying herbage with sufficient nutritive value is crucial for dairy production. For example, higher OMD of the herbage consumed can increase HDMI in dairy cows (Stakelum and Dillon, 2004).

Growth stage, maturity, regrowth interval and season can affect nutritive value of the herbage. During stem elongation during the reproductive growth stage the proportion of leaf to stem material in the sward decreases (Parsons and Chapman, 2000). The digestibility of a reproductive sward rapidly decreases with maturity as there is more structural carbohydrates formed to stabilise the elongated stem. As a result, water soluble carbohydrates, OMD and crude protein (CP) decrease (King et al., 2012). Therefore, the rate of decline in nutritive value with increasing sward height and maturity is higher in reproductive swards. A vegetative sward on the other hand only produces leaf material. Nevertheless, Bryant et al. (2012) concluded that with increasing sward height more leaf sheath material was present in the grazing horizon, which has a higher water soluble carbohydrate content but also higher fibre content. Furthermore, dead material accumulates at the bottom of the sward with sward maturity (Fulkerson and Donaghy, 2001). In dense vegetative swards with high herbage mass (HM) the effect of shading on lower lying leaves further increases accumulation of dead material (Parsons and Chapman, 2000). The effect of sward maturity or HM on nutritive value of grazing swards has been extensively investigated in pasture-based systems (McEvoy et al., 2009, Curran et al., 2010, Wims et al., 2014, Beecher et al., 2018) and is further discussed in 2.2.6.

The effect of season can be explained by a combination of sward growth stage and environmental conditions. The photoperiod affects the ratio of photosynthesis to respiration a sward is exposed to. If net production from photosynthesis is lower than loss through respiration HM declines. This mostly affects swards with high HM in autumn once day length is shorter than night length. The existing HM cannot be maintained by photosynthesis, HM is no longer accumulated and the proportion of dead material increases in the sward (Lawrence et al., 2017).

2.2.3. Rotational grazing systems

In a review of the history of pasture-based dairy systems Roche et al. (2017) stated that herbage growth and utilisation were hugely increased with the development of rotational grazing management. In a rotational grazing or rotational stocking system the grazing land is divided into paddocks and grazing animals spend a defined time in an area and then rotate to the next paddock (Allen et al., 2011).

A rotational system allows the sward a resting period between grazings and the application of controlled grassland management practices. The resting period is called rotation length or rotation interval. It determines the interval for regrowth and therefore the maturity and HM of the sward at the next grazing. This enables the grass plant to replenish energy reserves in the form of carbohydrates, which are required to rebuild photosynthetic potential after defoliation (Donaghy and Fulkerson, 1997, Fulkerson and Donaghy, 2001). Carbohydrate reserves are fully replenished at the three-leaf stage. Fulkerson and Donaghy (2001) suggested that a grassland management system which was built to utilise swards at the three-leaf stage improves herbage production and nutritive value of the sward while also ensuring the persistence of perennial ryegrass in the sward. As the interval a sward needs to reach three-leaf stage varies throughout the year, estimates of leaf appearance rate can be used as a guideline for determining rotation interval.

Other methods to determine correct timing of grazing a sward are based on assessment of HM. In the field different methods have been tested including measurement of compressed sward height, undisturbed sward height or extended tiller height (Roche et al., 2017). Sward height is used to estimate HM by associated regression equations either from ground level or 4 cm above ground level (AGL) (O'Donovan et al., 2002). Knowledge of HM of each paddock can considerably improve overall performance and profitability in a rotational grazing system as feed supply and demand can be managed accurately (Beukes et al., 2019).

2.2.4. Post-grazing sward height and utilisation

Roche et al. (2017) characterised post-grazing sward heights in rotational grazing systems as a balance between harvesting as much of the grown HM as possible while also ensuring future growth potential and meeting the dietary demand of the grazing dairy cow. Therefore, the effect of post-grazing height on overall dairy systems performance is a complex of several single effects comprising regrowth potential and annual herbage production and utilisation, nutritive value of the grazed herbage, HDMI and, finally, milk production.

Studies on the effect of post-grazing height have reported conflicting information regarding regrowth potential and annual herbage production. It has been reported that herbage production was not affected (Lee et al., 2007, Tuñon et al., 2013a, Crosse et al., 2015), increased (Ganche et al., 2015, Chapman, 2016) and decreased (Lee et al., 2009) with higher post-grazing sward height. Tuñon et al. (2013a) reported that although herbage production was not affected in their experiment, utilisation by grazing animals was improved with decreasing post-grazing height. In systems with lower post-grazing heights the build-up of rejected area during the grazing season was less compared to systems with higher post-grazing height (Figure 2.3). Reduced dead and stem material in the grazing horizon of swards grazed at 3.5 to 4 cm decreased neutral detergent fibre (NDF) and improved OMD of the grazed herbage especially in mid-season and autumn. Macdonald et al. (2008), Ganche et al. (2015) and Pembleton et al. (2017) found similar results. Therefore, Tuñon et al. (2013a) concluded that a continuously controlled post-grazing height between 3.5 to 4 cm can be an effective management tool to maintain herbage utilisation and nutritive value of grazed swards while not compromising herbage production.

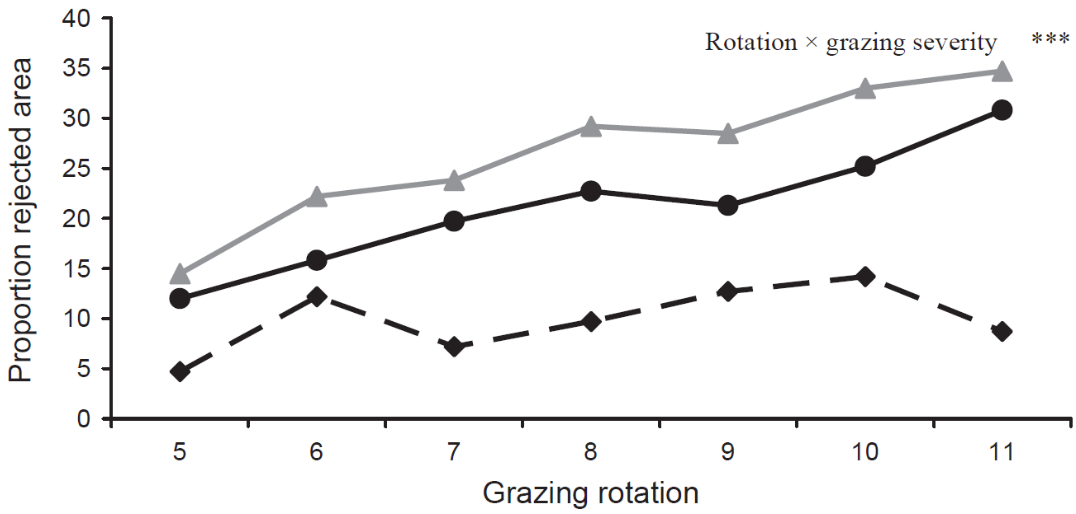

Figure 2.3: Effect of post-grazing sward height [high ▲ (4.5–5 cm), intermediate ● (4–4.5 cm) and low ♦ (3.5–4 cm)] on the proportion of rejected area at each grazing rotation (Rotation 5 = mid/late June, Rotation 11 = late October/early November). *** = P <0.001 (Tuñon et al., 2013a)

On the other hand, low post-grazing height can adversely affect milk production from grazing dairy cows. Ganche et al. (2013) and Crosse et al. (2015) reported significantly lower milk production in early spring when post-grazing height was reduced from 3.5 to

2.7 cm with an associated decrease in HDMI and a loss of body weight. Lee et al. (2008) suggested that the effect of post-grazing height can often be confounded by the effect of daily herbage allowance (DHA), which has been shown to improve HDMI and milk production (Pérez-Prieto and Delagarde, 2013). Low post-grazing heights are often associated with dietary restriction, where instead DHA is the effect imposing the restriction in HDMI. Nevertheless, in a study that applied similar DHA across treatments of varying post-grazing height, Lee et al. (2008) still reported a negative correlation of post-grazing height and milk yield. Milk solids yield was not affected in that study, therefore it was concluded that low post-grazing heights do not generally impact milk production. Phelan et al. (2013a) also reported no effect of post-grazing height (4, 5 and 6 cm) on milk production over three consecutive grazing seasons. Finally, Roche et al. (2017) agreed that the optimum post-grazing height is poorly defined in the literature but is most likely somewhere between 3.5 and 5 cm.

2.2.5. Stocking rates in grassland management

Stocking rate, the number of animals on the total land area of a farming system (Allen et al., 2011), has been identified as one of the main drivers of productivity in grazing systems (McCarthy et al., 2011, Roche et al., 2017). Macdonald et al. (2008) tested a wide range of stocking rates in pasture-based systems and concluded that stocking rate determines the amount of herbage consumed and linearly improves milk production per unit land. Fariña et al. (2011) showed that higher stocking rate can increase milk yield per ha more effectively then a higher milk yield per cow. Other studies found similar results (Valentine et al., 2009, McCarthy et al., 2013b, Coffey et al., 2018).

A negative relationship between stocking rate and milk production per cow was observed in many studies (Macdonald et al., 2008, Valentine et al., 2009, McCarthy et al., 2013a, McCarthy et al., 2014). However, many of these studies also reported simultaneously lower post-grazing height and lower herbage availability per cow (Kennedy et al., 2006, Macdonald et al., 2008, McCarthy et al., 2014, McCarthy et al., 2016). In contrast, studies where grazing decision rules were the same across stocking rate treatments and herbage deficits were met with supplemental feeding did not report an effect of stocking rate on herbage production, HDMI or milk production per cow (Fariña et al., 2011, Patton et al., 2016). Furthermore, in the study of Macdonald et al. (2008) higher stocking rate was associated with a shorter lactation length, which further reduced milk production per cow by 24%. This leads to the conclusion that not stocking rate alone but management factors associated with stocking rate caused the effects described above. The same applies for higher herbage accumulation, changes in morphological composition and improved nutritive value of the grazed swards with higher stocking rate (McCarthy et al., 2013b, McCarthy et al., 2016), which was likely caused by lower post-grazing heights as discussed in 2.2.4. Consistent across all stocking rate studies was a greater reliance on conserved feed with higher stocking rate, which has implications for profitability (see 2.1.2).

Macdonald et al. (2008) stated that an essential element of managing systems with higher stocking rates includes exploiting surplus herbage growth as well as longer rotation intervals in times of HM deficits. This was associated with higher pre-grazing herbage mass (PGHM), which is discussed in the following section.

2.2.6. Pre-grazing herbage mass in rotational grazing systems

In a rotational grazing system PGHM is controlled by rotation interval (Stakelum and Dillon, 2004, Pérez-Prieto et al., 2018). Rotation interval and PGHM have implications for herbage production as well as nutritive value of the grazed sward (Laidlaw and Mayne, 2000, Wims et al., 2014, Lawrence et al., 2017). Sward deterioration and decreased digestibility can negatively affect HDMI of grazing animals. Beecher et al. (2018) and Muñoz et al. (2016) reported a decline in DMI with increasing HM of cut or grazed perennial ryegrass swards. Both studies used relatively high PGHM in the high HM treatment (3700 kg DM ha^{-1}, 4 cm AGL, Beecher et al. (2018) and 5000 kg DM ha^{-1}, 3 cm AGL, Muñoz et al. (2016)). On the other hand, increasing HM can increase intake per bite (Stakelum and Dillon, 2004), which represents one of three main factors of HDMI of grazing dairy cows (Bargo et al., 2003). Wims et al. (2014) reported no effect of PGHM (1150, 1400 and 2000 kg DM ha^{-1}, 4 cm AGL) on DMI and concluded that lower intake per bite was compensated with longer grazing time. Several studies have shown that dairy cows in rotational grazing systems can adapt their grazing behaviour to maintain DMI across a range of PGHM (Barrett et al., 2001, Wims et al., 2014). Other studies also showed no effect of PGHM on HDMI (McEvoy et al., 2009, Curran et al., 2010, Wims et al., 2010) even when OMD was lower as a consequence of higher PGHM. O'Neill et al. (2013) concluded that PGHM was not associated with HDMI in autumn as opposed to spring and summer whereas DHA was associated with HDMI in autumn. McEvoy et al. (2010) and Stakelum and Dillon (2004) reported higher HDMI with high PGHM. However, both concluded that the effect of DHA on HDMI was greater than the effect of PGHM and that DHA is likely to influence the relationship between PGHM and HDMI. Pérez-Prieto et al. (2013) further highlighted that estimation height of PGHM can affect the DMI response to varying PGHM. The level of PGHM had positive, null and negative effect on DMI when PGHM was compared at 0, 2.5 and 5 cm AGL, respectively. The HM actually available for grazing at low or high PGHM differed between estimation heights.

With grazing high PGHM there is a risk of HM being trampled into the ground and target post-grazing heights not being achieved (Carton et al., 1988). Dillon et al. (1998) highlighted that especially in wet conditions herbage utilisation can suffer when PGHM is high. Curran et al. (2010) and McEvoy et al. (2009) both reported an interaction between DHA and PGHM on post-grazing height. Post-grazing height of swards grazed with high DHA (20 kg DM day^{-1} per cow) were higher at the higher PGHM level compared to the lower PGHM level (1600 vs. 2400 kg DM ha^{-1} (Curran et al., 2010) and 1150 vs. 2000 kg DM ha^{-1} (McEvoy et al., 2009), respectively). At a DHA of 15 (Curran et al., 2010) and 16 (McEvoy et al., 2009) kg DM day^{-1} per cow no difference in post-grazing height was reported between PGHM levels. As a result herbage utilisation was not affected by PGHM alone but only by interaction of PGHM and DHA between July and October in the study of Curran et al. (2010) and only by DHA in the study of McEvoy et al. (2009). Muñoz et al. (2016) reported similar results at a DHA of 20 kg DM day^{-1} per cow. In contrast, Wims et al. (2014) found higher post-grazing heights with higher PGHM at a DHA of 15 kg DM day^{-1} per cow over a whole grazing season. However, the difference of 0.2 cm in post-grazing height (4.0 vs. 4.2 cm for a PGHM of 1150 vs. 2000 kg DM ha^{-1}) was marginal. Therefore, there is no evidence from recent studies that grazing high HM in autumn causes lower utilisation and higher post-grazing height. DHA is more likely to affect herbage utilisation as already mentioned in 2.2.4.

There is no clear agreement about the effect of PGHM on milk production in the literature. Some studies hypothesised that as the digestibly of the grazed herbage and HDMI can be lower at higher PGHM, milk production is also likely to be negatively affected (Wims et al., 2010, Muñoz et al., 2016, Pérez-Prieto et al., 2018). A short term study in late spring demonstrated lower milk production with higher PGHM (2200 vs. 5000 kg DM ha^{-1}; 3 cm AGL) (Muñoz et al., 2016). Two other studies investigated the early/mid-season (April to July (Curran et al., 2010); June to August (Dillon et al., 1998)) and late season (august to end of grazing season in both studies) separately. Both studies reported lower milk production with higher PGHM (1600 vs. 2400 kg DM ha^{-1} (Curran et al., 2010) and 2300 vs. 3100 kg DM ha^{-1} (Dillon et al., 1998); 4 cm AGL) in the first half but no effect of PGHM in the second half of the grazing season. The findings of Evers et al. (2021) support this as they found no effect of PGHM in three different HM availability treatments on milk production during autumn (1 September to housing on 20 November). Spring calving dairy cows in seasonal pasture-based systems are in their last third of lactation during autumn. Furthermore, concentrate supplementation is usually introduced to increase total DMI (Wims et al., 2014, Reid et al., 2015). This means that lower quality grazed herbage can be easier tolerated in autumn than it could be in spring or summer. The response to concentrate feeding varies with the quality of the herbage consumed (Stockdale, 1999) and is greater in autumn compared to spring (O'Neill et al., 2013). In a meta-study predicting milk production and HDMI from animal and grassland management factors O'Neill et al. (2013) concluded that PGHM and OMD were not associated with milk production in autumn compared to spring and summer where there was a significant association. Studies where a full grazing season was analysed reported no negative effect on milk production of grazing high vs. low PGHM (1700 vs. 2200 kg DM ha^{-1} (Wims et al., 2014) and 1150 vs. 2000 kg DM ha^{-1} (McEvoy et al., 2009); 4 cm AGL). McEvoy et al. (2009) did however report higher milk yield in response to increasing DHA from 16 to 20 kg DM day^{-1}. Similar results were reported by Curran et al. (2010) for the autumn period with a DHA of 15 vs. 20 kg DM day^{-1}.

Consequently, effects of PGHM on milk production of grazing dairy cows cannot be generalized and must be evaluated in the context of season, DHA, cow lactation status and the level of supplementary feeding. It can be concluded that grazing high HM swards (> 1800 kg DM ha^{-1}; 4 cm AGL) in spring and mid-season potentially has negative effects on milk production in spring calving pasture-based systems. Nonetheless, no study has yet confirmed negative effects in the late season grazing period.

The accumulation of high HM in autumn has been discussed as management strategy to extend the grazing season (Laidlaw and Pineiro, 2006, Mata-Padrino et al., 2017), which will be discussed in the following section. Hence, more research is required to investigate the effect of grazing high HM in autumn on overall systems performance of pasture-based dairy production.

2.2.7. Grassland management to extend the grazing season

Läpple et al. (2012) concluded that there is scope to significantly increase herbage utilisation on Irish dairy farms through extending the grazing season. Dillon et al. (2002) showed that access to pastures for spring calving grazing dairy cows in early lactation reduced silage and concentrate requirement at the same level of milk production. The aim is usually to reduce costs rather than increase milk yield, but nonetheless studies have shown that milk production and especially milk protein content can also benefit from higher proportions of grazed herbage in the diet in early spring (Dillon et al., 2002, Kennedy et al., 2005, O'Donovan and Delaby, 2008) and autumn (Dillon et al., 1998, Reid et al., 2015). The implications of a longer grazing season on profitability are pointed out in 2.1.2.

To extend the grazing season by adapting grassland management excess herbage growth from the main grazing season is stored *in situ* and transferred into periods where demand for grazed herbage exceeds supply, usually late autumn, early winter and early spring. In early autumn rotation interval can be increased by ceasing to conserve excess HM as silage. As a result, the supply of HM and PGHM will increase. The additional stored HM facilitates more grazing towards the end of the grazing season and a shorter housing period. The literature describes this management strategy as deferred grazing or stocking (Allen et al., 2011), winter grazing (Hennessy et al., 2006), out of season grazing (Laidlaw and Mayne, 2000) or stockpiling (Mata-Padrino et al., 2017). Contraindications include effects of high PGHM on nutritive value of the sward, milk production and reduced utilisation, as discussed in 2.2.6.

Laidlaw and Mayne (2000) concluded that extending rotation interval above ceiling mass potential in autumn results in loss of herbage DM and especially loss of leaf lamina mass. Swards grown from August and early September showed ceiling mass in early November and declined in HM thereafter (Figure 2.4). Lawrence et al. (2017) and Hennessy et al. (2006) reported similar results. This also relates to the shorter photoperiod in autumn as discussed in 2.2.2.

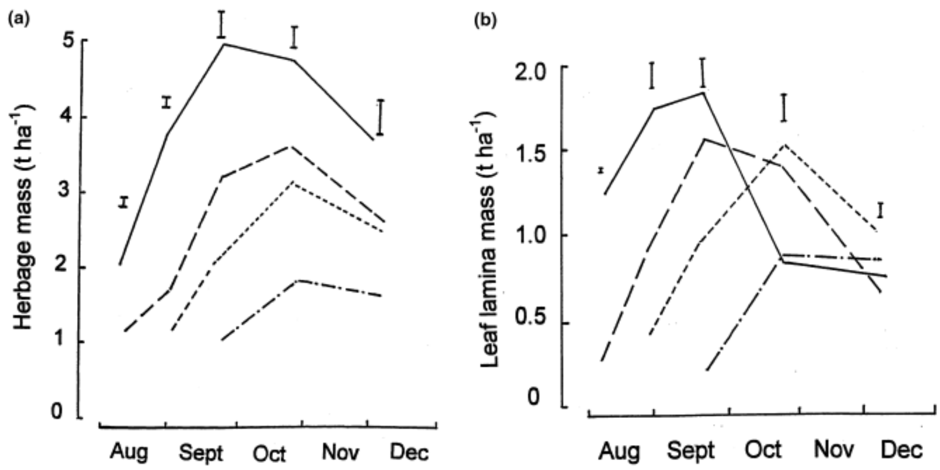

Figure 2.4: (a) Herbage mass (above ground level) and (b) leaf lamina mass in autumn affected by start of regrowth (▬▬ 19 July; ▬ ▬ 8 August; ---- 30 August; ▬ · ▬ · 20 September) and rotation length (Laidlaw and Mayne, 2000)

HM available for grazing in early spring is realised by a combination of herbage growth during winter months and deferred HM grown and stored during autumn. Ryan et al. (2010) reported that on average 35% of HM present in swards on 20 February was grown between 28 November and 30 January. Strategies to achieve higher HM available at turnout in early spring include earlier closing date, which allows for longer regrowth intervals over the winter period (Claffey et al., 2020). Some studies reported that time of closing in autumn can directly affect HM availability in spring (Ryan et al., 2010, Lawrence et al., 2017). On the other hand, Laidlaw and Mayne (2000) found no effect of timing of defoliation in autumn/early winter on HM in spring and Ryan et al. (2010) highlighted that the rate of spring growth was not affected by autumn closing date. Hennessy et al. (2006) found that HM present in autumn can affect herbage accumulation over winter both negatively and positively depending on start of regrowth interval and HM present before winter. Hennessy et al. (2006) also highlighted, that effects of imposing closing dates in successive years did not follow a consistent pattern. Claffey et al. (2020) found similar results. Therefore, the effect of HM in autumn on HM in spring likely depends on year-to-year variation in meteorological conditions.

Earlier closing however compromises HM availability in autumn and limits opportunities for extended late season grazing. As spring calving dairy cows require higher energy feed in early lactation the availability of HM for early turnout is often prioritised. More recent studies have indicated that accumulating HM during autumn can increase herbage availability in spring without earlier closing and a shorter grazing season in autumn (Evers et al., 2021). Nonetheless, there is still a lack of knowledge regarding timing and extent to which HM can be accumulated *in situ* and grazed in late season and how that affects milk production at system scale. Benefits and disadvantages of carrying high HM and extended grazing in autumn need to be evaluated. Besides, it remains unclear if HM grown in autumn can be successfully and reliably transferred into early spring and to what extent autumn grassland management affects this. This will be investigated in Chapter 5.

2.3. Dairy production on wet soils

2.3.1. Soil physical characteristics driving wet soil conditions

A soil is comprised of three main fractions: (i) solid mineral and organic soil material, (ii) soil air and (iii) soil moisture. The physical characteristics of the solid component and the occurrence and extent of soil air and water have implications for its suitability for agricultural purposes and productivity. The characteristics with the greatest effect on soil conditions are soil texture, structure, porosity and soil moisture content (SMC).

Soil texture describes the proportion of particle sizes in the fine mineral material (<2 mm), (USDA, 1951, FAO, 2006). Soil properties which are affected by soil texture include drainage, water holding capacity and porosity, three main aspects of wet soils (Arvidsson, 1998, Saxton and Rawls, 2006). Soils with a texture comprised mainly of clay (<2 µm) are referred to as heavy soils. Heavy wet soils can be problematic for agricultural management as discussed in the following sections.

Soil structure is formed by aggregation of primary soil particles into discreet soil units. This forms the porous structure of the soil. Porosity affects air and water flow through the soil and, in addition to soil texture, further impacts on permeability and drainage capacities (Arvidsson, 1998, Ball et al., 2007). Bulk density, the mass of a unit volume of dry soil, varies with SMC and reaches a maximum at what is called the critical water content (Mapfumo and Chanasyk, 1998). There is disagreement in the literature on the definition and number of pore classes (Drewry et al., 2008, Blume et al., 2016) but macropores are most commonly defined as pores with a diameter of >30 µm. Fine textured soils are characterised by a high proportion of micropores (<30 µm) (Arvidsson, 1998, Hodnett and Tomasella, 2002, Blume et al., 2016).

The ability of a soil pore to hold water against tension depends on pore diameter. Field capacity (FC) describes the SMC of a soil at a state of equilibrium when all excess water is drained and the remaining soil water is held in the soil by gravity (Blume et al., 2016). Consequently, the ability of a soil to hold water and therefore SMC at FC is largely dependent on soil texture and porosity. The volume of macropores is closely related to air-filled pore space at FC. If air-filled pore space is below 15% soil aeration can be impeded (Greenwood and McKenzie, 2001). A minimum macroporosity of 10% is required to support adequate herbage growth (Drewry et al., 2008). Therefore, macroporosity and inversely bulk density are important parameters for assessing soil quality and suitability for plant growth (Ball et al., 2007).

Excess water above FC is drained with the rate of drainage depending on the soil characteristics described above. Excess water above the saturation point, the point when all pores are filled with water, will cause overland flow or waterlogging. Gravimetric soil moisture content (mass of water per mass of dry soil; GSMC; g g^{-1}) can be converted into volumetric soil moisture content (volume of water per unit volume of a soil core; VSMC; m^3 m^{-3} or vol %) if soil bulk density is known (GSMC multiplied by bulk density) (Blume et al., 2016).

Another way of describing SMC is the concept of soil moisture deficit (SMD). SMD is the amount of precipitation (in mm) required to bring SMC back to FC. SMD effectively describes the balance between rainfall, actual evapotranspiration and drainage of a soil and can be modelled from weather forecast data by incorporating soil drainage classes (Creamer et al., 2016). A nationwide map of SMD is available for Ireland provided by the Irish Meteorological Service Met Éireann (www.meteireann.ie) which is modelled by a hybrid model following FAO guidelines (Schulte et al., 2005). However, other definitions of SMD can also be found in the literature i.e. Müller et al. (2011).

Soil type describes the layering of soil horizons in a specific location or site. Certain soil types can contain an impervious soil layer which impedes the passage of water (Blume et al., 2016). Those sites are more likely subject to waterlogging with events of high rainfall. Other soil types are formed by a high groundwater table, which further influences susceptibility to wet soil conditions. Soils that are saturated with groundwater for most of the year develop characteristic soil horizons and, in most cases, need to be drained artificially to allow agricultural use.

In Ireland fine loamy soils are most frequent whereas sandy soils with high natural drainage are rare (Figure 2.5). Of the total agricultural land area in Ireland 45% is

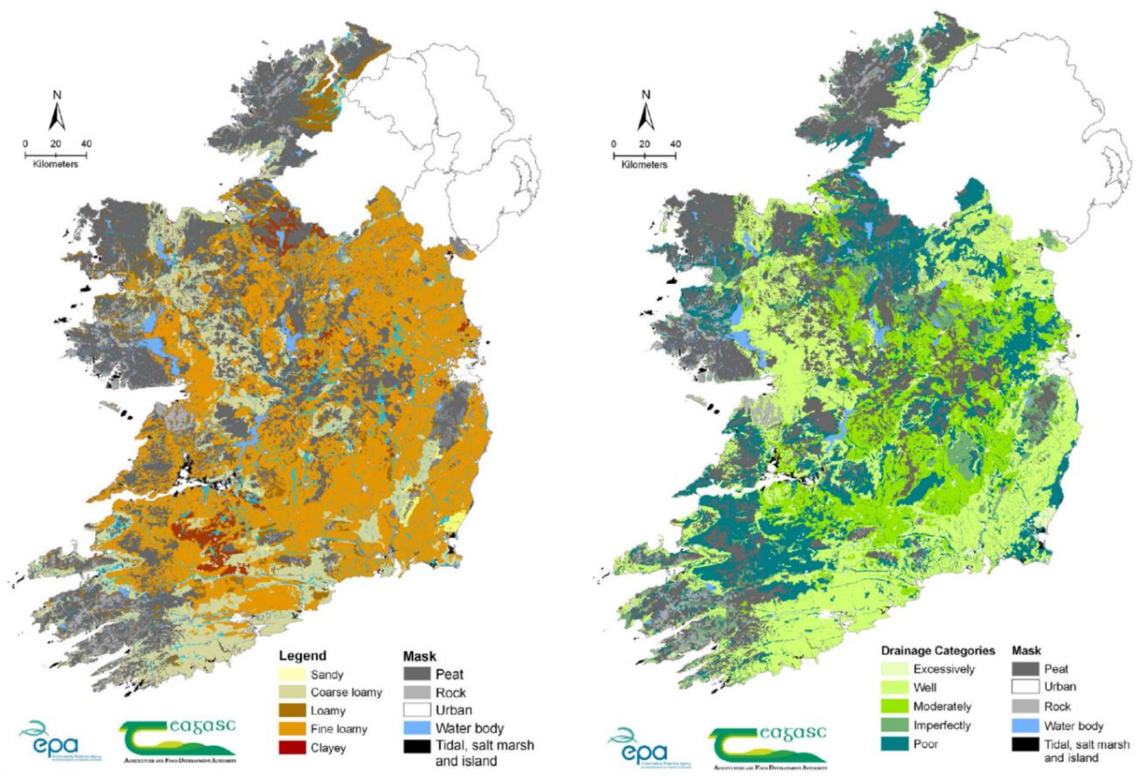

Figure 2.5: Indicative soil texture (left) and drainage status (right) of soils in Ireland (Creamer et al., 2016)

moderately to poorly drained, whereas only 35% are well to excessively drained (O'Sullivan et al., 2015, Creamer et al., 2016). These soil factors together with climate factors drive wet soil conditions, which are considered a major constraint for productivity and trafficability under agricultural use (Schulte et al., 2012).

2.3.2. Herbage production affected by wet soil conditions

Schulte et al. (2012) reviewed the effect of excess soil moisture on grass growth in Atlantic north western Europe and illustrated that maximum grass growth is realised at FC. Drought conditions and excess soil moisture both negatively impact grass production (Figure 2.6). In a study investigating the effect of prolonged periods of saturated soils and excessive soil moisture stress on perennial ryegrass growth Laidlaw (2009) found a decrease in grass production of up to 20%. The effect was explained by a combination

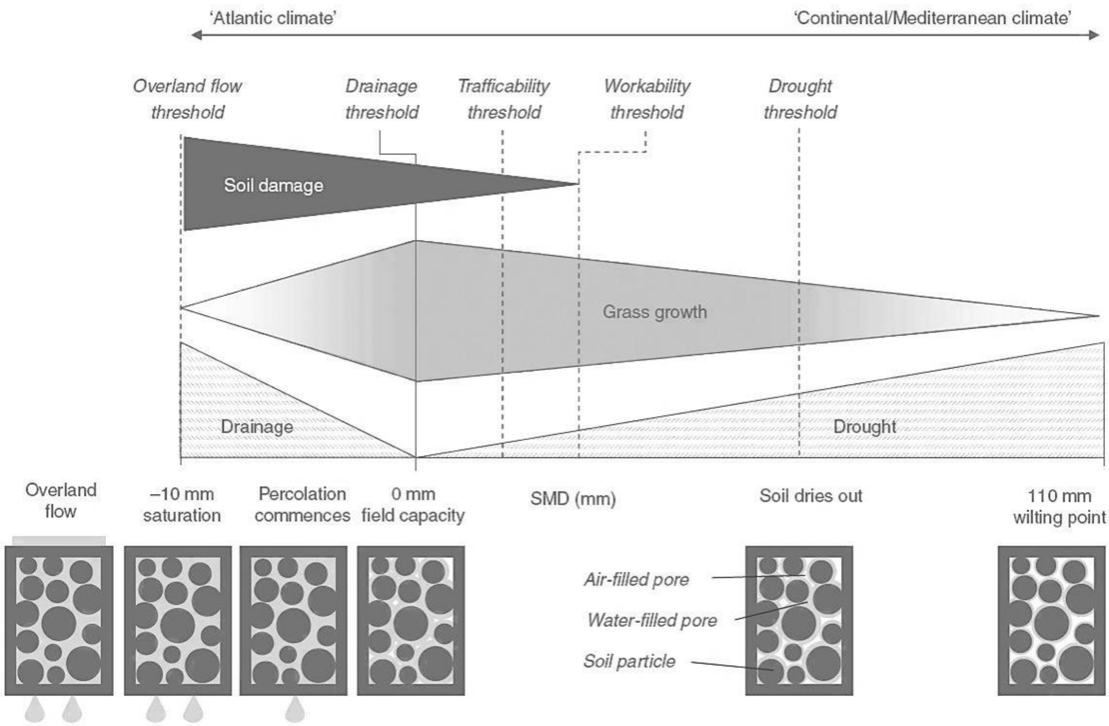

Figure 2.6: Effect of soil moisture deficit on grass growth and soil damage potential (Schulte et al., 2012)

of lower uptake of nutrients due to leaching and negative effects on rate of photosynthesis, leaf extension rate and shoot growth. Reduced photosynthesis and respiration is caused by oxidative stress in shoots and roots of the grass plant, which is even more present in submerged conditions, and can further reduce regrowth when excess SMC is drained (Liu and Jiang, 2015).

Fitzgerald et al. (2008) simulated the influence of poor soil drainage by integrating a soil moisture model into a dairy systems simulation based on farm data from Shalloo et al. (2004). Annual herbage production was reduced by between 1.5 and 3 t DM ha^{-1} on poorly drained soils compared to moderately and well drained soils under equal climatic conditions. Furthermore, herbage growth on poorly drained soils was limited on 289 days due to status of SMC (excess soil moisture and water stress), whereas on well and moderately drained soils it was only reduced on 97 and 68 days, respectively. Tuohy et al. (2014) found the SMD to be lower than 0 mm on 285 days and at -10 mm (saturation) on 88 days of a very wet year (2012) on a poorly drained soil. In the latter study, the distribution of the annual rainfall was especially driving wet soil conditions during the growing season with double the 10-year average rainfall occurring in the 3-month summer period of June, July and August. Air filled porosity was subsequently reduced to below optimum values for most times of the year (annual mean air filled porosity of 0.12 m^3 m^{-3}) which was concluded to be limiting herbage growth by 17% compared to the previous year 2011 (annual mean air filled porosity of 0.17 m^3 m^{-3}). The potentially long growing season typical for the mild Atlantic climate apparent in Ireland can therefore be limited by excess SMC especially on poorly drained soils. However, Fitzgerald et al. (2008) suggested that the limitations by excess SMC mostly occurred during winter months. Herbage growth in winter is reduced by other factors and dairy cows in pasture-based systems are fed from other feed sources such as silage. Hence, they concluded that wet soil conditions have less of an impact on herbage production because it occurs mainly during the winter rather than the summer months. Nevertheless, Shalloo et al. (2004) reported a much greater seasonality of herbage production on a poorly drained soil with high rainfall. Herbage growth was especially lower in the spring months which limited early spring grazing and total system performance. Likewise, the study by Tuohy et al. (2014) described above, which clearly showed limitations in herbage production due to wet soil conditions during the summer months, also contrasts the statement by Fitzgerald et al. (2008). It also highlights the importance of the time of year when wet soil conditions occurs and it's likely impact on herbage production and dairy cow carrying capacity.

More problematic in wet soil conditions, however, is not the effect on herbage production but the effect on herbage utilisation. Wet soil conditions may affect trafficability by farm machinery (Earl, 1997) as well as by grazing animals (Herbin et al., 2011) which is discussed in the following sections.

2.3.3. Soil susceptibility to structural damage

Extending the grazing season as discussed in 2.2.7 implies grazing in early spring and late autumn, which includes a higher risk of grazing under wet soil conditions compared with the main grazing season (April to October). Drewry et al. (2008) reviewed the effect of animal treading on soil physical properties and concluded, that soil consistency as effected by SMC is largely responsible for compaction and treading damage risk. Recent treading studies support the relationship of SMC and the risk of treading damage (Herbin et al., 2011, Phelan et al., 2013c, Tuohy et al., 2014). Figure 2.6 illustrates the increasing risk of soil damage with lower SMD (wetter soil conditions).

The consistency of a soil can be classified into liquid, plastic and dry or hard according to Atterberg (Atterberg limits) (Blume et al., 2016). These limits describe the GSMC at which a soils consistency changes from hard to plastic (plastic limit) and from plastic to liquid (liquid limit). The risk for soil structural damage by animal treading is high above the plastic limit and very high above the liquid limit. The plastic limit also represents the lowest GSMC at which visible soil surface deformation by grazing animals or machinery may occur. The risk of compaction is very high around the plastic limit at maximum bulk density (Drewry et al., 2008).

The soil strength behaviour and consistency limits also vary with soil texture (Mapfumo and Chanasyk, 1998, Drewry et al., 2008, Blume et al., 2016). Soils with higher clay content are more resistant to mechanical stress at the same SMC and change soil mechanical behaviour slower with increasing SMC than soils with lower clay content. For a sandy loam Mapfumo and Chanasyk (1998) found a GSMC at plastic limit of 0.25 kg kg^{-1} and at liquid limit of 0.30 kg kg^{-1}. For a clay loam, however, plastic limit was at 0.27 kg kg^{-1} and liquid limit at 0.51 kg kg^{-1}. Tuohy et al. (2014) reported an even higher GSMC at plastic limit for a clay-loam textured soil of 0.43 kg kg^{-1} at Solohead research farm. Furthermore, for the clay loam tested by Mapfumo and Chanasyk (1998) GSMC at FC was between liquid and plastic limit, meaning animal or machinery traffic at FC should be avoided before further soil moisture is removed by evapotranspiration. In the coarse-textured soil GSMC at FC was low enough, below plastic limit, so that trafficking was expected to be possible within time needed for drainage from saturation to FC after a high rainfall event. It was concluded that either FC or plastic limit, whichever is found at the lower GSMC can be used as a threshold for trafficability to avoid soil structural damage. It was also concluded that for coarse- to medium-textured soils bulk density is a determinant of soil strength whereas for fine-textured soils SMC dominantly accounts for variation in resistance against penetration.

Consequently, as heavy soils with higher clay content tend to be slow draining as discussed in 2.3.1 and are more likely to be deformable even after drainage to FC, the timeframe available for grazing is much shorter than on free-draining coarse-textured soils. Shalloo et al. (2004) found a reduction in grazing season length of 100 days on average over three years when comparing pasture-based dairy production on a farm with low rainfall on free draining soil with a farm with high rainfall on poorly drained soil. Fitzgerald et al. (2008) also reported an increase of 63 days in housing requirement on poorly drained soils. In a survey analysis of 453 Irish spring calving, pasture-based dairy farms it was concluded that wet soil conditions in spring and autumn are most commonly identified as limiting grazing season length (60% of participants), whereas HM availability was less commonly identified as limiting grazing season length (27% of participants) (Creighton et al., 2011).

In general, keeping cows indoors to avoid treading damage on farms on poorly drained soils shortens the grazing season compared with farms situated on well drained soils. Tuohy et al. (2014) reported a reduction in grazing season length by 34 days per cow between 2011 (1318 mm annual rainfall) and 2012 (1131 mm annual rainfall) on the same farm. Even though annual rainfall was higher in 2011 the distribution of rainfall during these years had a strong influence on the wetness of soil conditions during the grazing season 2012 with high rainfall in the summer months as described above in 2.3.2. It was concluded that SMC was above the plastic limit for a large part of the grazing season causing cows to be housed and limiting the length of the grazing season. Therefore, not only annual amount of rainfall and soil texture but also distribution of rainfall amounts during the year can affect grazing season length on pasture-based dairy farms. Other studies also found that grazing season length was influenced by wet soil conditions (Creighton et al., 2011, Humphreys et al., 2012).

2.3.4. Effects of treading on soil characteristics and herbage production

Treading damage to plants and soils is caused by the hooves of grazing animals. Grass swards can be damaged directly by a combined effect of dislodgement of and damage to plants (Menneer et al., 2005). A stress which exceeds the bearing strength of the soil results in soil structural damage. Changes in the physical condition of the soil following animal treading are considered indirect treading effects (Drewry et al., 2008). Direct and indirect effects are often difficult to distinguish. Furthermore, in the literature treading effects are discussed using different terminology (Greenwood and McKenzie, 2001, Drewry et al., 2008). In the present study treading will be considered ‘hoofprinting’ with plastic flow around the hoof on wet soil and ‘puddling’ will be used for describing treading effects in very wet condition, i.e. SMC above the liquid limit, with total remoulding of the soil without single defined hoofprints. Structural damage by plastic flow around the hoof and compaction and consolidation of soil particles in deeper layers can occur simultaneously (Greenwood and McKenzie, 2001). Compaction and soil structural damage is possible on dry soil with little visual evidence of surface damage (Herbin et al., 2011). The severity of soil damage is dependent on herbage cover at the time of grazing, SMC (see 2.3.3) and the characteristics and number of grazing animals (see 2.3.6) (Greenwood and McKenzie, 2001).

Singleton et al. (2000) tested different methods to measure changes in the physical condition of a soil after animal treading. It was found that hydraulic conductivity and aggregate size showed the greatest difference between trodden and untrodden soils.

Significant differences were most prominent in 0 to 10 cm depth below soil surface. Depending on soil type the bulk density, the total porosity, and the proportion of pores were not always indicative of change in soil structure. However, most studies reported increased bulk density, reduced macroporosity (Menneer et al., 2005, Drewry et al., 2008, Phelan et al., 2013c), reduced infiltration rate (Pietola et al., 2005) and reduced saturated hydraulic conductivity (Houlbrooke et al., 2009) with more treading damage which are all indicative of soil compaction. Changes in soil physical characteristics can be found in the soil long after a treading event and even when the soil surface and the sward are visually fully recovered. Singleton et al. (2000) still found differences in soil properties 18 months after a treading event on most soil types. On the other hand, Menneer et al. (2005) did not find a long-term effect of treading damage on macroporosity and bulk density one year later. Natural recovery processes of a soil after treading include shrinking and swelling due to wetting and drying, freezing and thawing, plant root penetration and decay and macro-invertebrates activity (Drewry, 2006). On permanent grasslands these processes play a major role in the recovery of poor soil structure as there is no soil disturbance through regular tillage.

Drewry et al. (2004) investigated relationships between soil physical characteristics and herbage production and found only few significant response relationships. Macroporosity showed the best fit to herbage production data and was positively related to relative DM yield in spring at both 0 to 5 cm and 5 to 10 cm soil depth. However, none of the investigated physical measurements tested by Drewry et al. (2004) were a reliable indicator of total DM yield.

Many studies investigated the effects of treading damage on herbage production. Drewry et al. (2008) reviewed studies with single severe treading events at high SMC as it is common in New Zealand and Australian high-density winter grazing management. They concluded that pasture productivity clearly decreased with increasing stocking rate and shorter intervals between grazing events; DM yield was up to 88% lower on trodden pastures compared to an untrodden control. Studies where repeated treading damage occurred during the grazing season reported a decrease of annual herbage production between 14% (Phelan et al., 2013c) and 0% (Houlbrooke et al., 2009).

The deformation of the soil surface can indicate the severity of treading damage after a grazing event. Howes et al. (2018) investigated correlations between methods of measuring soil surface deformation. It was concluded that measurements of hoof print depth and measurements of soil surface deformation with chain length reductions were highly correlated (R^2= 0.87) and equally as accurate as a newly developed method (pugometer) (R^2=0.74 and R^2= 0.86, respectively). Visual scoring was the quickest and simplest method to assess the severity of treading damage but was not accurate enough for research application and was therefore only suitable for on-farm application.

2.3.5. Methods to predict the risk of treading damage

Information about a soil's mechanical behaviour can be useful to develop decision support tools for on-farm grazing management. If conditions where the soil is susceptible to structural damage can be identified in advance of a grazing event, soil damage and negative effects on herbage production could be prevented. This could especially improve dairy production from soils tending to develop wet conditions causing limited availability of HM and increased risk of treading damage during spring and autumn.

Tested approaches include a visual scoring system proposed by Galvin (1983) which was used in the study by Shalloo et al. (2004) to determine soil suitability for grazing. While a visual scoring system is easy and quick to use on farm, it relies heavily on the observers' objectivity and can produce inaccurate results in a research environment.

Direct measurements of soil penetration resistance was tested in several studies for assessing trafficability by machinery as well as grazing animals (Müller et al., 1990, Drewry, 2003, Drewry et al., 2008, Houlbrooke et al., 2009). Penetration resistance varies depending on the penetrometer used and with soil properties (Müller et al., 2011) but offers applicability for on-farm use. Houlbrooke et al. (2009) concluded that the penetrometer used in the experiment to implement different grazing management strategies was not sensitive enough to prevent compaction of soil under grazing. Nevertheless, it was suitable to predict the risk of treading damage and to predict soil conditions where plastic deformation is likely to happen.

As there is a relationship between SMC and penetration resistance for most soils (Earl, 1997, Herbin et al., 2011, Kerebel et al., 2013), most approaches are based on assessment of the SMC to predict trafficability. In previous experiments, soil moisture has been measured as water table depth (Müller et al., 1990, Phelan et al., 2013c), critical water content (Laurenson and Houlbrooke, 2016, van der Weerden et al., 2017) or SMD for tillage (Earl, 1997) and grazing systems (Fitzgerald et al., 2008, Herbin et al., 2011, Piwowarczyk et al., 2011, Kerebel et al., 2013).

The concept of SMD, using daily nationwide forecast (www.meteireann.ie) as described by Schulte et al. (2005), was tested for on farm management of treading damage by Herbin et al. (2011). It was concluded that forecasted SMD was suitable as grazing management tool to protect physical soil structure. As a limit for trafficability with grazing dairy cows Herbin et al. (2011) suggested a SMD of 0 mm (FC). Piwowarczyk et al. (2011) and Kerebel et al. (2013) supported this in follow-up studies. However, the practicability and the impact of applying this concept on herbage and milk production have not been tested yet in a farming environment. Modelled SMD is easily accessible, however, predicted values may vary from actual values assessed afterwards as observed by Herbin et al. (2011). Furthermore, the conversion of SMC to SMD can result in loss of accuracy as SMD averages the SMC over the depth of the soil. Moreover, SMD is based on FC, which is not consistently quantified and defined in the literature (Hodnett and Tomasella, 2002, Schulte et al., 2005). Hence, the definition of SMD may also be inconsistent across the literature, which must be considered when comparing studies.

Measurements of the VSMC in the topsoil can provide a more direct approach to indicate trafficability on a specific soil site but has not been tested within a whole-farm approach yet. Besides, thresholds for trafficability with grazing dairy cows must be identified for each soil and cannot be easily transferred between soil types. Different focus, whether to avoid treading or soil compaction, may also require different SMC thresholds.

In conclusion, few of the approaches used to avoid treading damage have been tested in an actual dairy farming system. Direct measurement of VSMC may be used as simple on farm tool but has to be tested for functionality and relevance for on farm decision support. This will be evaluated in Chapter 3.

2.3.6. Management of dairy systems on poorly drained soils

Soil type and meteorological conditions are factors that cannot be influenced by the farm manager. Therefore, specific strategies are required to manage grazing systems during wet soil conditions in order to reduce soil damage while maintaining production.

Dairy cows differing in live weight were tested in animal treading studies. However, cow live weight showed no effect on soil properties, treading intensity or herbage production. This was explained by a direct correlation between live weight and hoof area causing similar static loading pressure between cow live weight groups (Herbin et al., 2011, Tuohy et al., 2014). Tuohy et al. (2014) also reported that a higher stocking rate significantly increased the severity of treading damage. This was confirmed in many other studies (Drewry et al., 2008). Tuñon et al. (2013b) emphasized the importance of high-quality perennial ryegrass swards to improve production and resilience against treading damage in grazing systems.

Many studies investigated restricted grazing management where dairy cows have limited access time to grazing paddocks per day. Less time at pasture decreases the number of hoof-soil interactions, which has the potential to lower the severity of soil damage. Cows with full day access to pasture only spend around 40% of the time grazing while the rest is spend ruminating or idling (Kennedy et al., 2009, Pérez-Ramírez et al., 2009). Furthermore, dairy cows can adapt their grazing behaviour by increasing intake per minute and intake per bite and by spending the majority of the time actually grazing when access to pasture is limited (Gregorini et al., 2009, Kennedy et al., 2009, Kennedy et al., 2011, Mattiauda et al., 2013, Soca et al., 2014). Hence, grazing cows can achieve a majority of their daily feed intake during a limited time at pasture.

The specific effect of restricting access time to pasture on HDMI depends on degree of restriction, DHA and level of supplementation when cows are housed and off pasture. Restricting access time to 9 hours per day in one grazing session has been shown to reduce HDMI of grazing dairy cows compared to full-time access (Kennedy et al., 2009, Pérez-Ramírez et al., 2009). Splitting the access time into two grazing sessions of 4.5 hours after each milking on the other hand did not lower HDMI compared to full-time grazing (Kennedy et al., 2009). In contrast, Gregorini et al. (2009) reported no effect on HDMI between full-time grazing, restricted access of 8 hours in one session per day or in two sessions of 4 hours per day. Similar results were reported by (Pérez-Ramírez et al., 2009) where one 9 hour session was compared to two sessions of 2.75 hours. In the study of Kennedy et al. (2009) cows were supplemented with concentrate whereas in the other studies (Gregorini et al., 2009, Pérez-Ramírez et al., 2009) no supplementation was fed. Pérez-Ramírez et al. (2009) found a decrease in milk production when cows were restricted to one grazing session of 9 hours per day, whereas Kennedy et al. (2009) found no effect on milk production when the same restriction was applied. The difference in concentrate feeding between the two studies as well as a difference in cow type may account for this difference between the studies. In the study of Kennedy et al. (2009) even a further restriction to only 6 hours total grazing time per day in two sessions of 3 hours each showed no significant impact on milk yield. However, as milk protein concentration tended to be lower and post-grazing height was increased compared to full time access or two grazing periods of 4.5 hours per day, Kennedy et al. (2009) concluded that total access time should be greater than 6 hours per day and should be split in two periods after each milking. This is supported by the finding that dairy cows grazing for 8 hours in one session showed a 36% lower rumination time (Gregorini et al., 2012) and the highest level of hunger indicators (Gregorini et al., 2009) compared to cows grazing for two sessions of 4 hours per day.

Kennedy et al. (2011) investigated if silage supplementation is required for dairy cows in early lactation when access time was restricted to two periods of 3 hours per day. It was concluded that milk production was not affected by additional silage supplementation compared to non-supplemented cows. Moreover, cows supplemented with silage at night had a lower HDMI than all other treatments tested (22 hours, 2 x 4.5 hours or 2 x 3 hours access to pasture without silage supplementation).

Pérez-Ramírez et al. (2009) investigated interactions of grazing time restriction and DHA and reported that the effect of time at pasture on grazing behaviour, HDMI and milk production was more apparent when DHA was high. The effect of DHA on intake rate was small compared to the effect that time at pasture had on intake rate.

Few studies tested the effect of restricted grazing time in response to wet soil conditions on soil properties or herbage production in a whole farm system approach. Houlbrooke et al. (2009) and Laurenson et al. (2016) tested the impact of different grazing management strategies on soil physical properties and herbage production on grazing plots. The studies applied different strategies for protecting soil structural damage (reduction of treading or reduction of soil compaction) and therefore different strategies to determine pasture suitability for grazing during wet soil conditions but came to the same conclusion; although soil physical properties were improved with less time at pasture, no impact on herbage production was found. Both studies did not measure impacts on milk production of dairy cows. Other studies investigating restricted grazing in a farming system are limited to whole farm modelling scenarios (Beukes et al., 2013, Laurenson et al., 2017). The modelling studies implemented herbage regrowth after a treading event as a function of stocking density and grazing duration and therefore found a positive herbage production response to restricted grazing. Laurenson et al. (2016) followed the same methodology in the modelling part of the study even though the grazing plot experiment included in the study showed no response of herbage production to varying time at pasture under wet soil conditions. Nonetheless, Laurenson et al. (2017) highlighted that suboptimal grazing management (i.e. the ideal time of grazing swards in three leaf stage was delayed) also decreased herbage production in the 'deferred grazing' treatment (no grazing in wet soil conditions) in the whole farm scenario. This resulted in low overall herbage production compared to full-time grazing under wet soil conditions. It was suggested that treading might not have such a significant impact on herbage production when assessed at system scale and over an entire grazing season.

Further research is required to determine the effect of restricted access to pasture under close-to-farming conditions where the focus of restrictions is to prevent treading damage. The impact of such a management strategy on a whole farming system with responses in terms of grazing season length, herbage and milk production has not yet been investigated. This will be investigated in Chapter 3.

2.3.7. Impact of grazing management on wet soils on profitability

Soil type and meteorological factors largely influence farm profitability in pasture-based systems. Lower profits and a higher level of production risk was reported on a poorly drained soil with high annual rainfall compared to free-draining soil with medium annual rainfall (1854 vs. 1044 mm in experimental years 1998 – 2000) (Shalloo et al., 2004). The up to 58% higher profitability was due to lower production costs and higher milk output per cow. Lower annual herbage production on the poorly drained soil (see 2.3.2) resulted in a lower stocking rate capacity. The shorter grazing season (see 2.3.3) resulted in a lower proportion of the diet coming from low cost grazed herbage (40 vs. 70%) which increased feed costs. Humphreys et al. (2012) also found an association between amount of rainfall and profitability in a system study on a poorly drained soil due to similar effects to those discussed above. In a sensitivity analysis Shalloo et al. (2004) further showed that farm profit of both systems was most sensitive to variations in milk price. Variations in silage quality and concentrate costs impacted the system on the poorly drained soil to a greater extent, as this system was more reliant on conserved feed as an alternative to grazed herbage. Moreover, Shalloo et al. (2004) evaluated the impact of a lower milk price and showed that the consequential decrease in profitability was greater for farms on poorly drained soils. This indicated limited economic sustainability of poorly drained dairy farms in Ireland. However, as milk price has increased substantially since this study was conducted, dairy farms on poorly drained soils can currently be economically sustainable, as recently demonstrated by Hanrahan et al. (2019). By comparing the physical and financial characteristics of dairy farms on poorly drained soils with the national average Hanrahan et al. (2019) concluded that efficient dairy farms operating on poorly drained soils can be as profitable as farms operating on any other soil type.

The economic impact of using restricted grazing as management strategies on wet soils as discussed in 2.3.5 and 2.3.6 have been analysed in modelling studies by Beukes et al. (2013) and Laurenson et al. (2017). Beukes et al. (2013) concluded that grazing for 6 to 8 hours when there was a risk of treading damage was a profitable option, whereas Laurenson et al. (2017) concluded that implementation of restricted grazing management (0, 13 or 17 hours instead of 21 hours of grazing time) was not profitable in most of the scenarios tested. Farm profit was lower due to higher costs of operating off-paddock holding areas. These New Zealand based studies modelled stand-off paddocks as an alternative to grazing paddocks, while in an European context, housing facilities are usually available to hold the cows when they are off pasture. Hence, in a European context, additional costs would only be caused by operating the housing facilities; i.e. slurry storage and management costs and labour costs for cleaning cubicles etc. Houlbrooke et al. (2009) also suggested that financial benefits from potential increases in DM yield with less treading damage are likely to be offset by the additional costs of using stand-off management practices.

No study has yet performed an economic evaluation of restricted grazing management (two grazing sessions after each milking) to avoid treading damage in a whole farm scenario over a full grazing season in the northern European context. Reduction potential of treading damage has to be quantified and analysed in relation to effects on herbage and milk production and profitability. This will be conducted in Chapter 3.

2.4. Farm area fragmentation and the impact on pasture-based dairying

2.4.1. Impacts of fragmentation on productivity of pasture-based farms

A number of studies have reported both negative and positive effects of farm area fragmentation on different types of agricultural production. In general, farm fragmentation increases production costs and decreases yields, revenue, profitability and efficiency (del Corral et al., 2011, Latruffe and Piet, 2014, Bradfield et al., 2020). Furthermore, fragmentation can lower the probability of using more extensive farming systems (Orea et al., 2015). However, the spatial distribution for example can also enable a more diverse crop variety and reduce production risks (Di Falco et al., 2010, Latruffe and Piet, 2014). Therefore, the impact fragmentation on productivity depends on the type of farming system and the production process. Latruffe and Piet (2014) further highlighted that a variety of dimensions (number of parcels, parcel size and shape, distance of parcels to the home farm and spatial scattering of parcels) need to be considered when the impact of fragmentation on farm performance is examined.

Previous studies showed that a higher number of parcels lowered technical efficiency of production of both confined and pasture-based dairy farms (del Corral et al., 2011, Bradfield et al., 2020). On fragmented Spanish dairy farms it was found that harvesting feed on parcels that are separated from the home farm was associated with increased costs, more complex management and reduced overall productivity (del Corral et al., 2011). Bradfield et al. (2020) concluded that the number of parcels, the distance between parcels and the home farm and the degree of fragmentation, i.e. the proportion of land that is separated from the home farm, all lower the efficiency of Irish pasture-based dairy farms. Fragmentation often dictates the extent to which grazing contributes to the feed budgets of livestock on dairy farms (del Corral et al., 2011).

A recent analysis has shown that Irish dairy farms are subject to fragmentation with an average of six parcels per farm (Bradfield et al., 2020). The grazing platform (GP), which is the land accessible with grazing dairy cows, is usually the portion of land on the home farm. This portion represented on average only 42 % of the total farm area (Bradfield et al., 2020). Stocking rate can be defined in two ways on fragmented farms: overall farm stocking rate and the stocking rate on the grazing platform (GPSR). An increased overall farm stocking rate generally coincides with a substantially higher GPSR (O'Donnell et al., 2008) depending on the degree of fragmentation and the size of the GP. O'Donnell et al. (2008) suggested that on a fragmented pasture-based dairy farm GPSR is the main indicator of potential to increase dairy cow stocking rate and milk output per hectare.

In traditional pasture-based dairy systems stocking rate is ideally matched to the herbage production potential of the farm (Ruelle et al., 2018). As discussed in 2.2.5 reliance on supplementary feed increases with higher stocking rate. On a fragmented farm this is typically the case when the feed demand as determined by the GPSR is higher than the supply from herbage growth rate on the GP. In a system designed to maximise production from home produced feed, this supplementary feed could be produced on the separated (non-GP) parcels of the farm. Patton et al. (2016) reported a requirement for imported silage of 1288 kg DM per cow with a GPSR of 4.5 cows ha^{-1} compared to 550 kg DM per cow at 3.1 cows ha^{-1}. However, deficits in HM during the grazing season were mainly filled with imported concentrates which resulted in higher concentrate input per cow with higher GPSR (Patton et al., 2016). Therefore, effects of GPSR on silage requirements were confounded with concentrate input. The high GPSR system showed higher milk production per cow. As discussed in 2.1.1, feed type and amount of supplemental feeding affects milk production per cow.

Despite its critical importance, few studies have quantified the impacts of higher GPSR on the productivity of fragmented pasture-based farms. No study has performed a whole farm analysis of the impact of fragmentation on pasture-based dairy production and assessed impacts of higher GPSR on grazing season length and supplementation feed requirements from non-GP parcels of the farm system and their impacts on milk production. This will be done in Chapter 4.

2.4.2. Impacts of fragmentation on economics of production

Farm area fragmentation affects the costs of production in pasture-based dairy systems. Some negative effects on profitability arise from more complex management and less efficient use of farm machinery (Di Falco et al., 2010, Latruffe and Piet, 2014). The greater reliance on conserved feed with higher GPSR (Patton et al., 2016) increases feed costs (Finneran et al., 2012a). The shorter grazing season and, hence, longer housing period as a result of higher GPSR increased slurry storage requirements and slurry handling costs (Shalloo et al., 2004, Clark et al., 2010, Laurenson et al., 2016). Beukes et al. (2013) assumed 10% higher health costs for cows that spent more time indoors as opposed to at pasture as lying behaviour was assumed to be negatively affected. However, the specific value of 10% was based on assumptions. Similarly, there might be implications of increased labour and machinery requirement for e.g. cleaning cubicles and feeding silage to cows (Deming et al., 2018) when cows are housed for longer. However, the exact extent of the increase in costs are difficult to assess. There are no recent studies that quantify health or labour costs on a ‘per day’ or ‘per hour’ indoors basis.

On fragmented farms, conserved feed can be produced on the non-GP parcels of the land. Depending on the spatial distribution of land parcels and the distance between GP and non-GP parcels, travel time and costs for fuel can be significantly higher (Latruffe and Piet, 2014). Especially for large dairy farms, fragmentation will result in longer travel time of agricultural vehicles on public roads (Jaarsma et al., 2013). When hired labour is used to contract out work on fragmented land parcels, variable costs may only increase if land parcels are considerably further away from the home farm and may depend on the type of work executed by the contractor. For example, spreading slurry on distant land parcels will limit the possibilities and methods used for spreading and might be unprofitable if parcels are far away and small.

In conclusion, fragmentation increases cost of production, but this does not mean that fragmented farms cannot be profitable. On many Irish dairy farms non-GP parcels are typically used for young stock rearing but tend to be under-utilized with considerable potential to increase pasture productivity (O'Donnell et al., 2008). Intensified production systems on the available GP could use non-GP parcels as feed support block for dairy production. Especially in a non-quota environment this could become more profitable than the alternative of renting out non-GP parcels or using them for rearing of young stock.

The prevalence of fragmentation in Ireland and a trend towards higher GPSR however require an economic evaluation of costs and benefits of increasing GPSR on fragmented pasture-based dairy farms. It is possible that at some point the benefits of higher milk output from the GP are counterbalanced by higher costs associated with farm fragmentation. Macdonald et al. (2011) investigated the effects of stocking rates on the economics of pasture-based systems in New Zealand and concluded that profitability was quadratically related to stocking rate. When milk payment was based on the value of milk fat and protein, profit was maximised at a stocking rate of 3.3 cows ha^{-1}. Ramsbottom et al. (2015) has indicated that there is a risk that increasing stocking rate on the milking platform could make some farms less profitable, particularly where higher stocking rate were supported by high input of concentrate feed. Macdonald et al. (2017) found similar results. Hence, there may be an optimum GPSR on fragmented dairy farms which needs further investigation. The impact of fragmentation on profitability will depend on degree of fragmentation and type of production system. No study has yet quantified the impacts of fragmented farm area on the profitability of pasture-based dairy farms in the context of typical Irish dairy systems. This will be evaluated in Chapter 4.

Chapter 3 Access time to pasture under wet soil conditions: the effects on productivity and profitability of pasture-based dairying

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Abstract

A long grazing season improves the profitability of pasture-based dairy production. It can entail grazing under wet soil conditions and the risk of damaging swards. Housing cows either temporarily or completely whilst soil moisture is high can avoid damaging swards. To evaluate if soil moisture measurements are an effective decision support to assess the risk of treading damage, impact on pasture productivity and dairy cow performance during wet soil conditions a three-year experiment with four grazing systems was set up. Access time to pasture per day and per hours per day between February and December of each grazing season was dependent on volumetric soil moisture content (VSMC m^3 m^{-3}) measured each morning: (CONTROL) cows were housed at VSMC >0.5 and otherwise allowed 22 h per day access to pasture; (S<7) cows were housed on days with VSMC >0.7 and otherwise allowed 22 h per day access to pasture; (S7-6) cows were housed at VSMC >0.7, allowed 8 h per day access to pasture at VSMC between 0.7 and 0.6 and 22 h per day access at VSMC ≤0.6; (S7-5) cows were housed at VSMC >0.7, allowed 8 h per day access to pasture at VSMC between 0.7 and 0.5 and 22 h per day access at VSMC ≤0.5. Cows with 8 h access per day received no other feeding when housed. All herds were compact spring-calving with a mean calving date of 19 February. Mean stocking rate was 2.57 cows ha^{-1}. Measurements of VSMC provided an objective indicator for the risk of treading damage. Less time spent at pasture under wet soil conditions lowered treading damage but had no effect on annual herbage production (mean 14.8 t organic matter (OM) ha^{-1}). Annual milk solids production per cow was lowest for CONTROL (485 kg) and not different between the other systems (503 kg). Reducing treading damage to grazing swards did not improve productivity or profitability of the grazing systems. Nevertheless, measuring soil moisture was a useful decision support for assessing the risk of treading damage when turning cows out to pasture.

3.1. Introduction

A long grazing season improves the profitability of pasture-based dairy production (Läpple et al., 2012, Hanrahan et al., 2018). However, grazing dairy cows, particularly during the winter, spring and autumn can damage both the sward and upper soil layers, which can lower herbage production (Pietola et al., 2005, Drewry et al., 2008, Phelan et al., 2013c, Tuñon et al., 2013b). Creighton et al. (2011) showed that 60% of Irish dairy farmers identified wet soil conditions as the most important factor influencing their decision whether or not to turn livestock out to pasture. Treading damage by the hooves of grazing animals, which is a plastic deformation of the soil surface, is most likely to occur under wet soil conditions (Drewry et al., 2008, Phelan et al., 2013c). At higher latitudes of the temperate zones soil moisture content is typically highest during the winter, spring and autumn due to seasonally higher rainfall combined with low evapotranspiration. In order to achieve a long grazing season it is often necessary to turn cows out to pasture under less than optimal soil moisture conditions.

Keeping cows indoors to avoid treading damage on farms on poorly drained soils shortens the grazing season and increases the cost of production compared with farms situated on well drained soils (Shalloo et al., 2004, Fitzgerald et al., 2008, Hanrahan et al., 2018). Restricting the time that cows have access to pasture per day to short grazing bouts is one way of incorporating more grazed herbage in the diet while limiting treading damage. Typically, cows are allowed access to pasture for two grazing bouts per day each of three to four hours in duration. Cows are housed or held on a standoff pad for the remainder of each day and often receive no additional feed during this time. Such an approach has been shown to maintain herbage intake and milk production (Gregorini et al., 2009, Kennedy et al., 2009, Pérez-Ramírez et al., 2009), cause less damage to soil structure (Houlbrooke et al., 2009, Laurenson et al., 2016) and lower the risk of nutrient losses to water (Clark et al., 2010, Christensen et al., 2019).

While many studies have measured the impact of treading on soil structure and herbage production the extent of treading is typically ascertained after the grazing event (Houlbrooke et al., 2009, Phelan et al., 2013c, Tuñon et al., 2013b, Laurenson et al., 2016). From a commercial farming perspective the concern is to prevent treading damage before it happens because it is likely to be detrimental to current and future productivity of pastures and/or the dairy cows. This requires the capacity to ascertain the soil moisture conditions that are not suitable for grazing in advance of the grazing event. Indeed, we are not aware of any unambiguous and objective definition of what are suboptimal conditions for grazing that can be used as on-farm decision support. Hence, the overall objective of the present study was to ascertain how soil moisture measured using a soil probe can be used to support the decision to (i) keep cows indoors, (ii) allow cows restricted access to pasture for a few hours per day or (iii) allow cows out to pasture for most of the day on days of the year when conditions are typically considered suboptimal for grazing. Ultimately, a decision support system should improve profitability or increase environmental sustainability of a production system. Hence, the present study was designed to simultaneously assess the impact of different grazing management strategies on the profitability of dairy production. Earlier studies at the same site of the present study (Phelan et al., 2013c, Tuohy et al., 2014) have shown that soil moisture can be above the plastic limit, which indicates the onset of possible treading damage, during much of the grazing season. Hence, a certain degree of treading damage throughout the grazing season is unavoidable at this site. Nevertheless, using the results of these two earlier studies (Phelan et al., 2013c, Tuohy et al., 2014) it was determined that there was a low risk of treading damage at a volumetric soil moisture content (VSMC m^3 m^{-3}) of

<0.5 and severe treading damage was likely at VSMC >0.7. Hence, four grazing systems were established, one with a low risk of treading damage and one that entailed a high risk of damage at risky times of the year. The other systems were designed to examine the practice of restricting daily access time to pasture under different criteria of VSMC as a means of curtailing damage to paddocks and potentially increasing herbage production.

3.2. Materials and Methods

3.2.1. Site description

The experiment was conducted at Solohead Research Farm (52˚30'N, 08˚12'W, 95 m above sea level) in south-west Ireland. Soils at the farm include poorly drained Gleysols (90%) and Podzols (10%) with a clay loam texture (FAO, 2015). Topographic relief causes variation in shallow groundwater with the water table depth ranging from 0 to 2.2 m below ground level. Much of the farm area is seasonally wet, waterlogged or flooded. The local climate is humid temperate oceanic with a long potential growing season (~10 months). The land has been under permanent grassland with predominantly perennial ryegrass and white clover swards for well over 50 years and approximately 5% of the grassland was renovated each year.

3.2.2. Experimental systems

The experiment was carried out over three consecutive years: from 1 September 2013 to 31 August 2016, with each year spanning the period between 1 September and 31 August. Four grazing systems were established where daily measured VSMC was used to determine (i) when (days per year) lactating cows were allowed access to pasture and (ii) the length of time per day that cows were allowed access to pasture in each of the four systems (Table 3.1). These access times ranged from entailing a very low risk of treading damage (CONTROL) to a high risk of damage (S<7). The CONTROL system was designed to reflect cautious management practice that is prevailing on Irish dairy farms currently. Management similar to that in S<7 is practiced very rarely on Irish dairy farms and was designed to test extreme management practices. The other two systems (S7-6 and S7-5) were intermediate in terms of treading risk and involved allowing the herds to have restricted access to pasture on the days that they were allowed out to pasture. Those two systems were designed to reflect current more progressive management and best practice recommendations, which involve restricted daily access time under wet soil conditions and periods of heavy rainfall (Kennedy et al., 2016).

Table 3.1: Volumetric soil moisture content (VSMC m^3 m^{-3}) and the number of hours per day that lactating cows in the four grazing systems were allowed access to pasture

	Grazing system			
	S<7	S7-6	S7-5	CONTROL
VSMC	Daily access to pasture (h)			
>0.7	0	0	0	0
0.7 – 0.6	22	8	8	0
0.6 – 0.5	22	22	8	0
≤0.5	22	22	22	22

At VSMC ≤0.7 cows in S<7 were allowed out to pasture for the entire day excluding milking times in the morning and evening; with milking times accounting for approximately 2h per day. When VSMC >0.7 the S<7 herd was housed. Likewise, the CONTROL herd was housed when VSMC >0.5 and allowed 22 h per day access to pasture once VSMC ≤0.5. Restricted access per day involved a 4 h grazing bout immediately after the morning milking and a 4 h grazing bout immediately after the evening milking. Herds were housed once the allotted time had elapsed. During the days that cows were allowed 8 h access to pasture they received no other additional feeding when housed; i.e. their entire diet was grazed herbage. The S7-6 herd was housed when VSMC >0.7, allowed 8 h access to pasture per day when VSMC was between 0.7 and 0.6, and allowed 22 h access to pasture per day when VSMC ≤0.6. Likewise, the S7-5 herd was housed when VSMC >0.7, allowed 8 h access to pasture per day when VSMC was between 0.7 and 0.5, and 22 h access to pasture per day when VSMC ≤0.5 (Table 3.1). All herds that were housed full time received silage (ensiled herbage) *ad libitum*.

The only exception to the above management rules was when herbage mass was too low to sustain herd demand, which occurred when herbage growth rates were below herd demand and pre-grazing herbage mass was <1000 kg DM ha^{-1} (measured to 4 cm above ground level (AGL)). Under such circumstances cows were housed and received silage *ad libitum*, and were occasionally supplemented with concentrates according to the feed budget for each herd (see below). Mean composition of silage fed to dry cows during the experiment ± *SD* was 84 ± 7.1 g kg^{-1} ash, 683 ± 39.2 g kg^{-1} DM digestibility, 128 ± 13.6 g kg^{-1} crude protein and 0.75 ± 0.05 unité fourragère lait (UFL; Jarrige, 1989). Mean composition of silage fed to lactating cows was 83 ± 9.7 g kg^{-1} ash, 740 ± 22.0 g kg^{-1} DM digestibility, 145 ± 10.8 g kg^{-1} crude protein and 0.83 ± 0.03 UFL. All silage fed during the experiment was harvested from the experimental area. Energy content of the concentrate feed (35% beet pulp, 26% barley, 26% maize gluten and 12% soybean meal) was 0.95 UFL.

Additional to the management rules outlined in Table 3.1 and above, the end of the grazing season (cows housed for the winter) was determined by an average herbage mass of 500 kg DM ha^{-1} across all the paddocks in each system. Housing dates at the end of the grazing for each system in each year are in Table 3.2.

3.2.3. Experimental set up and design

All cows used in the experiment were compact spring-calving with a mean calving date 19 February. Each spring all cows were divided into four main groups based on lactation number (1, 2, 3, and ≥ 4) and then sub-divided into subgroups of four on the basis of calving date. One cow from each subgroup was randomly assigned to each herd. Herds were randomly assigned to each grazing system. In 2013 all cows were managed as a single herd before the beginning of the experiment and were assigned to herds in August 2013 in the same manner as described above. Mean overall stocking rate on each system was 2.57 cows ha^{-1} (Table 3.2). There were 23 cows per herd in 2013/14, 25 cows per herd in 2014/15 and 24 cows per herd in 2015/16. Annual milk data for each experimental year encompassed 1 September to dry off at the end of lactation and from calving to 31 August of the following year. Blocks were used to join data across lactations.

Cows were turned out to pasture approximately three days after calving and dried off in late November and December. Only lactating cows were allowed out to pasture while non-lactating cows were kept indoors before calving in spring and after the end of lactation. Cows that calved before turnout (start of the grazing season) were kept indoors and fed silage *ad libitum*. In early lactation (February to April), cows received up to 6 kg concentrate per cow per day depending on the mass of herbage available on the grazing area. During the rest of the grazing season (from May onwards) between 0 to 2 kg concentrate per cow per day was fed. Concentrate supplementation per cow was the same on a day-to-day basis across all systems.

The experimental area was divided into six blocks based on soil type and drainage status in August 2013. Each block was divided into four paddocks. One paddock from each block was randomly assigned to each system and remained in that system until the end of the experiment, resulting in six paddocks per system (9.35 ha per system). Strip-grazing management was practised in all systems. Excess herbage mass per system was identified and removed as silage throughout the grazing-season. This was generally the case when herbage growth rate was higher than the feed demand of the grazing herd resulting in pre-grazing herbage masses >1600 kg DM ha^{-1} between April and July, and >2000 kg DM ha^{-1} from August onwards. The proportion of the area that was closed for silage in each system is presented in Table 3.2. Each system received annual nitrogen input of 280 kg N ha^{-1} in form of mineral fertilizer and 56 kg N ha^{-1} in form of cattle slurry, which is in line with national guidelines (DAFM, 2020). Mineral fertilizer was applied in form of urea from February to April and in form of Calcium Ammonium Nitrate from May to September, evenly distributed at monthly intervals.

Table 3.2: Details of the grazing systems imposed during the three years of the experiment (01 September 2013 to 31 August 2016)

	Grazing system[1]				
Item	S<7	S7-6	S7-5	CONTROL	*SEM*
End of grazing season 2013	19 Nov	19 Nov	07 Dec	13 Dec	
End of grazing season 2014	22 Nov	22 Nov	22 Nov	06 Nov	
End of grazing season 2015	29 Nov	29 Nov	29 Nov	08 Nov	
Start of grazing season 2014	24 Feb	24 Feb	24 Feb	04 Mar	
Start of grazing season 2015	17 Feb	17 Feb	17 Feb	20 Mar	
Start of grazing season 2016	08 Feb	08 Feb	08 Feb	16 Mar	
Overall stocking rate[2] (cows ha^{-1})	2.57	2.57	2.57	2.57	
Monthly stocking rates when areas closed for silage were accounted for (cows ha^{-1})					
September to December	2.57	2.57	2.57	2.57	0.06^{NS}
February to March	2.60	2.60	2.60	2.62	0.03^{NS}
April to June	3.92^{b}	3.81^{b}	3.87^{b}	4.65^{a}	0.14*
July to August	3.21	3.16	3.19	3.49	0.14^{NS}
Mean	3.03^{b}	2.99^{b}	3.02^{b}	3.29^{a}	0.05***
Proportion of area harvested for silage					
April to June	0.42	0.46	0.45	0.67	0.07^{NS}
July to mid-August	0.37	0.40	0.32	0.53	0.07^{NS}

$^{a–b}$ Mean values in the same row with different superscripts differ between grazing systems (P <0.05).
* P <0.05, *** P <0.001, ^{NS} P >0.05
SEM = standard error of grazing system means
[1] See Table 3.1 for a description of the grazing systems
[2] On overall farm area

3.2.4. Measurements

Meteorological data. Soil temperature (°C; at soil depth of 10 cm), rainfall (mm), wind speed ($m\ s^{-1}$) and direction (°) and solar radiation ($J\ cm^{-1}$) was measured at an automated weather-station on the research farm. Volumetric soil moisture content ($m^3\ m^{-3}$) was measured daily at the weather station in the upper 5 cm of the soil (Gleysol) using an ML2x soil moisture measurement kit (Delta-T Devices Ltd). Fully screened piezometers (HDPE pipes, internal diameter 19.6 cm - Eijkelkamp, Agrisearch Equipment) were installed to a depth of 2 m in each paddock before the beginning of the experiment. Groundwater table depth (WTD; m below soil surface) was measured every week during the experiment using a geosense electric water level meter with acoustic signal (Marton Geotechnical Services Ltd). Daily weather data (rainfall, temperature, wind speed and solar radiation) was used to calculate soil moisture deficit for each day of the experiment using the model of Schulte et al. (2005) and assuming a moderately drained soil.

Time at pasture. The length of the grazing season was measured in terms of days at pasture per cow where each day was where cows were allowed access to pasture for either 22 h or 8 h. The number of days with 22 h and 8 h at pasture per cow were recorded separately. Annual time at pasture (hours per cow) was calculated for each cow based on records of days at pasture as described above. The proportion of lactating cows at pasture vs. dry cows indoors was taken into account when accounting for the annual number of days at pasture per cow and the annual number of hours at pasture per cow.

Treading damage. Soil surface deformation and hoof print depth were recorded after a grazing event in each grazing system once per week during the grazing season. Soil surface deformation ($cm\ m^{-1}$) was measured at 30 randomly selected locations across the paddock by placing a 2 m long link chain along the surface of the soil, parallel to a 2 m long straight wooden pole. The chain was fitted to the contours of the soil. Surface deformation was quantified as the reduction in chain length (cm) relative to the staff (m); reduction in chain length being proportional to higher damage. The depth of hoof prints (cm) was measured with callipers at 100 random locations across the paddock.

Herbage production, utilization and nutritive value of the sward. Before each grazing event pre-grazing herbage mass was determined by harvesting a strip (1.2 x 10 m) of herbage using an Etesia Hydro 124DS Lawnmower (Etesia UK Ltd.) set at a cutting height of 4 cm AGL. All mown herbage was collected and weighed. A 100 g (fresh weight) subsample was dried for 16 h at 90°C for determination of DM content, which was then used for determination of pre-grazing herbage mass (kg DM ha^{-1}). Herbage masses of harvests for silage were determined likewise. Herbage growth rate was calculated for each cut by dividing herbage mass by regrowth interval.

A second 100 g subsample was freeze-dried and milled through a 0.2 mm sieve before analyses for ash content (550 °C muffle furnace for 12 h), crude protein (CP; N content; Leco 528 auto-analyser, Leco Corp), neutral detergent fibre (NDF; Van Soest, 1963) and in vitro organic matter digestibility (OMD) as described by Morgan et al. (1989).

Due to potential contamination of samples during the harvesting process in wet soil conditions, ash contents during spring were higher than usual. Hence, annual herbage masses are presented as organic matter (OM) and ash contents are not presented. Total annual herbage production (t OM ha^{-1}) for each paddock was determined as the sum of herbage mass removed as pre-grazing and pre-silage cuts.

Post-grazing sward height (cm) on each system was estimated using a rising plate meter (Grasstec) approximately once per week immediately after a grazing event. Herbage mass available for grazing in each system was measured typically once per week during the grazing season. On each occasion compressed sward height was recorded on each paddock, which was converted into herbage cover, an estimate of herbage mass DM 4 cm AGL, using a sward density of 240 kg DM cm^{-1} ha^{-1}.

Feed intake and milk production. The amount of concentrate fed per cow was recorded at each milking (Dairymaster). Silage fed was measured when the cows were housed based on the difference between what was fed and discards. Intake of grazed herbage for each cow was estimated as the difference between net energy provided from silage and concentrates and the net energy requirements for milk production, maintenance and pregnancy (Jarrige et al., 1986, Jarrige, 1989, O'Mara, 1996). Requirements for activity and walking were included in requirements for maintenance as an increase of 10% for each day indoors and 20% for each day at pasture (22h and 8 h access to pasture).
Cows were milked at 0730 and 1530 h daily throughout lactation. Milk yield from each cow was recorded at each milking and milk composition was measured twice weekly from the morning and evening milking using a Milkoscan 203 (Foss Electric DK-3400). The live-weight of each cow was recorded at 2 week intervals throughout each year using a weighing scale and the Winweigh software package (Tru-Test Limited). Body condition score (Edmonson et al., 1989) of each cow was recorded at 2 week intervals throughout each year.

3.2.5. Economic analysis

Profitability of each grazing system was determined using a whole farm spreadsheet model similar to that described by Humphreys et al. (2012). The biological data of each system from each year was used taking into account the statistical analysis of the data; where there was no statistical difference between systems within a year, the mean of the systems was used in the economic analysis to ensure that differences caused by residual errors did not lead to differences in profitability. Grazing systems were compared on the basis of a farm area of 50 ha stocked at 2.5 cows ha^{-1}. Replacement heifer calves were transferred to be reared on another farm on contract at approximately three weeks of age. Dairy replacements were reared at a total cost of €947 per animal, based on a cost of €1.30 per day per animal (Teagasc, 2013a). Likewise, surplus calves were sold at approximately three weeks of age for €250 per female calf and €50 per male calf. Culled cows were sold off the farm at the end of lactation in December at €550 per cow. The dairy cow replacement rate in all systems was 21%. Silage was produced on the farm to meet winter feed requirements. Surpluses of silage were sold each year and deficits were met by purchased silage at €130 per tonne of DM. Surpluses and deficits were calculated as the difference between preserved and consumed silage per system.

Basic annual labor requirement for all systems was set as 26.7 hours per cow, the national average of spring-calving pasture-based dairy farms in Ireland (Donnellan et al., 2020). Grazing system S<7 was considered to have the lowest requirements for labor, i.e. only the basic annual labor per cow. Systems S7-6, S7-5 and CONTROL all had additional requirements for labor. For each day that cows had 8 h access to pasture and needed more management; from field to house to milking shed (compared with from field to milking shed under 22 h access to pasture) labor requirements increased by 1 hour per day. In addition, labor requirements increased by 2 hours per day for each day that cows were housed longer compared to cows in S<7 and needed more management; feeding of silage and cleaning cubicles (compared with no feeding under 22 h access to pasture). The amount of slurry produced in each grazing system was calculated based on time spend indoors, i.e. hours of the year minus annual time at pasture (hours per cow), with 0.06 m^3 slurry produced per cow per 24 hours inside (Teagasc, 2013b).

For the economic interpretation of the experimental data secondary data resources were used for input and output prices such as the Central Statistics Office of Ireland (CSO, 2020a), Teagasc National Farm Survey (Donnellan et al., 2020), Teagasc Management Data for Farm Planning (Teagasc, 2013b) and Contracting Charges Guide (FCI, 2019) (Table 3.3). Estimates for fixed costs were taken from the results of the Teagasc National Farm survey (Donnellan et al., 2020) due to unavailability of representative fixed costs for the systems. Based on per ha farm area a cost of €858 per ha was used in all grazing systems which included the costs of car, electricity, phone, interests, machinery use and depreciation, buildings maintenance and depreciation, land improvement maintenance and depreciation and other miscellaneous fixed costs such as insurance, advisory fees etc.

Table 3.3: Economic data used in the economic assessment of the four grazing systems

Item	Value
Concentrate feed (€ t^{-1})	280
Fertilizer urea (€ t^{-1})	360
Fertilizer calcium ammonium nitrate (€ t^{-1})	260
Labor (€ h^{-1})	15
Veterinary and artificial insemination (€ per cow)	90
Silage harvest (€ per bale)	20
Slurry spreading (€ h^{-1})	65
Fertilizer spreading (€ t^{-1})	37

Profitability was expressed as net profit, which was calculated as total receipts (milk, livestock) less variable (feed, fertilizer, veterinary, artificial insemination and contractor charges) and fixed costs (as outlined above). No farm subsidy payments were included in the calculation. All land was considered to be owned. Opportunity costs of land were included as the difference between the returns on the best forgone option and the returns on the chosen option. The current land rental price (€450 per ha, Coulter et al., 2020) was defined as the best forgone option. If net profit per ha (returns on chosen option) was lower than land rental price (returns on best forgone option) the difference was applied as opportunity costs. In this way, opportunity costs of land represented the cost of not choosing the better alternative.

The analysis was conducted at a base milk price of €0.29 per L with a reference content of 33 g kg^{-1} milk protein and 36 g kg^{-1} milk fat at a relative price ratio of 1:1.5 (fat:protein) in a multiple component payment system (A + B – C) (Geary et al., 2010).

3.2.6. Statistical analysis

All results were subjected to ANOVA using the 'MIXED' procedure in SAS 9.4 (SAS Institute, 2014). For analysis of annual means grazing system was a fixed effect and year and block were random effects in the ANOVA. Year was considered a random effect as the environmental conditions were assumed to vary randomly from year to year and differences in rainfall and soil moisture status between years were small. Individual paddocks were experimental units for field-based variables and individual cows were experimental units for animal-related variables.

For measurements that were calculated on a system basis year was used as the replicate: herbage mass harvested as pre-silage or pre-grazing cuts and profitability of the systems. Simple relationships between values were analysed using correlation analysis (Pearson correlation coefficient) in the 'CORR' procedure and regression analysis in the 'GLM' procedure. Means are presented as least square mean ± *SEM*

3.3. Results

3.3.1. Rainfall and soil moisture status

Soil temperatures were mainly average throughout the experiment. Only between June and September of 2013/14 soil temperatures were above average (Figure 3.1a). Annual rainfall was 1162 mm in 2013/14, 1093 mm in 2014/15 and 1320 mm in 2015/16. The mean of the previous 15-year period was 1056 mm. Rainfall in spring (March to May) of 2014/15 and 2015/16 was above the 15-year mean (263 and 233 vs. 201 mm, respectively).

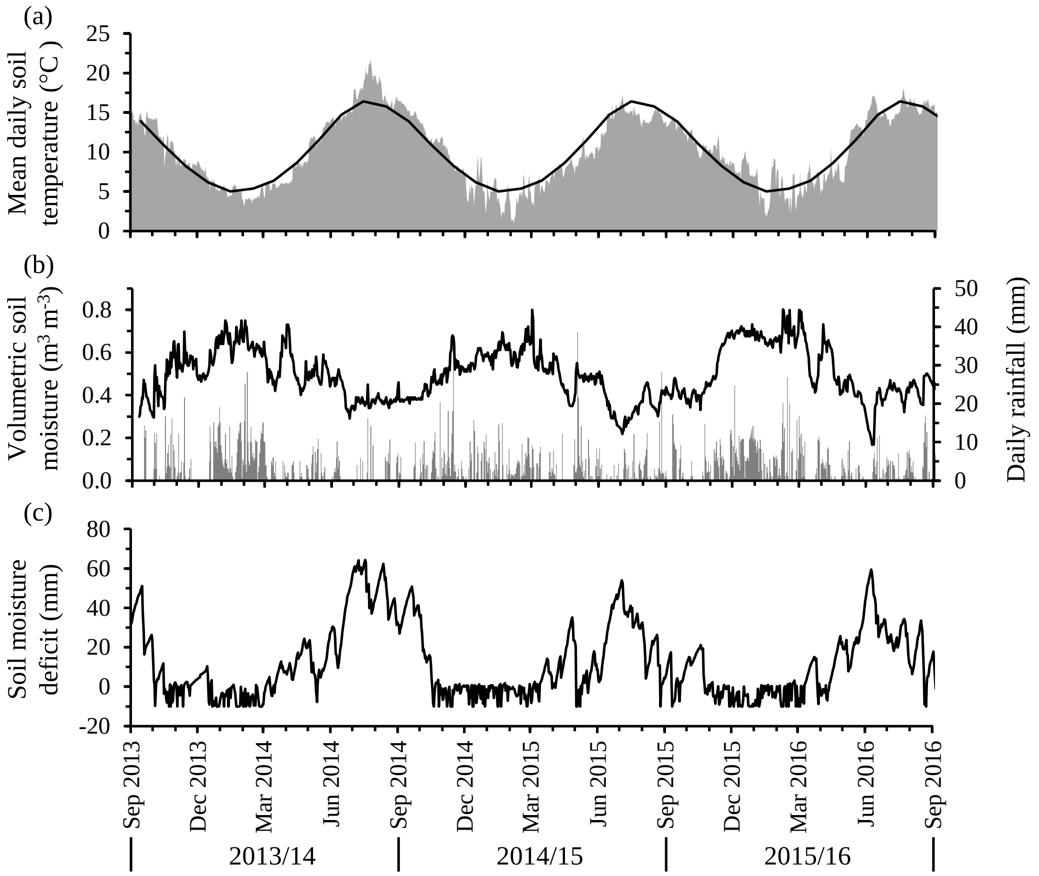

Figure 3.1: (a) Mean daily soil temperature (°C, below 10 cm soil surface) during the experimental period (grey area) compared to 15-year average (—); (b) Volumetric soil moisture content (m^3 m^{-3}, —), daily rainfall (mm, grey bars) and (c) soil moisture deficit (mm) during the experimental period.

All three experimental years had below average rainfall in summer (June to August) (154, 203 and 237 vs. 240 mm) and autumn (September to November) (241, 296 and 277 vs. 325 mm) and above average rainfall in winter (December to February) (595, 330 and 572 vs. 289 mm). During the main grazing season (April to October) VSMC only exceeded 0.6 once in April 2016. Values between 0.5 and 0.6 were measured mainly between October and the following May. Values greater than 0.7 occurred primarily between December and March and on four days in early April 2014. In 2013/14 rainfall was low during November and December resulting in a VSMC below 0.5 for 15 days in December 2013 (Figure 3.1b). Mean annual soil moisture deficit was 15, 12 and 9 mm in 2013/14, 2014/15and 2015/16, respectively. Saturated soil conditions (soil moisture deficit = -10 mm) occurred on 24, 17 and 22 days per year in each of the three experimental years, respectively (Figure 3.1c). There was a clear seasonal trend in WTD with the lowest WTD in September of each year (Figure 3.2).

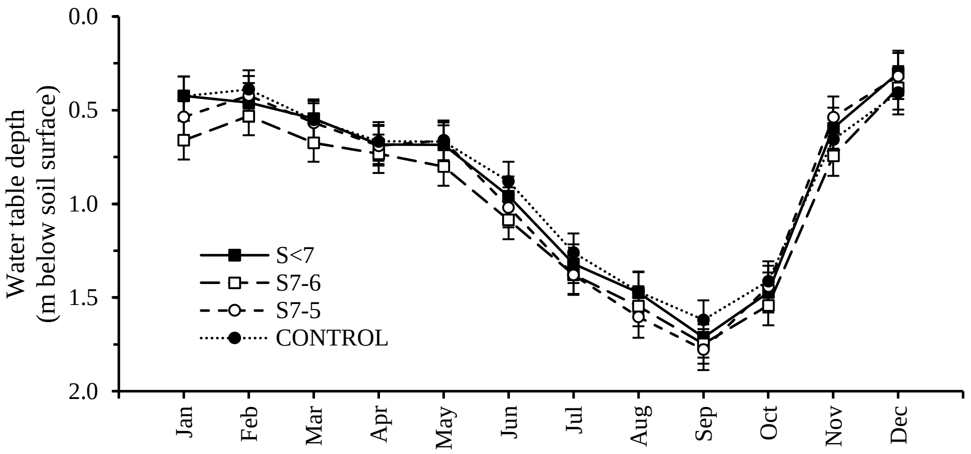

Figure 3.2: Three-year mean water table depth (m below soil surface) per month in the four grazing systems (S7, S6, S5 and S4; see Table 3.1 for a description of the grazing systems). Error bars show the standard error of the interaction between month by system mean (*P* = 0.91).

3.3.2. Time at pasture

The grazing season ended earlier and started later in CONTROL compared to the other three systems (Table 3.2). An exception was in 2013/14 when CONTROL and S7-5 were allowed out to graze due to the low VSMC during December 2013. Averaged over three experimental years cows on CONTROL spent 206 days at pasture per year, which was lower (*P* <0.001) than the cows on S<7, S7-6 and S7-5 (mean 259 days; *SEM* 1.64, which included both 22h and 8h days at pasture). The average number of days per year when cows had 8 h access to pasture was 30 on S7-6 and 51 on S7-5. Mean annual time at pasture was 5696 (S<7), 5251 (S7-6), 4980 (S7-5) and 4518 (CONTROL) h per cow (*SEM* 84.6, *P* <0.001). The difference in time at pasture between grazing systems occurred mainly between February and June and, to a lesser extent, during October and November of each grazing season (Figure 3.3).

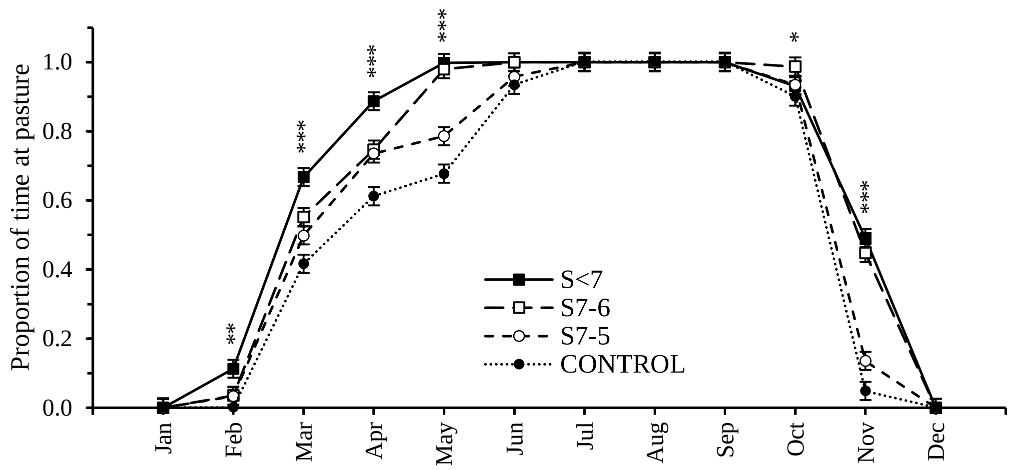

Figure 3.3: Proportion of total available time per month (22h per each day of the month) that was spent at pasture in the four grazing systems (S<7, S7-6, S7-5 and CONTROL) during the experiment (see Table 3.1 for a description of the grazing systems). Error bars show the standard error of the interaction between month by system mean (*P* <0.001). Differences between grazing systems within a month are indicated with * = *P* <0.05 ** = *P* <0.01 and *** = *P* <0.001

3.3.3. Treading damage

Grazing system affected (P <0.001) hoof print depth and soil surface deformation (Figure 3.4). There were close relationships between annual number of hours at pasture per cow and (i) mean annual hoof print depth and (ii) mean annual soil surface deformation. These relationships were improved with the addition of a quadratic term (P <0.05), indicating a declining influence of time at pasture on treading damage (Figure 3.4). Within individual grazing events in all grazing systems the strongest correlation between treading damage and soil moisture status was between VSMC and hoof print depth in spring (Table 3.4). At grazing events where VSMC was between 0.7 and 0.5 restricting access to 8 h per day lowered soil surface deformation (cm m^{-1}): 14.5 with 8 h access compared with 16.9 with 22 h access (*SEM* 0.66, P <0.01). It had no effect on hoof print depth (cm): 3.51 with 8 h access compared with 3.91 with 22 h access (*SEM* 0.20, P = 0.13).

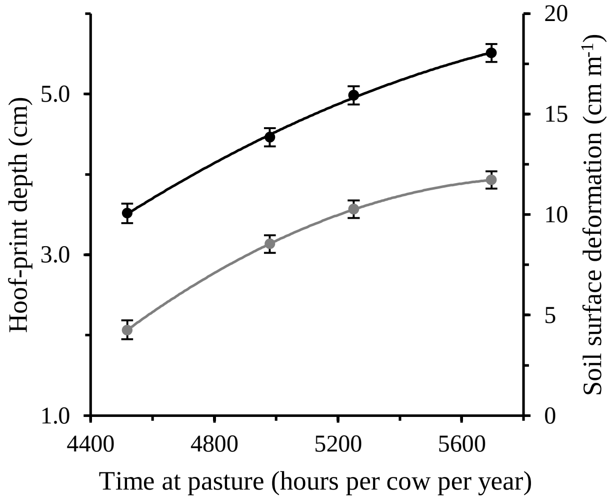

Figure 3.4: The impact of and the relationship between mean annual time at pasture per cow and mean annual (i) soil surface deformation (cm m^{-1}, black, $y = -2.41 * 10^{-6} x^2 + 0.03 x – 82.8$, R^2 = 0.99, P = 0.03) and (ii) hoof print depth (cm, grey, $y = -1.03 * 10^{-6} x^2 + 0.01 x – 31.7$, R^2 = 0.99, P = 0.003) in the four grazing systems (S<7 filled square, S7-6 empty square, S7-5 empty circle, CONTROL filled circle). Error bars show error of the grazing system mean. See Table 3.1 for a description of the grazing systems.

Table 3.4: Pearson correlation coefficient (r) between measures of treading damage (hoof print depth and soil surface deformation) and measures of soil moisture status at the time of grazing (volumetric soil moisture content (VSMC) and water table depth (WTD)) in spring (March to May), summer (June to August), autumn (September to November) and annually (year).

Measurement	Period	VSMC	WTD
Hoof print depth	spring	0.41^{**}	-0.01
	summer	-0.14	-0.29
	autumn	0.17	0.03
	year	0.27^{***}	-0.09
Soil surface deformation	spring	0.17	0.09
	summer	-0.25	-0.30
	autumn	0.20	-0.12
	year	0.15	-0.07

** P <0.01, *** P <0.001

3.3.4. Herbage production and nutritive value of the herbage

Averaged over the three years of the study annual herbage production was not affected by grazing system (mean 14.8 ± 0.97 t OM ha^{-1}, P = 0.76). In grazing system CONTROL more herbage mass was harvested for silage compared to S<7, S7-6 and S7-5 (Table 3.5).

Table 3.5: Effects of grazing system on annual herbage production and nutritive value (mean of three years)

	Grazing system[1]				
Item	S<7	S7-6	S7-5	CONTROL	*SEM*
Pre-grazing herbage mass[2] (kg DM ha^{-1})	1624	1661	1719	1765	101.1^{NS}
Post-grazing sward height (cm)	4.24	4.27	4.34	4.30	0.079^{NS}
Rotation length (days)	32.5	32.6	33.5	30.6	1.67^{NS}
Nutritive value of grazed herbage (g kg^{-1} DM)					
Crude protein	204	214	202	206	7.6^{NS}
Neutral detergent fibre	436^{a}	422^{ab}	435^{a}	419^{b}	9.5^{*}
Organic matter digestibility	793	796	803	803	6.2^{NS}
Annual herbage mass (t OM ha^{-1})					
Pre-silage cuts	3.97^{b}	4.16^{b}	3.98^{b}	5.48^{a}	0.422^{*}
Pre-grazing cuts	10.95^{a}	10.68^{a}	10.36^{a}	9.58^{b}	0.700^{*}
Total	14.91	14.84	14.34	15.07	0.970^{NS}

$^{a–b}$ Mean values in the same row with different superscripts differ between grazing systems (P <0.05).
* P <0.05, ** P <0.01, ^{NS} P >0.05
SEM = standard error of grazing system means
DM = dry matter
OM = organic matter
[1] See Table 3.1 for a description of the grazing systems
[2] 4 cm above ground level

3.3.5. Feed intake and milk production

Cows on CONTROL consumed on average 628 kg DM per cow more (*P* <0.001) silage per year compared to cows on S<7, S7-6 and S7-5, which consumed a mean of 1145 ± 51.0 kg DM per cow (Table 3.6). The difference in silage intake by CONTROL compared to the other systems was mainly during the period from January to May (400 kg DM per cow) and to a lesser extent during the period between September and December, when the difference was 217 kg DM per cow (Table 3.6). CONTROL had lower intake of grazed herbage with 2858 kg DM per cow compared with S<7 (3675), S7-6 (3643) and S7-5 (3561 kg DM per cow, *SEM* 140.7, *P* <0.001). Annual concentrate intake was not different between systems (548 ± 30.3 kg DM per cow, *P* = 0.74).

Table 3.6: Effects of grazing system on silage intake per cow during different times of the year (mean of three years)

	Grazing system[1]				
Silage intake (kg DM per cow)	S<7	S7-6	S7-5	CONTROL	*SEM*
September to December	428^b	427^b	420^b	645^a	33.3^{***}
January to May	708^b	734^b	720^b	1108^a	22.3^{***}
June to August	0^b	0^b	0^b	10^a	1.6^{***}
Total	1135^b	1159^b	1140^b	1763^a	51.0^{***}

$^{a–b}$ Mean values in the same row with different superscripts differ between grazing systems (*P* <0.05).
*** *P* <0.001
SEM = standard error of grazing system means
[1] See Table 3.1 for a description of the grazing systems

Annual milk solids production was lowest in CONTROL although annual milk yield was not different between systems (Table 3.7). Annual average milk protein content was 37.7 g kg^{-1} in CONTROL compared to a mean of 38.6 g kg^{-1} for the other systems (*P* <0.01). There was a significant interaction (*P* <0.01) between grazing system and week of lactation for daily milk and milk solids yield: both were lower in CONTROL compared with the other systems during the first 14 weeks of lactation (Figure 3.5).

Table 3.7: Effect of grazing system on three-year mean annual milk production and composition, body weight and body condition of dairy cows

	Grazing system[1]				
Item	S<7	S7-6	S7-5	CONTROL	*SEM*
Milk yield (kg per cow)	5,998	6,047	5,906	5,839	161.8^{NS}
Milk solids yield[2] (kg per cow)	503^{a}	509^{a}	496^{ab}	485^{b}	14.4^{*}
Milk fat content (g kg^{-1})	45.3	45.9	45.5	45.8	1.09^{NS}
Milk protein content (g kg^{-1})	38.8^{a}	38.5^{a}	38.6^{a}	37.7^{b}	0.33^{**}
Milk lactose content (g kg^{-1})	48.6^{ab}	48.6^{ab}	48.4^{b}	48.9^{a}	0.32^{*}
Mean body weight (kg per cow)	547	553	544	546	11.1^{NS}
Mean body condition score	3.10^{a}	3.06^{b}	3.06^{b}	3.05^{b}	0.042^{**}
Days in milk	283	283	283	282	5.9^{NS}

$^{a–b}$ Mean values in the same row with different superscripts differ between grazing systems (P <0.05).
* P <0.05, ** P <0.01, ^{NS} P >0.05
SEM = standard error of grazing system means
[1] See Table 3.1 for a description of the grazing systems
[2] Total milk solids yield = kg of milk fat + protein.

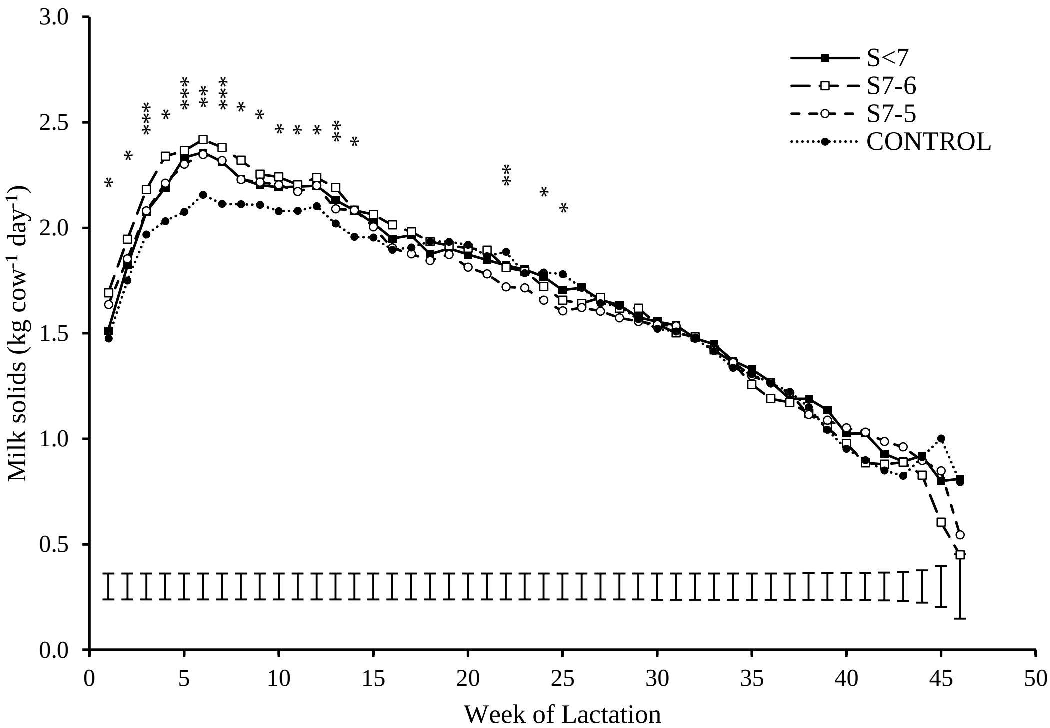

Figure 3.5: Effect of week of lactation and grazing system (S<7, S7-6, S7-5 and CONTROL) on daily milk solids (fat + protein) yield (kg per cow per day) (see Table 3.1 for a description of the grazing systems). Error bars show error of week of lactation mean (P <0.001). Differences between grazing systems within a week of lactation are indicated with * = P <0.05, ** = P <0.01 and *** = P <0.001

3.3.6. Economic analysis

The total annual requirement for labour increased from 3338 h (S<7) to 3368 h (S7-6), 3389 h (S7-5) and 3445 h (CONTROL), which is equivalent to annual labor requirements of 26.7, 26.9, 27.1 and 27.5 hours per cow, respectively. As a result, labor costs increased (*P* <0.001) with less time spent at pasture (Table 3.8).

Net profit was lowest (*P* <0.001) in CONTROL due to a combination of higher costs and lower milk sales compared to the other three grazing systems, which were not different from each other. The difference in net profit between CONTROL and S<7 comprised of lower milk sales (0.26 of the difference in net profit), higher labor costs (0.10) and higher variable costs (0.64) in CONTROL. Higher variable costs in CONTROL compared with S<7 were mainly related to silage (higher silage making costs and lower silage sales; 0.79 of the difference in variable costs) and to a lesser extent by higher slurry handling costs (0.21). Numerically higher total costs of production in S7-6 and S7-5 compared with S<7 were caused by an increase in contracting costs for slurry spreading (0.37 and 0.36) and

Table 3.8: Effect of grazing system on annual profitability at a base milk price of 0.29 € L^{-1}

	Grazing system[1]				
Item	S<7	S7-6	S7-5	CONTROL	*SEM*
Cows (no.)	125	125	125	125	
Farm size (ha)	50	50	50	50	
Milk output (kg)	741,101	741,101	741,101	741,101	2,401.3^{NS}
Milk solids[2] output (kg)	62,405^{a}	62,405^{a}	62,405^{a}	61,691^{b}	732.0***
Gross output (€)	282,734^{a}	282,734^{a}	282,734^{a}	278,721^{b}	3,097.1***
Variable cost (€)	89,239^{b}	90,040^{b}	90,527^{b}	99,134^{a}	1,389.9**
Labor cost (€)	50,063^{d}	50,508^{c}	50,823^{b}	51,653^{a}	116.2***
Fixed cost excl. Labor (€)	42,923	42,923	42,923	42,923	27.6^{NS}
Total costs (€)	182,224^{b}	183,470^{b}	184,273^{b}	193,709^{a}	1,385.7**
Net profit (€)	100,510^{a}	99,264^{a}	98,461^{a}	85,011^{b}	2,335***
Net profit (€ ha^{-1})	2,010^{a}	1,985^{a}	1,969^{a}	1,700^{b}	46.7***
Net profit (€ per cow)	804^{a}	794^{a}	788^{a}	680^{b}	18.7***

$^{a–d}$ Mean values in the same row with different superscripts differ between grazing systems (*P* <0.05).
** *P* <0.01, *** *P* <0.001, ^{NS} *P* >0.05
SEM = standard error of grazing system means
[1] See Table 3.1 for a description of the grazing systems
[2] Milk solids = kg of milk fat + protein

higher requirements for labor (0.63 and 0.64 of increase in total costs from S<7 to S7-6 and S7-5, respectively). Over the three years of the study variable costs, total costs, gross output and net profit were not significantly different between S7-5, S7-6 and S<7 (*P* <0.01, Table 3.8).

3.4. Discussion

3.4.1. Effect of soil moisture and time at pasture on treading damage

Many previous studies have shown that higher soil moisture lowers penetration resistance making soils more susceptible to treading damage by grazing dairy cows (Drewry et al., 2008, Houlbrooke et al., 2009, Kerebel et al., 2013, Phelan et al., 2013c), similar to that observed in the present study. Hoof print depth was most closely related to VSMC in spring. In spring soil moisture was relatively high. Progressively shorter rotation lengths, as herbage growth rates increase during spring, makes it a high risk period for repeated treading damage (Phelan et al., 2013c). During the autumns of the present study rainfall was below average and VSMC was relatively low compared with earlier studies at this site (Phelan et al., 2013c, Tuohy et al., 2014), which explains the lack of correlation between hoof print depth and VSMC during the autumns in the present study. Phelan et al. (2013c) reported that hoof print depth followed the same monthly trend as VSMC during the grazing season. The trend in soil surface deformation during the autumn did not follow these trends. This is somewhat similar to what was recorded in the present study.

The correlation coefficients between hoof print depth/soil surface deformation and VSMC at individual grazing events were relatively low in the present study. One factor contributing to that was the location of the VSMC measurement. It was centrally measured at the weather station of the farm and not on the individual paddock before a grazing event. There are natural variations in soil moisture between paddocks of the farm caused by slopes and differences in drainage. The objective was to test an easily adaptable decision support tool that can be stationary on farms with minimal additional management requirements. The centrally located measurement was a useful decision support for assessing the risk of treading damage when turning cows out to pasture. Governing grazing management based on VSMC effectively lowered treading damage.

Restricting access time to pasture to 8 h per day had a greater effect on soil surface deformation than on hoof print depth because it decreased the frequency of soil-hoof interactions but not the depth to which each individual hoof print penetrated into the soil. In contrast, WTD showed no correlation with soil surface deformation or with hoof print depth at individual grazing events in the present study. WTD is an indicator of the underlying moisture status of the subsoil. In late summer when WTD is typically low, slow draining soils can still develop a short duration of high VSMC in the top soil after a high rainfall event making the top layers susceptible to treading damage while not significantly increasing WTD. Phelan et al. (2013c) showed a relationship between mean annual WTD and mean annual soil surface deformation and hoof print depth in an earlier study at the site, which highlighted the relevance of land drainage in relation to susceptibility of soils to treading damage during periods with high WTD. The study of Phelan et al. (2013c) was during 2008 and 2009. The rainfall during the summer months of these two years was significantly higher than the previous 10-year average, which is in contrast to the present study. The wetter conditions might have facilitated prolonged periods of higher WTDs and more treading damage during summer which resulted in a closer relationship between soil surface deformation/hoof print depth and WTD.

Nevertheless, the results of the present study demonstrated that at individual grazing events WTD was of less usefulness as it did not directly indicate the current moisture status of, and likelihood of damage to, the top soil to the same extent as VSMC in the present study. Besides, measuring WTD involved the installation of piezometers making it a more complex and expensive measurement of soil wetness. Hence, WTD was not particularly useful as a decision support for daily grazing management in the present study.

3.4.2. Effect of grazing system on herbage production

Keeping cows indoors to a greater or lesser extent during periods of wet soil conditions in order to lower treading damage did not result in differences in total annual herbage production between grazing systems. In two plot-scale experiments in New Zealand Houlbrooke et al. (2009) compared 3 h access to pasture per rotation vs. a control treatment (access to pasture for the whole day except milking times). Likewise, Laurenson et al. (2016) compared 8 h vs. 21 h access to pasture. Both studies found that restricting access time to pasture under wet soil conditions improved soil physical properties compared with unrestricted access time. However, both studies found no impact on herbage production, which is in agreement with the results of the present study. Previous studies have shown that well managed perennial ryegrass swards can recover well from single grazing events with intensive treading damage in spring with no effect on subsequent herbage production (Tuñon et al., 2013b). Besides, soils have innate capacity to recover from treading damage during the grazing season (Drewry, 2006). Hence, it is likely that sward and soil recovery was sufficient to counteract potential negative effects of treading damage on herbage production in the present study. In the systems that had access to pasture at VSMC >0.5 (S<7, S7-6 and S7-5) there were on average two grazing events per paddock per year when VSMC was above 0.5. Hence, repeated one after the other severe treading damage during wet soil conditions may have occurred only once per paddock per grazing season. Following a modelled evaluation of economic and production benefits of removing dairy cows from wet pastures Laurenson et al. (2017) suggested that treading damage might not impact herbage production as severely when assessed at system scale over an entire grazing season. This is confirmed by the results of the present study.

There is evidence that even a light to moderate amount of treading damage may have already negatively affected pasture productivity. In the present study, treading damage occurred in all four grazing systems when VSMC was <0.5. Phelan et al. (2013c) compared herbage production under two intensities of repeated treading damage (moderate and severe) with that from plots that were protected from treading damage throughout the study. While there was higher herbage production from the protected (non-damaged) plots, there was no difference in herbage production between the treading treatments, which is in agreement with the results of the present study. The results of the present study also help to explain the absence of a difference between treatments in the study of Tuohy et al. (2014). Although hoof print depth was higher with heavier Holstein Friesian cows compared with lighter Holstein Friesian x Jersey cross bred cows, there was no effect of the lower intensity of treading damage on herbage production (Tuohy et al., 2014).

During the grazing season VSMC values >0.7 typically occur only occasionally (on average 10 days per grazing season between February and December in the years of the present study). Allowing cows out to pasture up to VSMC 0.7 encompassed almost the entire growing season. However, the results indicate that the severity of treading damage observed was not detrimental to herbage production in the present study. Using VSMC of 0.7 as an upper limit in the three grazing systems with medium to high risk of treading (S<7, S7-6 and S7-5) may have avoided excessive damage. Hence, the result of this study indicate that grazing with dairy cows may be possible even above the upper limit of 0.7 VSMC tested in the present study. Further research is required to determine if there is a 'tipping point' above which treading damage is detrimental to herbage production.

3.4.3. Effect of grazing system on feed intake, milk production and profitability

Operating a grazing system with high risk of treading damage (S<7), i.e. keeping cows at pasture up to VSMC 0.7, resulted in more time at pasture, a lower proportion of silage in the diet, higher body condition score, higher milk protein content and higher annual milk solids production compared to a grazing system with low risk of treading damage (CONTROL). Similarly, other studies have found that replacement of grazed herbage with silage in the diet negatively affects milk protein content, especially if the silage is fed during early lactation (Dillon et al., 2002, Kennedy et al., 2005, Claffey et al., 2020). A higher proportion of silage in the diet also increased costs of production in pasture-based systems (Finneran et al., 2012a, Hanrahan et al., 2018). Hence, in the present study, net profit was lowest in CONTROL due to a combination of higher costs and lower milk sales. Laurenson et al. (2016) modelled the impact of restricting access of dairy cows to pasture and reported higher costs when cows were taken off compared with turned out to pasture during wet soil conditions. The difference was primarily due to higher feed costs. Operational costs of stand-off areas (maintenance and slurry handling) were of less importance. This is similar to the results of the present study where 0.50 of the total difference in net profit between CONTROL and S<7 was caused by higher silage related costs alone. In contrast, the contribution of higher slurry handling costs to the lower net profit of CONTROL compared with S<7 was marginal (0.14). Lower milk sales (0.26) and higher labor costs (0.10) accounted for the remainder of the lower net profit.

Restricting daily access time to pasture to 8 h did not result in higher silage intake compared to when cows had 22 h access to pasture. The decrease in grazed herbage intake from S<7 to S7-5 was minimal. As a result, milk production was maintained in both systems with restricted daily access (S7-6 and S7-5) compared to the system with 22 h access up to VSMC of 0.7 (S<7) in the present study. Previous studies have documented that dairy cows can adapt their grazing behaviour in response to restricted daily grazing time with no decrease in grazed herbage intake when daily access to pasture was similar to that in the present study; i.e. two grazing bouts of four hours each (Gregorini et al., 2009, Kennedy et al., 2009, Clark et al., 2010). There were no improvements in herbage and milk production by restricting daily access time to 8 h. S7-5 and S7-6 were numerically less profitable than S<7, due to higher labor and slurry related costs. However, the difference in net profitability was not significant over the three years of the study.

With higher intake of grazed herbage and lower feed costs both S7-5 and S7-6 were more profitable than CONTROL. Similarly, Beukes et al. (2013) concluded in a modelling study that six to eight hours access to pasture per day under conditions conducive to treading damage was more profitable than keeping cows indoors completely. The two main differences between the present study and previous modelling studies of whole farm scenarios (Beukes et al., 2013, Laurenson et al., 2016, Laurenson et al., 2017) are that (i) previous studies were using a modelling approach with an assumed decreasing herbage production as a function of stocking density and access time to pasture when animals were turned out during wet soil conditions and (ii) capital costs increased when cows were taken off during wet soils conditions (completely or temporarily). However, the above studies were conducted in New Zealand under the premise that stand-off facilities had to be purpose-built for holding cows off pasture. Generally, these studies concluded that potential benefits associated with removing cows from pastures during wet soils conditions completely or temporarily were offset by investment costs in stand-off facilities. Under Irish conditions it is typically the case that housing facilities are available for livestock on dairy farms along with regulated requirements for minimum slurry storage capacity for the winter period. Hence, there was no need for additional capital investment in the present study.

Laurenson et al. (2016) concluded that a deferred grazing management strategy, similar to CONTROL in the present study, was not economically viable in New Zealand. In contrast, CONTROL in the present study represented a profitable system of dairy production albeit less profitable than the other options. Over the three years of the study, there was no significant difference in net profit when cows had a restricted daily access time to pasture of 8 h compared to when cows had 22 h access to pasture. Furthermore, restricted daily access time to pasture increased the complexity of grazing management. Previous studies indicated that restricting daily access time to pasture can have other benefits such as decreasing nutrient leaching and manure-derived emissions as a higher proportion of the excreta is captured and can subsequently be mechanically spread more evenly across pastures (Clark et al., 2010, van der Weerden et al., 2017, Christensen et al., 2019).

3.5. Conclusion

A centrally located measurement of VSMC was used to ascertain the risk of treading damage in advance of turning cows out to pasture. Treading damage increased with higher VSMC. Restricting access time to pasture based on VSMC effectively lowered the severity of treading damage and, hence, measurement of VSMC provided an objective indicator of the risk of treading damage in this study. However, operating a grazing system with low risk of treading damage (CONTROL) resulted in a lower value of milk sales and higher costs associated with keeping cows indoors and, hence, lower profit. Restricting access time to 8h per day (S7-6 and S7-5) maintained similar milk sales to 22 h per day while also marginally increasing the costs of production. However, as there were no benefits of keeping cows indoors completely or temporarily during periods with VSMC between 0.5 and 0.7, the grazing system with the highest risk of treading damage (S<7) generated the highest net profit in the present study. The results of the present study indicate that the degree of plastic deformation incurred within a whole farm system is not necessarily aligned with herbage production or with profitability, because treading damage happened only to small proportions of paddocks on the farm at any one time. This study demonstrated the positive effect of a long grazing season on profitability albeit when a high degree of treading damage was tolerated at the soil surface over the course of the three grazing seasons.

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Chapter 4 The effect of grazing platform stocking rate on the productivity and profitability of pasture-based dairying in a fragmented farm scenario

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Abstract

Farm area fragmentation limits the availability of grazing land adjacent to the milking parlour; i.e. the grazing platform (GP), the size of which can determine the extent of pasture-based milk production. A fragmented farm with a moderate overall farm stocking rate typically has a much higher stocking rate of dairy cows on the grazing platform (GPSR). This study quantified the impacts of farm fragmentation on the productivity and profitability of pasture-based systems where a higher GPSR is supplemented with silage produced on non-GP parcels of the farm. A three year (2017 to 2019) whole-farm systems study with four grazing systems was conducted at Solohead Research Farm in Ireland (52˚51'N, 08˚21'W). Each system had an overall stocking rate of 2.5 cows ha^{-1} but different proportions of area available as GP (100%, 83%, 71% and 63%) resulting in four different GPSRs of 2.5, 3.0, 3.5, and 4.0 cows ha^{-1}. The GP area was available for grazing and silage (ensiled herbage) production and non-GP parcels solely for silage production. All systems were compact spring-calving with 24 cows per system. The data from the systems study was used to model the economic implications of altering GPSR on fragmented farms in two scenarios: Scenario 1 quantified the cost associated with different extents of farm area fragmentation. Scenario 2 investigated the optimum GPSR on pasture-based dairy farms depending on variable criteria. Annual herbage production was not different between GPSRs (15.4 t DM ha^{-1}, *SEM* 0.82, $P = 0.94$). Likewise there was no difference in annual milk production per cow (5916 kg per cow, *SEM* 159.7, $P = 0.4$) albeit with a higher proportion of silage and a lower proportion of grazed herbage in the diet with higher GPSR ($P < 0.001$). Milk output per ha of GP increased linearly with increasing GPSR. All feed produced on outside parcels was required to support higher GPSR resulting in similar milk production per ha of the overall system area. Costs of production increased with smaller area of GP and longer distances between GP and non-

GP parcels (scenario 1). At a fixed GP size (scenario 2), the profitability of increasing GPSR was mainly determined by external factors. It was most profitable to increase to 4 cows ha^{-1} on the GP when milk price was high (base price of €0.34 L^{-1}), land rental price was low (€300 ha^{-1}) and the distance between GP and non-GP parcels was short (2 km). A greater extent of farm fragmentation lowered the profitability of pasture-based dairy production. Nevertheless, it was possible to achieve an acceptable farm income from dairy production on fragmented farms by optimising GPSR depending on the extent of fragmentation, milk and land prices and distance between parcels.

4.1. Introduction

It is a common feature of many farms across the world that they are fragmented into more than one parcel of land (del Corral et al., 2011, Lu et al., 2018, Holohan et al., 2021). In Ireland, the majority of farms are fragmented, with an average of 3.8 parcels per farm (CSO, 2012). A recent analysis has shown that Irish dairy farms, in particular, are subject to a greater extent of fragmentation with an average of six parcels per farm (Bradfield et al., 2020). The grazing platform (GP) is the parcel of land adjacent to the milking parlour and accessible by grazing dairy cows. On average the GP represented 42% of the total farm area (Bradfield et al., 2020).

In traditional pasture-based systems in higher latitudes the calving date and feed demand of the lactating dairy herd is synchronized to coincide with the period of herbage growth. The farm stocking rate is set at a level that matches the herbage production potential of the farm (Roche et al., 2017). Ideally, sufficient herbage for grazing by lactating cows is available during the main grazing season with minimal inputs of purchased supplements. Surplus herbage mass in mid-season is harvested and stored to meet winter feed requirements (Dillon et al., 2005). Hence, pasture-based systems are typically almost self-sufficient in home-produced feed. Such systems tend to be the most profitable because they include a high proportion of low cost grazed herbage in the diet (Finneran et al., 2012a, Hanrahan et al., 2018, Ruelle et al., 2018).

On fragmented farms all lactating dairy cows tend to be concentrated on the GP, which means that the stocking rate on the grazing platform (GPSR) is typically much higher than the overall farm stocking rate. High GPSR results in high daily feed demand per ha for grazed herbage, which can exceed daily herbage accumulation (growth) rates particularly during the spring and autumn. Furthermore, farm fragmentation reduces efficiency and increases costs of production in both confined and pasture-based system due to increased travel times between parcels and reduced machinery and labor efficiency (del Corral et al., 2011, Latruffe and Piet, 2014, Bradfield et al., 2020).

The abolition of the EU milk quota led to an increase in milk output in many European countries. In Ireland milk production increased by + 47% between 2014 and 2020, mainly driven by an increase in dairy cow numbers and stocking rates on farms (Läpple and Sirr, 2019, CSO, 2021). Hence, the area of the GP and the stocking rate that can be sustained on it becomes an increasingly important constraint on further expansion of pasture-based dairy production (Dillon et al., 2006, Läpple and Hennessy, 2012, Ramsbottom et al., 2015).

Several previous studies have highlighted the importance of stocking rates for the productivity and profitability of pasture-based systems. Higher stocking rates can increase herbage utilisation and milk output per unit of land area but can decrease milk production per cow (Macdonald et al., 2008, McCarthy et al., 2011, McCarthy et al., 2014). Higher stocking rates can also mean a shorter grazing season where feed deficits on the GP increases the requirements for alternative feed such as silage (Macdonald et al., 2008, Patton et al., 2016). A lower proportion of grazed herbage in the diet and an increase in the quantity of silage fed to cows can impact negatively on milk production per cow (Dillon et al., 2002, Claffey et al., 2019) and increase costs of production (Finneran et al., 2012a, Hanrahan et al., 2018).

Despite its critical importance, few studies have quantified the impacts of higher GPSR on fragmented pasture-based farms. High occurrence of farm fragmentation in Ireland and the trend towards higher GPSR require an economic evaluation comparing costs and benefits of increasing GPSR. On Irish dairy farms non-GP parcels are typically used for rearing of replacement heifers and beef cattle but tend to be under-utilized with considerable potential to increase pasture productivity (O'Donnell et al., 2008). In order to maximise milk production from home-produced feed, non-GP parcels could act as support block producing conserved feed for the dairy herd to support higher GPSR. The overall objective of this study was to determine the optimum GPSR of fragmented pasture-based dairy farms within a system designed to maximise the utilization of home-produced feed. This involved determining how GPSR affects herbage production, the length of the grazing season and milk production where silage produced on non-GP parcels is incorporated into the diet of lactating dairy cows to fill feed deficits during the grazing season. The key question to be addressed by this study was to determine if a point exists where the benefits of higher milk output from the GP are counterbalanced by negative impacts and increased costs associated with farm fragmentation.

4.2. Materials and Methods

4.2.1. Site description

The experiment was conducted at Solohead Research Farm (52˚30’N, 08˚12’W, 95 m above sea level) in south-west Ireland. Soils at the farm include poorly drained Gleysols (90%) and Podzols (10%) with a clay loam texture (FAO, 2015). Topographic relief causes variation in shallow groundwater with the water table depth ranging from 0 to 2.2 m below ground level. Much of the farm area is seasonally wet, waterlogged or flooded. The local climate is humid temperate oceanic with a long potential growing season (~10 months). The land has been under permanent grassland with predominantly perennial ryegrass and white clover swards for well over 50 years and approximately 5% of the grassland was renovated each year.

4.2.2. Experimental systems, setup and design

The experiment was carried out over three consecutive years from 2017 to 2019. Four grazing systems were established each containing one herd of 24 spring-calving dairy cows at an overall stocking rate of 2.5 cows ha^{-1}. Differing proportions of the farm area were available as GP for each system resulting in four different GPSRs of 2.5 (GP2.5), 3.0 (GP3.0), 3.5 (GP3.5) and 4.0 (GP4.0) cows ha^{-1} (Table 4.1). The remaining area of each system was non-GP parcels, which were not accessible for grazing dairy cows. Thus, the GP area was available for grazing and silage (ensiled herbage) production whereas the non-GP parcels were used solely for silage production.

All four herds were compact spring-calving with a mean calving date of 21 February; a mixture of Irish Holstein and Jersey cross cows. Each spring all cows were divided into four main groups based on lactation number (1, 2, 3, and ≥ 4) and then sub-divided into subgroups of four on the basis of calving date. One cow from each sub-group was randomly assigned to each herd. Herds were randomly assigned to each GPSR. The experimental area was divided into six blocks based on soil type and drainage status before the beginning of the experiment. Each block was divided into four paddocks. One paddock from each block was randomly assigned to each GPSR, resulting in six paddocks per system (9.75 ha per system). In the fragmented systems (GP <100%) paddocks were randomly assigned to either GP or non-GP parcels resulting in following number of paddocks on the GP per system: 6 (GP2.5); 5 (GP3.0); 5 (GP3.5); 4 (GP4.0).

Table 4.1: Overall system stocking rates and grazing platform stocking rates of the four grazing systems

	GP2.5	GP3.0	GP3.5	GP4.0
Overall system stocking rate (cows ha^{-1})	2.5	2.5	2.5	2.5
Overall system area available as grazing platform (%)	100	83	71	63
Grazing platform stocking rate (cows ha^{-1})	2.47	3.01	3.52	4.02

4.2.3. Management of the grazing systems

All GPSRs were managed according to the same grazing and cow management guidelines in a whole farm system approach with equitable management rules to remove bias towards one GPSR or another (Macdonald and Penno, 1998). Cows were turned out to pasture approximately three days after calving and dried off in late November and December. Herbage cover was measured in all paddocks on a weekly basis using a Filips rising plate meter (Grasstec, Mallow, Cork, Ireland) to estimate weekly herbage growth. Strip grazing with temporary fencing was practiced in all GPSRs. Each herd was moved to the next strip when a post-grazing sward height, measured with a rising plate meter, of 4 cm was reached. The grazing management decision rules were based on matching daily herbage allowance per herd with herbage growth rate and on the principle of maximizing grazed herbage in the diet. Stocking density on the GP in each system was adjusted on a weekly basis in line with herbage growth rates and a daily allowance of 16 kg DM per cow per day. Herbage cover on each GPSR was managed during the main grazing season (April to August) to set up a feed wedge with a pre-grazing herbage mass of between 1400 and 1600 kg DM ha^{-1}, with an average herbage cover per ha on the area in the grazing rotation in that week of 700 to 800 kg DM ha^{-1}.

Approximately 95% of the feed (grazed and ensiled herbage) was produced within the system boundary (overall system area). A combination of silage and concentrates was fed in the early spring and late autumn while targeting a maximum mean concentrate input of 5% of the feed budget. In early lactation (February to April) cows received up to 6 kg concentrate per cow per day depending on herbage mass available on the grazing area. During the rest of the grazing season (from May onwards) between 0 to 6 kg concentrate per cow per day was fed depending on availability of herbage mass for grazing. Concentrate supplementation was used only when a feed deficit occurred in all GPSRs and concentrate supplementation per cow was the same across all GPSRs. Feed deficits in individual GPSRs were filled by feeding silage.

During the grazing season cows were housed when ground conditions were too wet (vol. soil moisture >60%) or when herbage mass was too low to sustain herd demand, which occurred when herbage growth rates were below herd demand and pre-grazing herbage mass was <1000 kg DM ha^{-1} (measured to 4 cm above ground level (AGL)). Under such circumstances cows were housed either at night only or day and night and received silage *ad libitum*, which was occasionally supplemented with concentrates according to the feed budget for each herd (see below). Cows turned out to pasture full-time were allocated no silage. Mean composition of silage fed to dry cows during the experiment (± *SD*) was 86

± 12.2 g kg^{-1} ash, 666 ± 45.3 g kg^{-1} DM digestibility, 129± 15.0 g kg^{-1} crude protein (CP) and 0.73 ± 0.05 unité fourragère lait (UFL; Jarrige, 1989). Mean composition of silage fed to lactating cows was 88 ± 11.5 g/kg ash, 712 ± 44.9 g/kg DM digestibility, 146 ± 24.1 g/kg crude protein and 0.80 ± 0.06 UFL. Energy content of the concentrate feed (35% beet pulp, 26% barley, 26% maize gluten and 12% soybean meal) was 0.95 UFL.

Additional to the management rules outlined above, the end of the grazing season (cows housed for the winter) was determined by an average herbage mass of 500 kg DM ha^{-1} across all the paddocks in each GPSR. Between August and the end of the grazing season, silage was introduced to the diets of cows at higher GPSR depending on the weekly feed budget in order to maintain a similar herbage cover per system per week during this timeframe and a similar closing herbage cover in all GPSRs at the end of the grazing season. This approach maintained at least some grazed herbage in the diet of each herd during the autumn and early winter. Furthermore, there were similar herbage covers in all GPSRs during the closed period over the winter. These management decisions were also influenced by rainfall and soil VSMC as outlined above.

Excess herbage mass on the GP of each GPSR was identified and removed as silage throughout the grazing season. This was generally the case when herbage growth rate was substantially higher than feed demand of the grazing herd resulting in pre-grazing herbage masses >1600 kg DM ha^{-1} between April and July and >2000 kg DM ha^{-1} from August onwards. On the non-GP parcels, silage was harvested three times per year (mid-May, Mid-July and end of August) and residual herbage mass was zero-grazed between October and November (fresh cut herbage fed to housed cows). Mean composition of zero-grazed herbage fed during the experiment (± *SD*) was 114 ± 15.4 g kg^{-1} ash, 822 ± 40.1 g kg^{-1} organic matter digestibility (OMD) and 224 ± 33.5 g kg^{-1} CP. Each GPSR received an annual nitrogen input of 280 kg N ha^{-1} in form of mineral fertilizer. Mineral fertilizer was applied in form of urea from February to April (0.35) and in form of Calcium Ammonium Nitrate from May to September (0.65), evenly distributed at monthly intervals. On average, each GPSR received an annual input of 65 kg N ha^{-1} in form of cattle slurry across all paddocks. In the fragmented systems the annual proportion of total cattle slurry applied to non-GP parcels was 0.41 (GP3.0), 0.56 (GP3.5) and 0.65 (GP4.0).

4.2.4. Measurements

Meteorological data. Soil temperature (°C; at soil depth of 10 cm), rainfall (mm), wind speed (m s^{-1}) and direction (°) and solar radiation (J cm^{-1}) was measured at an automated weather station on the research farm. Volumetric soil moisture content (m^3 m^{-3}) was measured daily at the weather station in the upper 5 cm of the soil using an ML2x soil moisture measurement kit (Delta-T Devices Ltd, Burwell, Cambridge, UK).

Herbage production, utilization and nutritive value of the sward. Exclusion plots (13 x 3 m) surrounded by electrified wire were set up in each GP paddock. Plots were moved two times per year to an adjacent area in the paddock. Before each grazing event pre-grazing herbage mass was determined by harvesting two strips (1.2 x 10 m) of herbage using an Etesia Hydro 124DS Lawnmower (Etesia UK Ltd., Shenington, Oxon, UK) set at a cutting height of 4 cm AGL. One strip from inside the exclusion plot and one from outside, adjacent to the exclusion plot. All mown herbage from each strip was collected and weighed. A 100 g (fresh weight) subsample from each strip was taken and dried for 16 h at 90°C for determination of DM content, which was then used for determination of pre-grazing herbage mass (kg DM ha^{-1}). Herbage masses of harvests for silage were determined likewise. Total annual herbage production for each paddock was determined as the sum of herbage mass removed as pre-grazing and pre-silage cuts from inside the exclusion plot. Herbage growth rate was calculated for each cut by dividing herbage mass by regrowth interval. The production of herbage harvested for silage on non-GP parcels was determined likewise. A 100 g sub-sample of herbage from the strip cut outside of the exclusion plot the was freeze-dried and milled through a 0.2 mm sieve before analyses for ash content (550 °C muffle furnace for 12 h), CP (N content; Leco 528 auto-analyser, Leco Corp., St. Joseph, MI, USA), neutral detergent fibre (NDF; Van Soest, 1963) and in vitro OMD as described by Morgan et al. (1989). Silage fed was randomly sampled throughout the experiment by taking a grab sample of approximately 100 g before feeding which was then analyzed for ash, OMD, and CP using near infrared spectroscopy (model 6500, Foss-NIR System, Hillerød, Denmark). Post-grazing sward height (cm) on each paddock was determined immediately after a grazing event throughout the grazing season using a rising plate meter. Herbage mass available for grazing in each GPSR was measured typically once per week during the grazing season. On each occasion, compressed sward height was recorded on each paddock, which was converted into herbage cover, an estimate of herbage mass DM 4 cm AGL, using a sward density of 240 kg DM cm^{-1} ha^{-1}.

Days at pasture. The length of the grazing season was measured in terms of days at pasture per cow. One day at pasture was defined as when all cows per system were out day and night and one-half day when cows were out only by day. Only lactating cows were allowed out to pasture while non-lactating cows were kept indoors before calving in spring and after the end of lactation. This was taken into account when accounting for the annual number of days at pasture per cow.

Feed intake, milk production, body weight and condition score. The amount of concentrate fed per cow was recorded at each milking (Dairymaster, Causeway, Co. Kerry, Ireland). Silage fed was measured when the cows were housed based on the difference between what was fed and discards. Intake of grazed herbage for each cow was estimated as the difference between net energy provided from silage and concentrates and the net energy requirements for milk production, maintenance and pregnancy (Jarrige et al., 1986, Jarrige, 1989, O'Mara, 1996). Requirements for activity and walking were included in requirements for maintenance as an increase of 10% for each day indoors and 20% for each day at pasture.

Cows were milked at 0730 and 1530 h daily throughout lactation. Milk yield from each cow was recorded at each milking and milk composition was measured twice weekly from the morning and evening milking using a Milkoscan 203 (Foss Electric DK-3400, Hillerød, Denmark). The live-weight of each cow was recorded at 2 week intervals using a weighing scale and the Winweigh software package (Tru-Test Limited, Auckland, New Zealand). Body condition score (Edmonson et al., 1989) of each cow was recorded at 2 week intervals throughout each year.

4.2.5. Statistical analysis

The effect of GPSR on herbage and milk production variables was determined using a mixed model with GPSR as a fixed effect and year and block as random effects in an ANOVA using the 'MIXED' procedure in SAS 9.4 (SAS Institute, 2014). Individual paddocks were considered as the experimental units for field based variables and individual cows were considered as the experimental units for animal related variables. Year was used as the replicate for measurements that were calculated on a system basis:

herbage mass harvested as pre-silage or pre-grazing cuts; monthly stocking densities on the GP when removal of silage areas were accounted for; proportion of GP area harvested for silage. Linear and quadratic effects of GPSR were also evaluated in a general linear model by including GPSR as a continuous variable in the 'GLM' procedure in SAS. Means are presented as least square means ± *SEM*

4.2.6. Economic analysis

To fully investigate the different aspects and economic implications of farm area fragmentation and altering GPSR on pasture-based dairy farms a two-step farm modelling approach was employed. Hence, two scenarios were created: Scenario 1 quantified the cost associated with different degrees of farm area fragmentation. Scenario 2 was designed to identify the optimum GPSR on pasture-based dairy farms at a fixed degree of fragmentation.

Scenario 1. This scenario was based on the design of the systems experiment in the present study with the proportion of overall system area available as grazing platform in the four GPSRs as described in Table 4.1. Overall farm area (50 ha) and herd size (125 cows) were fixed across all modelled GPSR (2.5, 3.0, 3.5 and 4.0 cows ha^{-1}). Profitability of each GPSR was determined using a whole farm spreadsheet model similar to that described by Humphreys et al. (2012). The three-year mean of the biological data of each GPSR was used taking into account the statistical analysis of the experimental data; where there was no statistical difference between GPSRs, the mean of the GPSRs was used in the economic model to ensure that differences caused by residual errors did not lead to differences in profitability. Where there was a significant linear relationship between a variable and GPSR, the regression estimates where used to calculate the variable for each GPSR step in the economic model.

Replacement heifer calves were transferred to be reared on another farm on contract at approximately three weeks of age. Dairy replacements were reared at a total cost of €947 per animal, based on a cost of €1.30 per day per animal (Teagasc, 2013a). Likewise, surplus calves were sold at approximately three weeks of age for €250 per female calf and €50 per male calf. Culled cows were sold off the farm at the end of lactation in December at €550 per animal. The dairy cow replacement rate in all GPSRs was 21%. Silage was produced on the GP and, where applicable, on non-GP parcels to meet winter feed requirements. Surpluses of silage were sold each year and deficits were met by purchased silage at €130 per tonne of DM. Surpluses and deficits were calculated as the difference between preserved and consumed silage per system.

Basic annual labor requirement for all GPSRs was set as 26.7 hours per cow per year, the national average of spring-calving pasture-based dairy farms in Ireland (Donnellan et al., 2020). Labor requirements were assumed to be higher in systems where cows spent more time indoors and needed more management; feeding of silage and cleaning cubicles (compared with no feeding while at pasture). Hence, labor requirements increased by 2 hours per day for each day that cows were housed longer relative to the system with the highest number of days at pasture (GP2.5). The amount of slurry produced was calculated for each GPSR based on days housed with 0.06 m^3 slurry produced per cow per day spent indoors.

For the economic interpretation secondary data resources were used for input and output prices such as the Central Statistics Office of Ireland (CSO, 2020a), Teagasc National Farm Survey (Donnellan et al., 2020), Teagasc Management Data for Farm Planning (Teagasc, 2013b) and Contracting Charges Guide (FCI, 2019) (Table 4.2). Costs of contracting charges were assumed to increase with increasing distance between GP and non-GP parcels. Hourly rates for the transport of slurry, silage and zero-grazed herbage (Table 4.2) were included in the calculation at a travel speed of 25 km h^{-1}. To quantify the impact of varying distance between GP and non-GP parcels a sensitivity analysis at 2, 10 and 20 km distance was carried out.

Table 4.2: Economic data used in the profitability analysis

Item	Value
Concentrate feed (€ t^{-1})	280
Fertilizer urea (€ t^{-1})	360
Fertilizer calcium ammonium nitrate (€ t^{-1})	260
Labor (€ h^{-1})	15
Veterinary and artificial insemination (€ per cow)	90
Silage harvest (€ per bale)	20
Silage transport[1] (€ h^{-1})	63
Slurry spreading and transport (€ h^{-1})	65
Zero-grazing (€ per load[2])	65
Fertilizer spreading (€ t^{-1})	37

[1] with 17 bales per load
[2] at 1.2 t of DM per load

Estimates for fixed costs were taken from the results of the Teagasc National Farm survey (Donnellan et al., 2020), due to unavailability of representative fixed costs for the systems. Based on per ha of overall farm area, a cost of €858 per ha was used in all GPSRs, which included the costs of car, electricity, phone, interests, machinery use and depreciation, buildings maintenance and depreciation, land improvement maintenance and depreciation and other miscellaneous fixed costs such as insurance, advisory fees etc. Profitability was expressed as net profit, which was calculated as total receipts (milk, livestock) less variable (feed, fertilizer, veterinary, artificial insemination and contractor charges) and fixed costs (as outlined above). No farm subsidy payments were included in the calculation. All land was considered to be owned. Opportunity costs of land were included as the difference between the returns on the best forgone option and the returns on the chosen option. The current land rental price (€450 per ha, Coulter et al., 2020) was defined as the best forgone option. If net profit per ha (returns on chosen option) was lower than income from land rental (returns on best forgone option) the difference was applied as opportunity costs. In this way, opportunity costs of land represented the cost of not choosing the better alternative; in this instance renting out the land for a higher profit per ha compared to that generated by milk production. The analysis was conducted at a base milk price of €0.29 L^{-1} with a reference content of 33 g kg^{-1} milk protein and 36 g kg^{-1} milk fat at a relative price ratio of 1:1.5 (fat:protein) in a multiple component payment system (A + B – C, Geary et al., 2010)

Scenario 2. This scenario tested the effect of increasing GPSR on a farm with a fixed degree of fragmentation/GP size to evaluate the extent to which higher costs associated with farm area fragmentation were counterbalanced by higher milk outputs associated with a higher number of dairy cows. Fragmentation was fixed at 63% of the farm area available as GP (31 ha GP) in all four GPSR systems. Herd size was dictated by GPSR and increased from 78 cows (GP2.5) to 125 cows (GP4.0) per farm. Overall farm stocking rate on all GPSRs was 2.5 cows ha^{-1}. The remaining land on non-GP parcels was rented out.

Profitability in scenario 2 was calculated in the same manner as for scenario 1 with following additions: (i) there was income generated from land rental where applicable; (ii) the costs for electricity were assumed to increase with higher cow numbers due to operating milking machines etc. and were calculated at a rate of 1.15 cent L^{-1} of milk produced; (iii) increasing herd size incurred costs for expansion in form of additional animals, new buildings and associated interest costs. GP2.5 served as the baseline for the calculation of expansion costs. Requirements for additional dairy cows compared to the baseline were filled by rearing additional replacements or a combination of additional replacements and in-calf dairy heifers purchased at €1200 per animal where there was not a sufficient number of replacement heifer calves born on the farm. The total annual costs for additional animals consisted of the net present value of the animals (value of animal minus value of culled cow divided by a lifetime period of 5 years; Schulz and Gunn, 2016) and annual interest cost for a loan for the total costs of additional animals (annual interest rate of 6.45% and loan repayment period of 5 years; UlsterBank, 2021). Total costs for new buildings (winter housing incl. slurry storage, additional silage storage space, milking parlour extension, larger milk tank, expansion of farm road infrastructure, paddock water system and fencing) were calculated at €4500 per additional cow. Annual costs for new buildings consisted of annual depreciation for the total value of the new buildings over a period of 20 years and annual interest cost for a loan for the total costs of new buildings (annual interest rate of 4.2% and loan repayment period of 15 years; UlsterBank, 2021). The marginal benefit per cow was the additional benefit in net profit per farm that arose from an increase in the number of cows and was calculated as the additional net profit per farm compared to the lower GPSR step divided by the additional number of dairy cows per farm compared to the lower GPSR step.

Similar to scenario 1 the impact of distance between GP and non-GP parcels was evaluated in a sensitivity analysis. To further investigate the impact of varying land rental and base milk prices a sensitivity analysis was carried out across three different land rental prices (€300, €450 and €600 ha^{-1}) and three different base milk prices (€0.24, €0.29 and €0.34 L^{-1}). Linear and quadratic effects of GPSR on profitability were evaluated in a general linear model by including GPSR as a continuous variable in the 'GLM' procedure in SAS.

4.3. Results

4.3.1. Meteorological data and grazing season

Relatively high rainfall in February and March in 2017 (Figure 4.1a) resulted in a relatively late turnout date at the start of the grazing season with no difference in turnout dates between GPSRs in 2017 (Table 4.3). In contrast, the exceptionally mild winter of 2018/19 (Figure 4.1b) caused a much earlier turnout date with no difference between GPSRs in 2019. The turnout date in 2018 differed between GPSRs with later turnout dates at higher GPSR (Table 4.3).

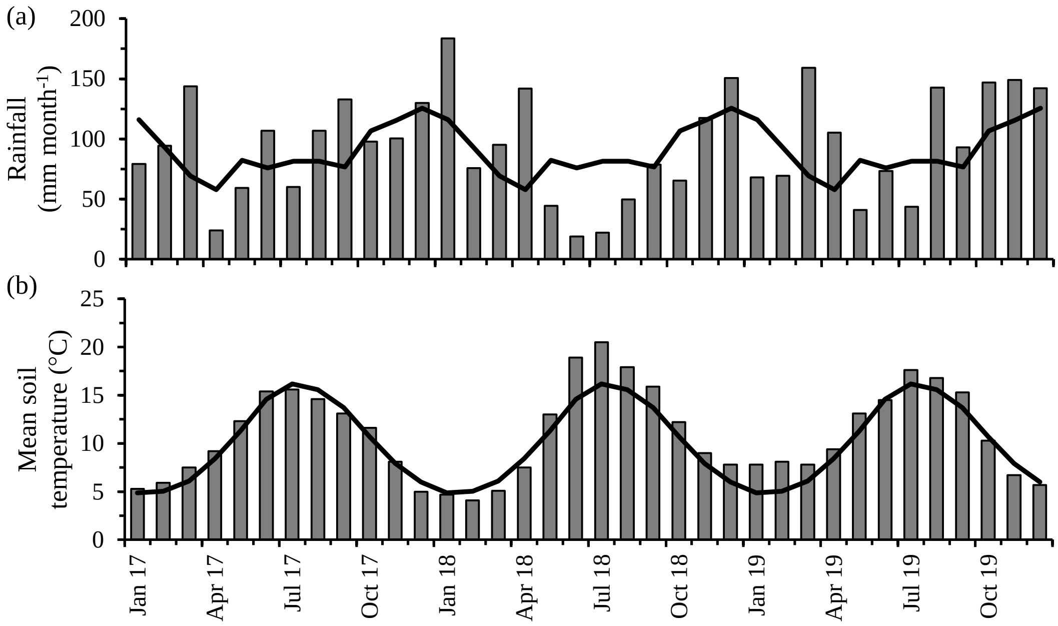

Figure 4.1: (a) Monthly rainfall (mm) and (b) mean monthly soil temperature (°C, below 10 cm soil surface) during the study between 2017 and 2019 (grey bars) compared to 15-year average (black line)

The end of the grazing season was not different between GPSRs in 2017. Likewise in 2018, except that the grazing season was seven days shorter on GP4.0 compared to the other GPSRs. There was an 11-day difference in the end of the grazing season between GPSRs in 2019. This was influenced by very high rainfall in October and November 2019

Table 4.3: Effect of grazing platform stocking rate on the grazing season and stocking densities during the three years of the experiment

	Grazing platform stocking rate[1]				
	GP2.5	GP3.0	GP3.5	GP4.0	*SEM*
Start of the grazing season					
2017	1 Mar	1 Mar	1 Mar	1 Mar	
2018	21 Feb	22 Feb	09 Mar	20 Mar	
2019	05 Feb	05 Feb	05 Feb	05 Feb	
End of the grazing season					
2017	14 Nov	14 Nov	14 Nov	14 Nov	
2018	23 Nov	23 Nov	23 Nov	16 Nov	
2019	20 Nov	12 Nov	10 Nov	09 Nov	
Days at pasture					
2017	239^{a}	230^{b}	214^{c}	213^{c}	2.1^{***}
2018	231^{a}	216^{b}	199^{c}	183^{d}	1.0^{***}
2019	260^{a}	249^{b}	235^{c}	218^{d}	3.0^{***}
Mean	243^{a}	232^{b}	216^{c}	205^{d}	9.7^{***}
Monthly stocking densities on grazing platform when removal of areas harvested for silage were accounted for (cows ha^{-1})					
February to March	2.49^{d}	3.03^{c}	3.52^{b}	4.02^{a}	0.01^{***}
April to June	3.65	3.89	3.94	4.17	0.126^{NS}
July to August	2.87^{c}	3.37^{b}	3.64^{b}	4.08^{a}	0.106^{**}
September to December	2.47^{d}	3.01^{c}	3.52^{b}	4.02^{a}	0.005^{***}
Mean	2.84^{d}	3.29^{c}	3.64^{b}	4.06^{a}	0.042^{***}

$^{a–d}$ Mean values in the same row with different superscripts differ between GPSRs (P <0.05).
* P <0.05, ** P <0.01, *** P <0.001, ^{NS} P >0.05
SEM = standard error of GPSR means
[1] See Table 4.1 for a description of the grazing systems

(Figure 4.1a). An exceptionally prolonged period of drought conditions and high temperatures in 2018 (Figure 4.1) impacted herbage growth during the summer months (Figure 4.2).

There was a significant effect of year on days at pasture per cow (P <0.001): Across all GPSRs 2018 had the lowest mean days at pasture (207 days per cow) and 2019 the highest (240 days per cow). In all years, days at pasture per cow decreased with higher GPSR (Table 4.3). For each increase in GPSR of one cow ha^{-1} days at pasture per cow per year decreased (P = 0.01) by on average 26 ± 7.98 days (18 in 2017, 32 in 2018 and 27 days in 2019).

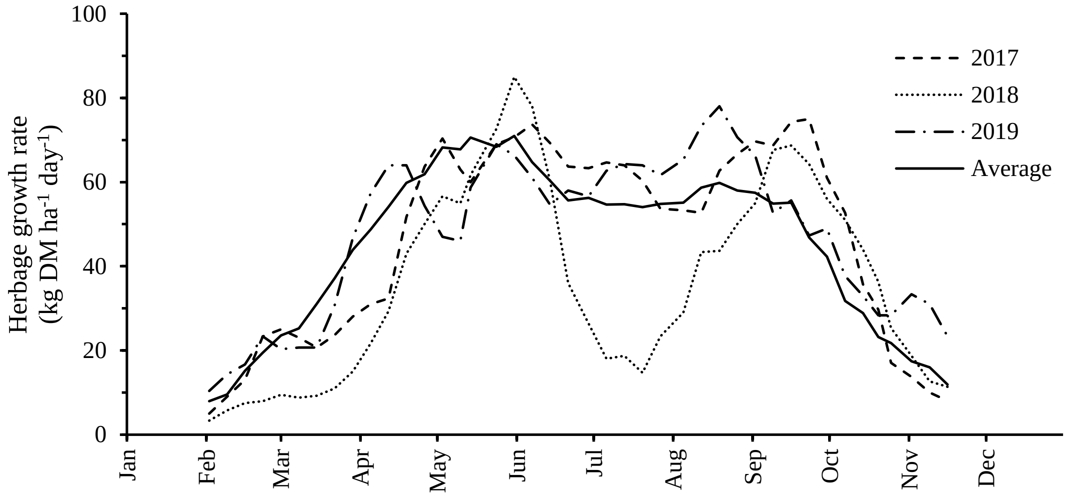

Figure 4.2: Weekly herbage growth rate (three-week rolling average) at Solohead Research Farm in 2017 (short dash), 2018 (dotted line) and 2019 (dash dot) compared to average of the previous 14 years (solid line)

4.3.2. Herbage production and nutritive value of the herbage

There was no effect of GPSR on pre-grazing herbage mass, post-grazing sward height, rotation length, herbage growth rate or nutritive value of the grazed herbage on the GP (Table 4.4). Total herbage mass harvested was not different between GPSRs on either the GP (mean: 15.2 t DM ha^{-1}, *SEM* 1.27, P = 0.99) or on the overall system area (GP + non-GP parcels) (15.4 t DM ha^{-1}, *SEM* 0.82, P = 0.94, Table 4.4). On the non-GP parcels mean total herbage production was 15.9 t DM ha^{-1} with 13.9 t DM ha^{-1} harvested for silage and 2.1 t DM ha^{-1} harvested as zero-grazed herbage. Total herbage production on the overall system area was different between years with the highest yield in 2017 (16.6 t DM ha^{-1}), intermediate in 2019 (15.6 t DM ha^{-1}) and lowest in 2018 (14.0 t DM ha^{-1}, *SEM* 0.30, P <0.01). This was similar on the GP area. On the non-GP parcels the third cut in 2018 was delayed into September which led to no decrease in annual silage yields compared to the other two years of the study.

Differing proportions of herbage mass were harvested for silage from the GP between the different GPSR; less herbage mass was harvested for silage per ha with higher GPSR (*P* = 0.001, Table 4.4). On the other hand, more herbage mass was harvested for silage with higher GPSR (*P* = 0.01) from the overall system area, mainly from the non-GP parcels. On average over the three years GPSR had a linear effect (*P* = 0.001) on herbage mass harvested for silage with 2.1 ± 0.46 t DM ha^{-1} less harvested from the GP area and 1.6 ± 0.37 t DM ha^{-1} more harvested from the overall system area with each increase of one cow ha^{-1} GP. This trend was opposite to the mass of herbage harvested as pre-grazing cuts.

With higher GPSR herbage harvested for silage on both the GP and the overall system area was less affected by year, i.e. the difference between years was small at a high GPSR

Table 4.4: Effect of grazing platform stocking rate on three-year mean annual herbage production and nutritive value of the grazed herbage

	Grazing platform stocking rate[1]				
Item	GP2.5	GP3.0	GP3.5	GP4.0	*SEM*
Pre-grazing herbage mass (kg DM ha^{-1})	1695	1614	1820	1709	118.5^{NS}
Post-grazing sward height (cm)	4.75	4.77	4.55	4.66	0.262^{NS}
Rotation length (days)	27.9	27.5	27.9	28.0	2.27^{NS}
Nutritive value of the grazed herbage (g kg DM^{-1})					
Crude protein	232	235	238	233	12.2^{NS}
Ash	118	113	110	116	4.7^{NS}
Neutral detergent fibre	415	417	424	411	15.1^{NS}
Organic matter digestibility	812	808	813	819	8.3^{NS}
Herbage mass harvested on the grazing platform (t DM ha^{-1})					
Pre-silage cuts	4.5^{a}	3.4^{a}	2.2^{b}	1.3^{b}	0.58^{**}
Pre-grazing cuts	10.8	11.9	13.1	13.8	0.92^{NS}
Total	15.2	15.4	15.3	15.2	1.27^{NS}
Herbage mass harvested on the overall system area[3] (t DM ha^{-1})					
Pre-silage cuts[2]	4.5^{c}	5.7^{b}	6.3^{ab}	7.0^{a}	0.44^{**}
Pre-grazing cuts	10.8	9.8	9.2	8.5	0.59^{NS}
Total	15.2	15.5	15.5	15.5	0.82^{NS}

$^{a–d}$ Mean values in the same row with different superscripts differ between GPSRs (*P* <0.05).
* *P* <0.05, ** *P* <0.01, *** *P* <0.001, ^{NS} *P* >0.05
SEM = standard error of GPSR means
[1] See Table 4.1 for a description of the grazing systems
[2] including zero-grazed herbage
[3] grazing platform + non-grazing platform parcels

and larger at a low GPSR. Similarly, there was no difference between years in herbage harvested as pre-grazing cuts at low GPSR but a large variation between years at high GPSR. In 2018 there was no effect (P = 0.63) of GPSR on herbage mass harvested as pre-grazing cuts from the GP area whereas in 2019 herbage mass harvested as pre-grazing cuts increased linearly (P = 0.03) with increasing GPSR.

4.3.3. Feed intake

There was a significant effect of year on the components of the diet of dairy cows (P <0.001): Across all GPSRs 2018 had the highest average intake of silage (2044 kg DM per cow) and the highest intake of concentrate feed (837 kg DM per cow). In 2019 there was the lowest average intake of silage (1516 kg DM per cow) and lowest intake of concentrate feed (410 kg DM per cow).

Table 4.5: Effect of grazing platform stocking rate on feed intake during the three years of the experiment

	Grazing platform stocking rate[1]				
Annual feed intake (kg DM per cow)	GP2.5	GP3.0	GP3.5	GP4.0	*SEM*
Grazed herbage					
2017	3324	3322	3198	3134	82.4
2018	2565^{a}	2395^{b}	2319^{b}	1961^{c}	83.9^{***}
2019	3390^{a}	3212^{b}	3009^{c}	2857^{c}	92.0^{***}
Mean	3093^{a}	2976^{b}	2842^{c}	2651^{d}	301.1^{***}
Silage[2]					
2017	1300^{c}	1426^{b}	1600^{a}	1617^{a}	29.3^{***}
2018	1733^{d}	1932^{c}	2166^{b}	2347^{a}	33.8^{***}
2019	1111^{d}	1237^{c}	1362^{b}	1563^{a}	29.4^{***}
Mean	1381^{d}	1532^{c}	1709^{b}	1842^{a}	220.7^{***}
Concentrate					
2017	494	486	476	491	18.0^{NS}
2018	838	840	837	835	12.6^{NS}
2019	413	408	411	409	14.3^{NS}
Mean	582	578	574	578	131.9^{NS}

$^{a–d}$ Mean values in the same row with different superscripts differ between GPSRs (P <0.05).
*** P <0.001, ^{NS} P >0.05
SEM = standard error of GPSR means
[1] See Table 4.1 for a description of the grazing systems
[2] including zero-grazed herbage

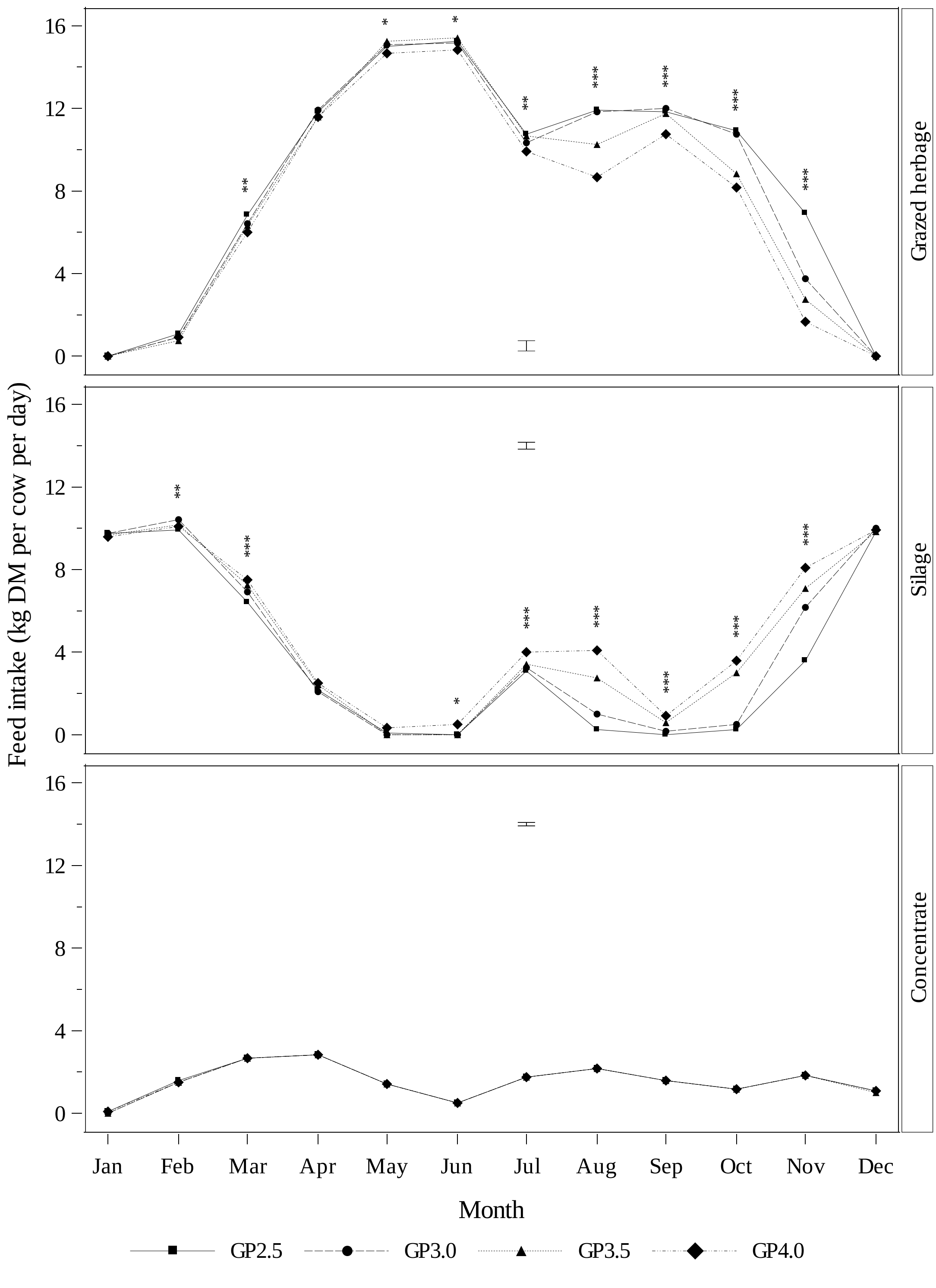

Figure 4.3: Effect of month and grazing platform stocking rate (GPSR; GP2.5, GP3.0, GP3.5, GP4.0) on three-year mean daily feed intake as grazed herbage (P <0.001), silage (incl. zero-grazed herbage) (P <0.001) and concentrates (P = 0.99) (see Table 4.1 for a description of the grazing systems). Differences between GPSRs within a month are indicated with * = P <0.05, ** = P <0.01 and *** = P <0.001; Error bars show the standard error of the interaction between month and GPSR mean

GPSR affected the components of the diet (grazed herbage and silage) (*P* <0.001, Table 4.5): intake of grazed herbage decreased while silage intake increased with higher GPSR in all years except for 2017 where herbage intake was only numerically different between GPSRs. Annual average concentrate feed intake was not different between GPSRs (mean: 578 kg DM per cow, Table 4.5). The majority of the differences in components of the diet between GPSRs occurred primarily during the second half of the grazing season between August and November of each year (Figure 4.2).

Intake of grazed herbage per ha of GP increased (*P* = 0.04) by 1926 ± 812.1 kg DM ha^{-1} for each increase in GPSR of one cow ha^{-1}. The amount of silage which was fed during lactation increased with higher GPSR (684 (GP2.5), 830 (GP3.0), 1010 (GP3.5) and 1154 (GP4.0) kg DM per cow, *SEM* 199.8, *P* <0.001). The increase in silage fed during lactation with each increase in GPSR of one cow ha^{-1} was highest in 2018 (410 ± 11.8 kg DM per cow, *P* <0.001) and lowest in 2017 (225 ± 26.3 kg DM per cow, *P* = 0.01).

4.3.1. Milk production

There was no effect of GPSR on milk yield per cow, milk composition, body weight, body condition score or days in milk (Table 4.6). There was no (*P* >0.05) difference in daily milk yield and daily milk solids yield between GPSRs for each week of lactation.

At systems level milk and milk solids yield per ha of GP increased linearly with higher GPSR (*P* <0.01). On average over the three years of the study this was an increase of 5686 ± 357.6 kg ha^{-1} of milk and 470 ± 26.1 kg ha^{-1} of milk solids for each increase in GPSR of one cow ha^{-1} GP. Milk production per ha overall system area was not affected by GPSR (annual milk yield 14790 kg ha^{-1}, *SEM* 324.4, *P* = 0.75, annual; milk solid yield 1218 kg ha^{-1}, *SEM* 22.0, *P* = 0.74).

Table 4.6: Effect of grazing platform stocking rate on three-year mean annual milk production and composition, body weight and body condition of dairy cows

	Grazing platform stocking rate[1]				
Item	GP2.5	GP3.0	GP3.5	GP4.0	*SEM*
Milk yield (kg per cow)	5916	5945	6000	5803	159.7^{NS}
Milk solids yield[2] (kg per cow)	487	490	492	479	13.9^{NS}
Milk fat content (g kg^{-1})	46.2	46.3	45.8	46.4	0.50^{NS}
Milk protein content (g kg^{-1})	36.3	36.3	36.4	36.2	0.21^{NS}
Milk lactose content (g kg^{-1})	46.1	46.1	45.8	45.8	1.11^{NS}
Body weight (kg per cow)	554	556	558	555	17.1^{NS}
Body condition score	3.00	3.01	2.97	3.01	0.013^{NS}
Days in milk	293	292	291	292	3.2^{NS}

^{NS} P >0.05
SEM = standard error of GPSR means
[1] See Table 4.1 for a description of the grazing systems
[2] Total milk solids yield = kg of milk fat + protein.

4.3.2. Profitability

The profitability of the four GPSR within scenario 1 at a milk price of €0.29 L^{-1}, a land rental price of €450 ha^{-1} and a distance of 2 km between GP and non-GP parcels is presented in Table 4.7. Gross output was the same across all GPSRs. Labour requirements increased from 26.7 (GP2.5) to 27.3 (GP4.0) h per cow per year due to more time spent indoors. Labour costs increased accordingly. Total costs per farm increased and net profit per farm decreased linearly (P <0.001) with higher GPSR by €4,995 for each one cow ha^{-1} increase in GPSR. The higher total costs in each of the fragmented systems (GP3.0, GP3.5 and GP4.0) compared to the non-fragmented system (GP2.5) were caused by higher variable costs (0.84 of difference in total costs) and by higher labour costs (0.16 of difference) (Table 4.7). The majority of the higher variable costs were feed related costs (silage purchase, harvest and transport and zero-grazing), which accounted for 0.62 of the difference in variable costs in each of the fragmented systems. The remainder of the difference were higher slurry spreading and transport costs (0.38 of the difference). At the distance of 2 km these proportions were very similar across all GPSRs.

Table 4.7: Profitability of the four grazing platform stocking rates in scenario 1 (increasing degree of fragmentation) at a base milk price of €0.29 L^{-1}, a land rental price of €450 ha^{-1} and at a distance of 2 km between the grazing platform and non-grazing platform parcels

Item	Grazing platform stocking rate[1] GP2.5	GP3.0	GP3.5	GP4.0
Farm area (ha)	50	50	50	50
Overall system area available as grazing platform (%)	100	83	71	63
Grazing platform (ha)	50	42	36	31
Cows (no.)	125	125	125	125
Milk produced (kg)	737,000	737,000	737,000	737,000
Milk solids[2] output (kg)	60,782	60,782	60,782	60,782
Gross output (€)	273,331	273,331	273,331	273,331
Variable costs (€)	95,203	97,207	99,319	101,512
Labor cost (€)	50,063	50,456	50,850	51,243
Fixed cost excl. Labor (€)	42,876	42,876	42,876	42,876
Total costs (€)	188,141	190,539	193,044	195,631
Net profit (€)	85,189	82,792	80,287	77,700
Net profit per hectare (€ ha^{-1})	1,704	1,656	1,606	1,554
Net profit per cow (€ per cow)	682	662	642	622

[1] See Table 4.1 for a description of the grazing systems
[2] kg of milk fat + protein.

The sensitivity analysis for scenario 1 showed that costs increased more per km distance between GP and non-GP parcels at higher GPSR and less area available as GP compared to GP2.5 (Figure 4.4). In GP3.0 (83% GP) total costs per ha increased (P <0.001) by €5.8

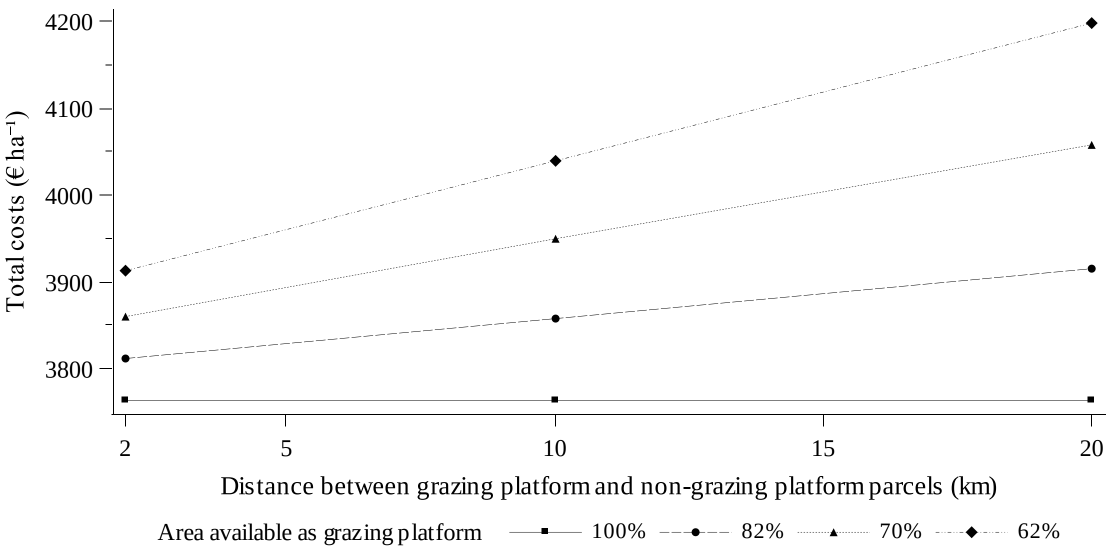

Figure 4.4: Effect of distance between the grazing platform (GP) and non-GP parcels on total costs per ha depending on the proportion of whole farm area available as GP in scenario 1

per km whereas in GP4.0 (63% GP) costs increased (P <0.001) by €15.9 with each additional km between GP and non-GP parcels. In GP4.0 the proportion of total costs caused by transport costs (for silage, slurry and zero-grazing) increased from 0.21 at 2 km distance to 0.73 at 20 km distance. Nonetheless, net profit per ha at 10 and 20 km distance between GP and non-GP parcels was greater than the land rental price in all GPSRs (Table 4.8).

Table 4.8: Profitability of the four grazing platform stocking rates in scenario 1 at a base milk price of €0.29 L^{-1}, a land rental price of €450 ha^{-1} and varying distance between the grazing platform and non-grazing platform parcels

	Grazing platform stocking rate[1]			
Item	GP2.5	GP3.0	GP3.5	GP4.0
10 km distance between GP and non-GP parcels				
Net profit (€)	85,189	80,480	75,909	71,355
Net profit per hectare (€ ha^{-1})	1,704	1,610	1,518	1,427
Net profit per cow (€ per cow)	682	644	607	571
20 km distance between GP and non-GP parcels				
Net profit (€)	85,189	77,591	70,437	63,424
Net profit per hectare (€ ha^{-1})	1,704	1,552	1,409	1,268
Net profit per cow (€ per cow)	682	621	563	507

[1] See Table 4.1 for a description of the grazing systems

The profitability of the four GPSRs within scenario 2 at a milk price of €0.29 L^{-1}, a land rental price of €450 ha^{-1} and a distance of 2 km between GP and non-GP parcels is presented in Table 4.9. Gross output increased (P <0.001) linearly with higher GPSR by €62,710 per farm or €1,254 per ha for each increase in GPSR of one cow ha^{-1}. Total costs were higher with higher GPSR; compared with the baseline (GP2.5) there were higher variable costs (0.47 of increase in total costs compared to GP2.5), higher labour costs (0.23), higher fixed costs (0.04) and expansion costs (0.26, Table 4.9). Compared to the baseline, higher variable costs were caused by feed related costs (concentrate, silage and zero-grazing, 0.43), animal related costs (rearing replacements, artificial insemination and vet, 0.33), fertilizer and reseeding (0.13) and slurry related costs (spreading and

Table 4.9: Profitability of grazing platform stocking rate models in scenario 2 (fixed degree of fragmentation and increasing herd size) at a milk price of €0.29 L^{-1}, a land rental price of €450 ha^{-1} and at a distance of 2 km between the grazing platform (GP) and non-GP parcels

	Grazing platform stocking rate			
Item	GP2.5	GP3.0	GP3.5	GP4.0
Farm area (ha)	50	50	50	50
Overall system area available as grazing platform (%)	63	63	63	63
Grazing platform (ha)	31	31	31	31
Cows (no.)	78	94	109	125
Grazing platform stocking rate (cows ha^{-1})	2.5	3.0	3.5	4.0
Milk produced (kg)	460,625	552,750	644,875	737,000
Milk solids[1] output (kg)	37,988	45,585	53,183	60,782
Land rented out (ha)	19	13	6	0
Gross output (€)	179,265	210,618	241,971	273,331
Variable costs (€)	59,502	72,905	86,904	101,512
Labor (€)	31,289	37,940	44,592	51,243
Total fixed cost excl. Labor (€)	39,697	40,757	41,816	42,876
Annual net present value and interest of additional animals (€)	0	2,677	5,355	8,033
Annual depreciation and interest for new buildings (€)	0	5,154	10,308	15,462
Total annual expansion costs (€)	0	7,831	15,663	23,496
Total costs (€)	130,488	159,433	188,975	219,126
Opportunity costs for land (€ ha^{-1})	0	0	0	0
Net profit (€)	48,777	51,185	52,996	54,205
Net profit per hectare (€ ha^{-1})	976	1,024	1,060	1,084
Net profit per cow (€ per cow)	624	546	485	434
Marginal benefit per cow (€ per cow)		154	116	77

[1] kg of milk fat + protein.

transport; 0.11 of increase in variable costs). At the distance of 2 km these proportions were very similar across all GPSRs.

The relationship between GPSR and total costs per ha was improved with the addition of a quadratic function (P <0.01) indicating that total costs increased proportionally more with higher GPSR ($y = 24x^2 + 1025x - 104$). Net profit per ha increased quadratically (P <0.001); the increase in net profit diminished with higher GPSR ($y = -24x^2 + 228x + 555$). Likewise, marginal benefit per cow was lower with higher GPSR (Table 4.9).

In the sensitivity analysis milk price showed the greatest impact on net profit (Figure 4.5). At the high milk price a higher GPSR (up to GP4.0) was always more profitable (Figure 4.5a). At the low milk price increasing GPSR always resulted in a lower net profit compared with GP2.5 (Figure 4.5b). The lower profitability caused by increasing GPSR at the low milk price resulted in opportunity costs for land, which was exacerbated by higher land rental price. At the medium milk price the impact of increasing GPSR on profitability compared to the baseline depended on distance and land rental price (Figure 4.5c). At a land rental price of €450 ha^{-1}, GP4.0 was the most profitable up to a distance of 6 km between GP and non-GP parcels. Between 6 and 9 km distance GP3.5 was most profitable and between 9 and 12.5 km GP3.0 was most profitable. From 13 km onwards, GP2.5 (baseline) generated the highest net profit (Figure 4.5c).

Across all milk prices, the net profit of the baseline GP2.5 was not affected by distance (no transport costs). At higher GPSR, transport costs for silage, zero-grazing and slurry increased disproportionally with longer distances: at 2 km distance transport costs caused around 1% of the total variable costs in all of the higher GPSRs whereas at 20 km distance transport costs caused between 6% (GP3.0) and 14% (GP4.0) of the total variable costs. Land rental price had the greatest effect on net profit at the lowest GPSR (GP2.5) and less effect on net profit with higher GPSR (less land was rented out at higher GPSR). Net profit per cow was always lower at higher GPSR. Marginal benefit per cow decreased for each additional increase of one cow ha^{-1} by €77 at 2 km distance and by €189 at 20 km distance (at medium to high milk price).

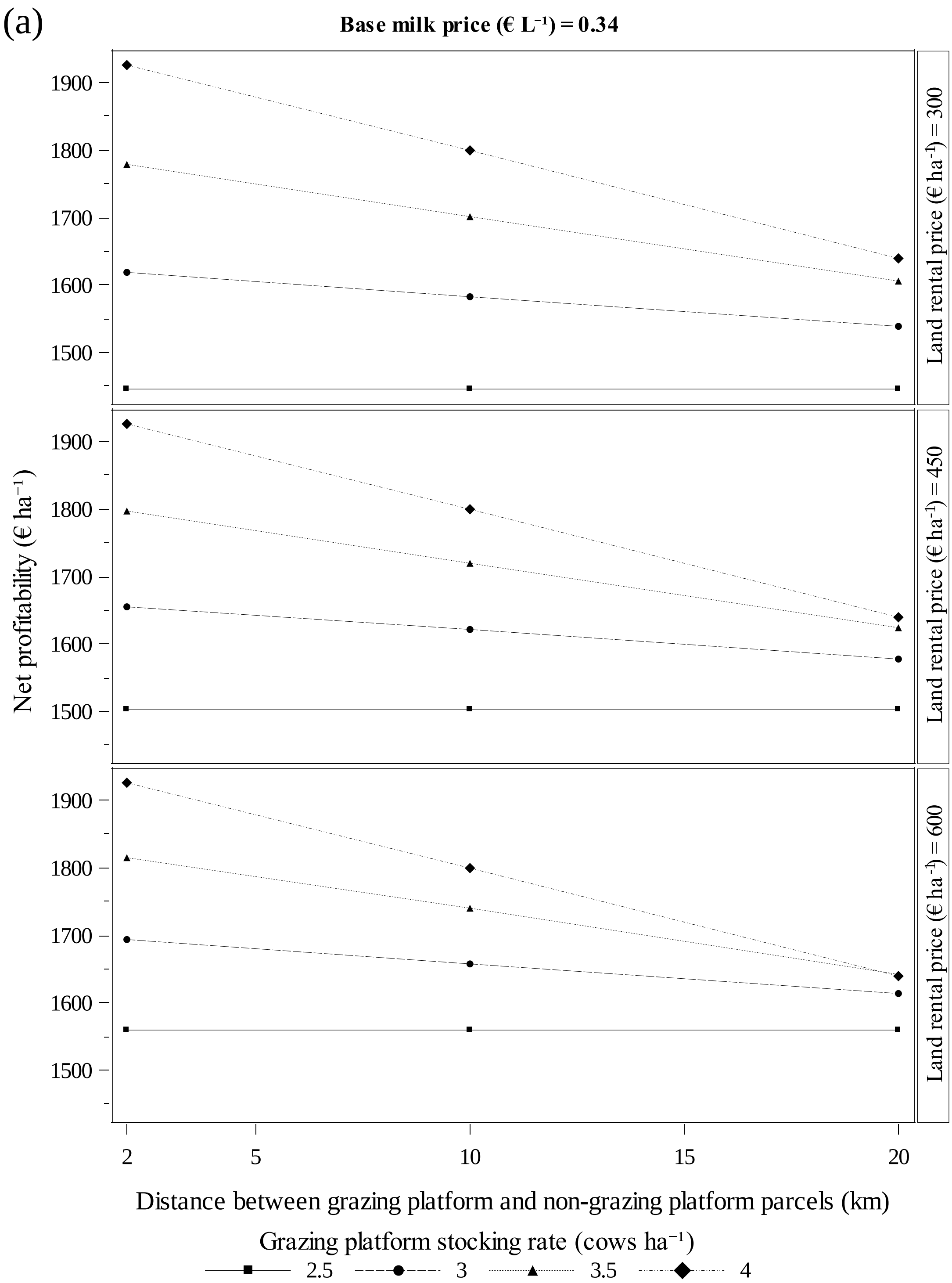

Figure 4.5: Effect of distance between the grazing platform and non-grazing platform parcels on net profit per ha overall farm area depending on the grazing platform stocking rate across varying land rental prices in scenario 2 at a milk price of (a) €0.34 L^{-1} (b) €0.24 L^{-1} and (c) €0.29 L^{-1}
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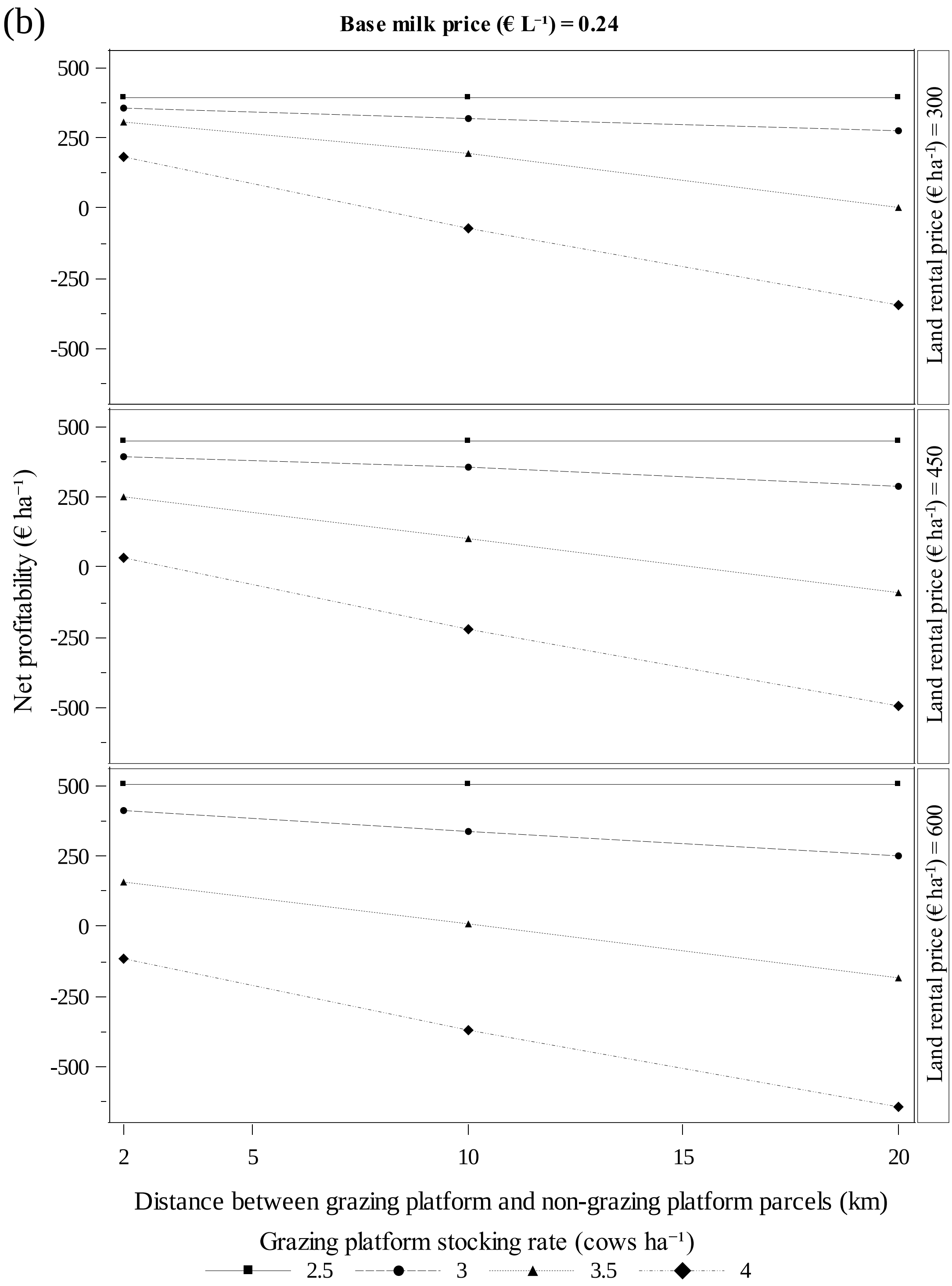

Figure 4.5 continued

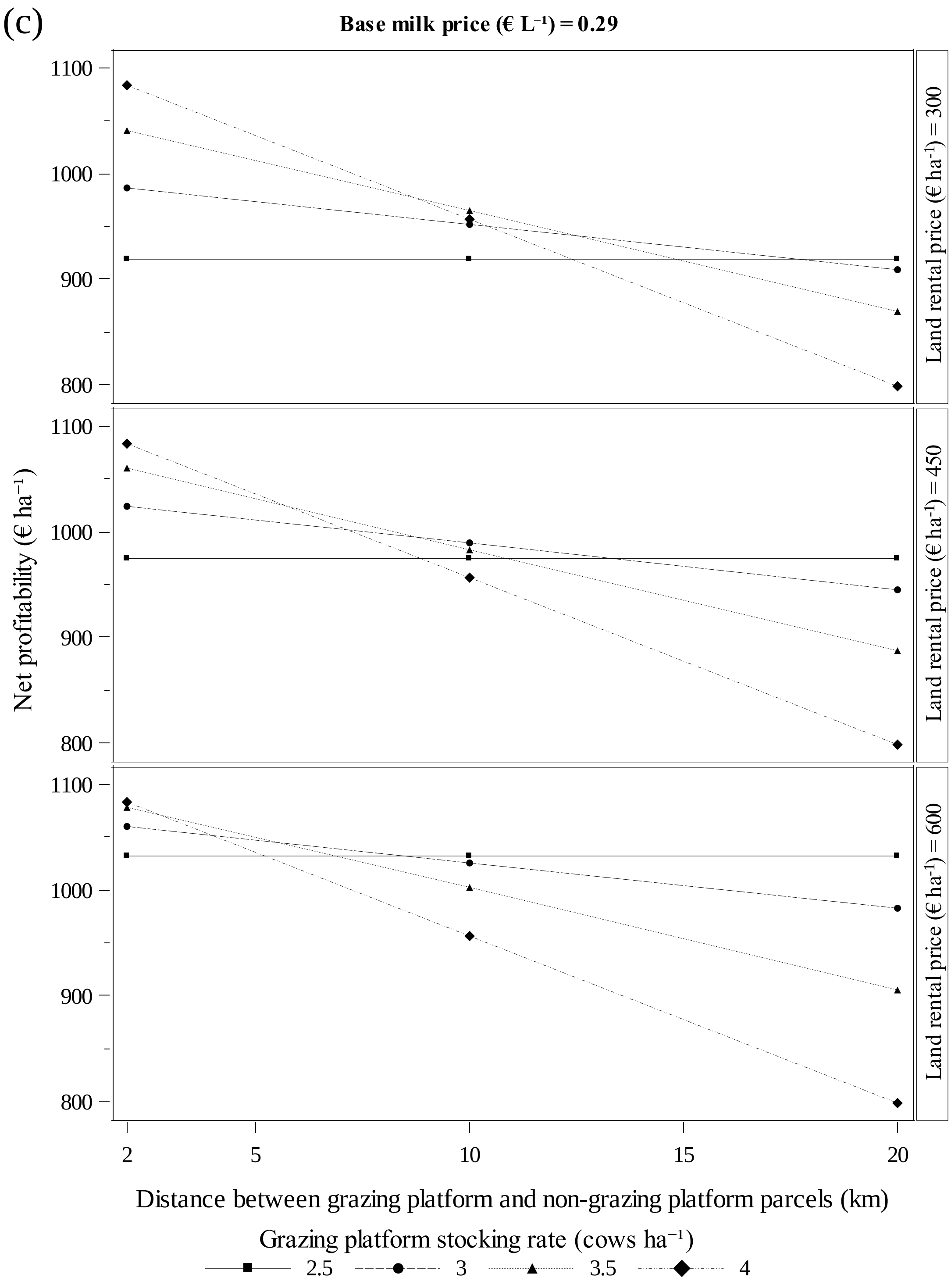

Figure 4.5 continued

4.4. Discussion

4.4.1. Effect of GPSR on herbage production, the length of the grazing season, feed intake and milk production

The overall system stocking rate was common across all GPSRs in the present study. The associated herd-demand for feed on each of the GPSR was well aligned with the production of home-produced feed in the present study. Deficits in the availability of herbage for grazing on the GP were met with silage from non-GP areas. Grazing decision rules, pre-grazing herbage mass and post-grazing sward height were similar across all GPSRs. There was no underutilisation of home-produced herbage mass in any of the GPSR. The high GPSR systems were managed to avoid overgrazing of pastures and consequential underfeeding of dairy cows. As a result annual herbage production, nutritive value of the grazed herbage and milk production per cow was not different between GPSRs. This is supported by the findings of Patton et al. (2016) where higher GPSR (3.1 vs. 4.5 cows ha^{-1}) did not affect herbage production, nutritive value or milk production per cow when post-grazing sward height was the same across both GPSRs. Similarly, other studies have shown that herbage production and milk production per cow were not affected where grazing management practices were similar across stocking rate treatments (Valentine et al., 2009, Fariña et al., 2011).

This is in contrast to when an increase in GPSR was associated with alternative grazing management, mainly lower post-grazing sward height. In that case, previous studies have reported an effect of GPSR on herbage production, nutritive value and milk production per cow (Macdonald et al., 2008, McCarthy et al., 2011, McCarthy et al., 2014, McCarthy et al., 2016). The lower herbage mass availability per cow in the latter studies was not sufficiently replaced by conserved feed and, hence, milk production per cow declined with increasing stocking rate. The effect reported by the latter studies was more likely to have been caused by differences in post-grazing sward height rather than by GPSR alone. In addition to the lower herbage availability, Macdonald et al. (2008) attributed 24% of the decline in milk production per cow to a shorter lactation length with higher GPSR, which further explains the difference in results compared to the present study. Fales et al. (1995) reported a positive effect of GPSR on herbage production but no effect on milk production per cow. However, it was also reported that at the low stocking rate (2.47 cows ha^{-1}) more herbage was wasted due to trampling, fouling and rejection, indicating an underutilisation of herbage at the low stocking rate in the latter study.

As expected, there was less herbage mass conserved from the GPs with higher GPSR in the present study similar to previous studies (Macdonald et al., 2008, Valentine et al., 2009, McCarthy et al., 2016, Patton et al., 2016). In 2017 and 2019, the two years of the present study without drought, sufficient herbage was conserved to meet requirements for silage in all GPSRs. In 2018 all GPSRs were in deficit of silage. However, the deficit was almost twice as high in GP2.5 compared to that in GP4.0. This was because herbage production on the GP was lower in the drought year compared to the other two years whereas on the non-GP parcels annual yield was similar in all years of the study.

Silage production on non-GP parcels counterbalanced the lower amount of herbage conserved from the GP in the high GPSRs and filled feed deficits during the grazing season. The higher proportion of silage fed to cows on the high GPSRs had no effect on milk production per cow in the present study. The additional silage was mainly introduced during late summer and autumn (August to November) where dairy cows were in their second half of lactation and dietary requirements were lower than in early lactation. Claffey et al. (2020) and Reid et al. (2015) found similar results. This is in contrast to previous findings where additional silage was fed in early lactation and had a negative impact on milk production (Dillon et al., 2002, Claffey et al., 2019).

The deficit of herbage for grazing only during the second half of the grazing season can be explained by a combination of daily herbage growth and grazing management. At the beginning of the grazing season (February to March) dairy cows were turned out to pasture as they calved with a high input of concentrates (up to 6 kg per cow per day). Hence, the feed demand by each lactating herd was relatively low and a proportion of cows were still indoors. Herbage growth was generally sufficient to meet feed demand in all GPSRs. Between April to June feed demand increased in all GPSRs. However, herbage accumulation rates were also highest during this timeframe. There was surplus herbage on the GP of all GPSRs, which was removed as silage; the lower the GPSR the greater the areas that were harvested for silage. As a result, monthly stocking densities were not different between GPSRs (Table 4.3) and availability of herbage for grazing per cow was similar.

In mid-season (July to August), as herbage growth rates declined, lower stocked GPSRs were able to bring more of the GP paddocks harvested for silage in May/early June back into the grazing rotation. The combination of lower herbage growth and higher stocking density in high the GPSRs at this time of the year (Table 4.3) resulted in lower availability of herbage for grazing per cow on the GP compared to the lower stocked GPSRs. With lower GPSR there was also greater capacity to accumulate and store herbage mass *in situ* that was used to extend the length of the grazing season (Fenger et al., 2021b). From August onwards, increasing amounts of silage were fed per cow at the higher GPSRs to maintain similar average herbage covers across the four GPSR.

In general, systems with higher GPSR were more sensitive to changes in herbage growth rate on the grazing area. Consequently, the GPSRs reacted differently to the impacts of low rainfall and drought in the present study. There was greater flexibility with a moderate GPSR with regard to the management of grazing paddocks. For example, paddocks that were planned to be harvested for silage could, in a drought situation, instead be grazed to maintain low-cost grazed herbage in the diet. Non-GP paddocks within higher GPSRs provided a more stable supply of ensiled herbage mass but there was little or no flexibility on the grazing area. The advantage of high GPSR to utilise more grazed herbage per ha (Macdonald et al., 2008, McCarthy et al., 2016, Patton et al., 2016) was only evident when herbage growth was sufficient. In 2018, the same amount of grazed herbage was harvested per ha of GP from each of the GPSRs in the present study.

At high GPSR times of deficit during the grazing season have to be supplemented with conserved feed and this will inevitably be fed to dairy cows during lactation. This was exacerbated in 2018 but was still relevant in the years with average herbage production. Although this did not negatively impact milk production per cow in the present study, it increased requirements for high quality silage compared to traditional pasture-based systems were silage is mainly fed to non-lactating cows during winter (Roche et al., 2017).

4.4.2. Effects of fragmentation and GPSR on system productivity and profitability

The results of the present study have shown that fragmented pasture-based systems can be managed without a loss in productivity up to a GPSR of 4 cows ha^{-1} when the grassland management imposed ensures optimum utilization of grazed herbage. However, all feed produced on non-GP parcels was required to support the higher GPSR resulting in similar milk production per ha of overall system area. Hence, the increase in milk production per ha of GP with higher GPSR was solely driven by importing silage from the non-GP parcels. This is supported by the studies of Valentine et al. (2009) and Patton et al. (2016) where an increase in milk output per ha with increasing stocking rate was entirely attributed to an increase in imported feed. Ramsbottom et al. (2015) has shown that there is a risk that grazed herbage can be substituted by imported feed and, hence, there is a need for careful management of grazing and of supplemental silage to avoid this. This was also demonstrated in the present study, where herbage utilisation on the GP did not decline with higher amounts of silage feeding.

Nonetheless, the higher reliance on conserved feed had implications for profitability so that fragmented systems were less profitable than non-fragmented systems. Similarly, del Corral et al. (2011) highlighted that no access for grazing dairy cows to separated parcels is one of the negative impacts of fragmentation on dairy production. Several studies have shown that fragmentation decreases technical efficiency of farms, increases production costs and decreases profitability (del Corral et al., 2011, Latruffe and Piet, 2014, Bradfield et al., 2020). Bradfield et al. (2020) highlighted that particularly long distances between home farm and non-GP parcels decrease technical efficiency. This supports the results of the present study where profitability decreased with a higher degree of fragmentation or longer distances between GP and non-GP parcels. Nevertheless, it was still possible to achieve an acceptable farm income from dairy production on the system with the smallest GP and the highest GPSR (GP4.0).

4.4.3. Optimum grazing platform stocking rate

In the present study the GPSR that maximised net profit per farm mainly depended on external factors like milk price and distances between GP and non-GP parcels. In most cases it was either more profitable to increase to the maximum GPSR tested or not to increase GPSR at all. This can be explained by following factors: (i) milk production per cow did not decline with higher GPSR. This resulted in a linear increase in gross output with increasing GPSR; (ii) Even though expansion costs and transport costs were incorporated in the economic model, the effect of the diminishing increase in profitability with higher GPSR was relatively small.

Baudracco et al. (2010) highlighted that the optimum stocking rate in pasture-based systems depends on the genetic potential of the cow, the value of milk and the cost of feeding supplements and managing additional cows. Many previous studies which have identified economic or biological optimum stocking rates in pasture-based systems reported declining milk yield per cow with increasing stocking rate (Macdonald et al., 2008, Macdonald et al., 2011, McCarthy et al., 2011), which, as discussed above, was confounded by other factors such as post-grazing height and lactation length. Similar to the present study, Fales et al. (1995) reported no effect of GPSR on milk production per cow and no economic optimum within the range of GPSR tested (2.47 to 3.95 cows ha^{-1}). Maximum profitability was determined by input and output factors and their interactions, which was also the case in the present study. Overall, there was no specific GPSR where the benefits of higher milk output from the GP were always counterbalanced by negative impacts and increased costs associated with farm fragmentation. However, there were cases where a moderate increase in GPSR was more profitable than the baseline and more profitable than a high increase in GPSR, indicating an economic optimum GPSR at that point. The results of the present study have shown that higher milk prices, shorter distances and lower land rental prices increase the optimum GPSR of fragmented systems and vice versa.

The higher GPSRs were less efficient and profitable per cow compared to the baseline due to costs caused by fragmentation. Furthermore, the results of the present study showed that the GP2.5 was less vulnerable to changes in milk price. Recent developments in the dairy sector and changes in climate and production potential of pasture-based dairy farms have increased volatilities in output (milk price) and input (feed) prices. Hence, dairy farms that expand and increase cow numbers in a favourable price environment could be more significantly affected by those volatilities. Furthermore, an investigation into differences in environmental footprints of the different GPSRs would clarify if positive impacts of increasing GPSR on profitability are accompanied by negative environmental effects.

It is possible that there is a point where milk production per cow is negatively affected by shorter grazing seasons and higher inclusion rates of silage than those tested in the present study. Especially where the availability of herbage for grazing is limited in spring. In the three years of the present study herbage growth during autumn was significantly above average. This allowed all GPSRs including the higher stocked systems to accumulate herbage and store *in situ* for an extension of the grazing season and an increase of herbage available for grazing in the following spring (Fenger et al., 2021b). Low to average autumn herbage growth on the other hand could limit the length of the grazing season at high GPSR more severely than what was observed in the present study. This would further increase feed costs and also potentially decrease availability of herbage for spring grazing and milk production per cow (Claffey et al., 2019). Hence, a further investigation of fragmented dairy farms at a GPSR higher than 4 cows ha^{-1} could be successful in identifying a maximum GPSR under certain circumstances similar to that described in the present study.

4.5. Conclusion

A higher GPSR decreased the length of the grazing season in the fragmented pasture-based systems. This did not affect total herbage production or milk production per cow albeit with a higher proportion of silage and a lower proportion of grazed herbage in the diet. Hence, overall productivity was not affected by fragmentation. However, the higher proportions of conserved herbage required to fill feed deficits on the GP at high GPSR had implications on profitability. Fragmented systems were less profitable mainly due to higher variable costs in form of feed and transport costs. Variable costs increased with a smaller GP and with longer distances between GP and non-GP parcels.

At a fixed GP size the profitability of increasing GPSR from the baseline of 2.5 cows ha^{-1} was mainly determined by external factors: Higher milk prices, shorter distances and lower land rental price increased the optimum GPSR of fragmented systems and vice versa. There was no specific point detected within the range of GPSR tested in this study where the benefits of higher milk output from the GP always counterbalanced negative impacts and increased costs associated with farm fragmentation. It was possible to achieve an acceptable farm income from dairy production on fragmented farms by optimising GPSR depending on the extent of fragmentation, milk and land prices and distance between parcels.

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Chapter 5 Accumulating herbage during autumn to extend the grazing season in pasture-based dairy systems

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Abstract

A longer grazing season can lower the costs of pasture-based dairy production. Accumulating herbage during autumn increases herbage available for grazing in late autumn and the following spring but results in higher pre-grazing herbage mass (PGHM). This could affect sward nutritive value and milk production. The effects of accumulating herbage during autumn on the length of the grazing season, nutritive value, milk production and the supply of herbage mass in the following spring (OPENING) were examined at systems scale in this study. The dataset was 60 grazing systems from systems comparisons conducted between 2001 and 2018 with spring-calving dairy herds (mean stocking rate 2.4 cows ha^{-1}) at Solohead Research Farm, Ireland. Herbage mass accumulated per system was measured as average herbage cover (AHC; herbage mass >4 cm; average of all paddocks). A higher PGHM (1783 vs. 1445 kg dry matter (DM) ha^{-1}, P <0.001, *SEM* 32.5) and peak AHC (highest AHC; 1345 vs. 1139 kg DM ha^{-1}, P = 0.002, *SEM* 39.2) during AUTUMN (1 August to end of grazing season [CLOSING]) did not affect herbage nutritive value or milk production (P >0.05). Each increase in peak AHC of 100 kg DM ha^{-1} increased days at pasture per cow in AUTUMN by 2.2±0.44 (P <0.001, partial R^2 = 0.46) and increased CLOSING AHC by 46±6.5 kg DM ha^{-1} (P <0.001, partial R^2 = 0.42). OPENING AHC in February increased with CLOSING AHC (P <0.001, R^2 = 0.41). Accumulating herbage during AUTUMN facilitated a longer grazing season while not impacting on milk production.

5.1. Introduction

Rates of herbage growth are highly seasonal in temperate latitudes (Hurtado-Uria et al., 2013). The period when herbage growth meets the demand by grazing dairy cows is limited. In Western Europe herbage deficits due to low growth rates typically occur in late autumn, winter and early spring (March). Hence, in Ireland, dairy cows are compactly calved in February, March and April and are typically dried off and housed during the winter. A long grazing season and a short period of winter housing are key elements of low cost pasture-based dairy production (Finneran et al., 2012a, Läpple et al., 2012, Hanrahan et al., 2018).

At moderate stocking densities during August and early September herbage growth rates are sufficient to enable the accumulation of a surplus of herbage that can be transferred *in situ* to meet deficits later in the grazing season. This is typically achieved by ceasing to harvest surplus herbage as silage, strategic fertilizer input and increasing rotation interval (Macdonald and Penno, 1998, Laidlaw and Mayne, 2000, Hennessy et al., 2008). Accumulating herbage results in increasing average herbage cover (AHC; average herbage mass of all paddocks >4 cm above ground level [AGL]) at farm level. Whereas feed demand by the grazing herd remains more-or-less constant, at some date during the early autumn (typically mid-September in Ireland) growth rate falls below feed demand and, thus, AHC goes into decline. Peak AHC marks the transition between the accumulation and the decline of herbage mass available on the farm. Four timeframes were delineated in the present study: (i) herbage accumulation interval (typically starting 1 August until peak AHC), (ii) interval when accumulated herbage was fed to cows (from peak AHC to the end of grazing), (iii) the timeframe encompassing (i) and (ii), which was denoted AUTUMN; (iv) the winter or 'closed' period when all cows were housed, generally encompassing December and January, which ended with turnout in February. CLOSING denotes the end of grazing and the beginning of the closed period. The beginning of grazing in the following February was denoted by OPENING in this study. Hence the term 'AUTUMN' is used to describe the later part of the grazing season and the later part of lactation in this study, which is somewhat similar to, but not the same as the autumn season which encompasses September, October and November in the Northern hemisphere (Figure 5.1c).

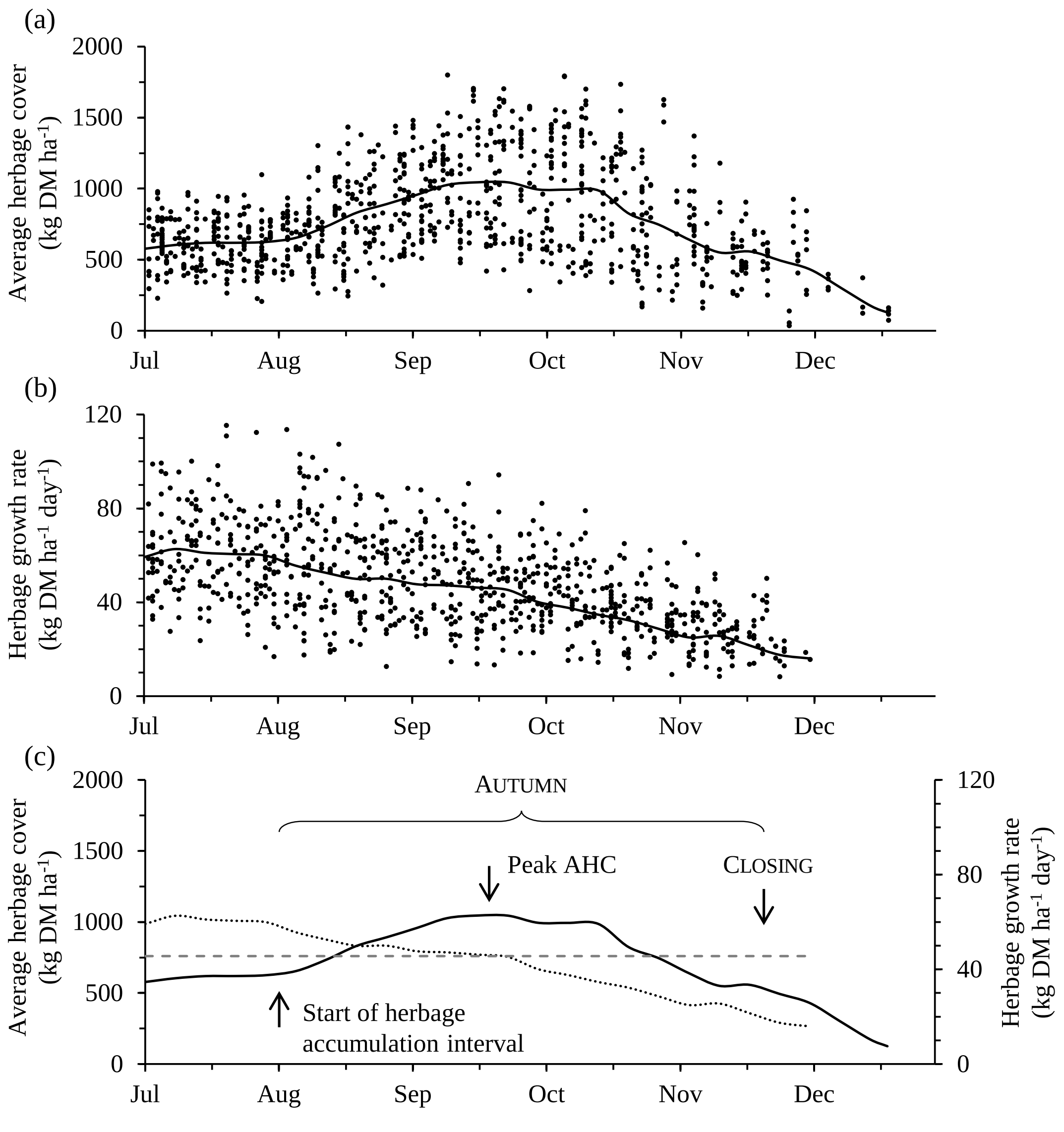

Figure 5.1: (a) Average herbage cover (kg DM ha^{-1}) and (b) daily herbage growth rate (kg DM ha^{-1} day^{-1}) for each grazing system during AUTUMN (1 August to CLOSING date) between 2001 and 2018 (●) compared to weekly mean of 2001 to 2018 (——); (c) mean development of average herbage cover (——) and average herbage growth rate (·······) during AUTUMN compared to the daily herbage demand for 2.4 cows ha^{-1} (kg DM ha^{-1} day^{-1}, — —); CLOSING date varied between systems (Table 5.2).

The magnitude of the peak in AHC is a useful indicator of autumn herbage availability. A higher peak AHC means that more herbage is available for the interval where accumulated herbage was fed to cows. On the other hand, storing herbage *in situ* involves the risk of (i) self-shading and net senescence particularly in the late AUTUMN (Fulkerson and Donaghy, 2001, Lawrence et al., 2017), (ii) poor utilisation (Carton et al., 1988), (iii) decline in nutritive value (Holmes et al., 1992, Curran et al., 2010) and (iv) low ryegrass tiller density that can be carried over into the following spring (Hennessy et al., 2006). Hence, accumulating herbage could negatively impact on sward nutritive value and milk production during AUTUMN. Delaying the end of the grazing season in AUTUMN could lower the mass of herbage for grazing in the following spring and offset benefits gained by extending the grazing season in AUTUMN.

The concept of accumulating herbage over the autumn period in a grazing system has rarely been described in the scientific literature and no recent studies have examined this question at dairy systems scale. The objective of this study was to examine the implications of accumulating herbage during the AUTUMN in terms of herbage production and nutritive value, milk production, the length of the grazing season and the mass of herbage at OPENING in the following spring.

5.2. Materials and Methods

5.2.1. Dataset

A dataset was compiled for the purpose of this study from grazing system experiments conducted at Solohead Research Farm (52˚30’N, 08˚12’W, 95 m above sea level) in south-west Ireland between 2001 and 2018. They were all system studies examining grassland management practices with spring-calving pasture-based dairy herds over an entire grazing season. There were between three and five experimental systems each year resulting in a total of n = 60 systems within the 17 years (Table 5.1).

5.2.2. Site description

Soils include poorly drained Gleys (90%) and Grey Brown Podzolics (10%) with a clay loam texture. Topographic relief causes variation in shallow groundwater with a water table depth ranging from 0 to 2.2 m below ground level. The local climate is humid temperate oceanic with a long potential growing season. The land was permanently under grassland with predominantly perennial ryegrass and white clover swards for well over 50 years before the beginning of this study with an average of approximately 5% of the grassland renovated each year during the experimental years.

5.2.3. Experimental design

The design and the scale of the experiments were similar in all years. Assignment of cows to herds and paddocks to systems, grazing management and recording of days at pasture was as described by Humphreys et al. (2008; 2009) , Phelan et al. (2013a) and Tuohy et al. (2014). Each spring all cows were divided into 4 main groups on the basis of lactation number (1, 2, 3, and ≥ 4) and then sub-divided into sub-groups on the basis of calving date (mean 23 February, *SD* 6.47 days); the number of sub-groups being the same as the number of experimental systems in each year. From within each subgroup, one cow was randomly assigned to each herd. Herds were then randomly assigned to each experimental system. This procedure was repeated each spring. The experimental area was grassland used for grazing and production of silage (ensiled herbage) and the mean area per herd

Table 5.1: Details of the 60 grazing systems included in the dataset; PGH= Post-grazing sward height

Study	Year of study	System name	n	Target PGH (cm)	Cows per system	Stocking rate (cows ha^{-1})	Mineral N† (kg ha^{-1})	Reference
1	2001-2002	N205	2	6	18	1.75	178	Humphreys et al. (2008)
1	2001-2002	N230	2	6	18	2.10	189	Humphreys et al. (2008)
1	2001-2002	N300	2	6	18	2.50	251	Humphreys et al. (2008)
1	2001-2002	N400	2	6	18	2.50	353	Humphreys et al. (2008)
2	2003-2006	FN	4	6	22-24	2.0-2.2	238	Humphreys et al. (2009)
2	2003-2006	WC	4	6	22-24	2.0-2.2	202	Humphreys et al. (2009)
2	2003-2006	S0	4	6	22-24	2.0-2.2	220	Unpublished
3	2007-2009	6 cm	3	6	18-27	1.99-2.12	189	Phelan et al. (2013a)
3	2007-2009	5 cm	3	5	18-27	1.99-2.12	195	Phelan et al. (2013a)
3	2007-2009	4 cm	3	4	18-27	1.99-2.12	225	Phelan et al. (2013a)
4	2010	S1	1	4	24	2.0	205	Unpublished
4	2010	S2	1	4	24	2.2	205	Unpublished
4	2010	S3	1	4	24	2.2	205	Unpublished
4	2010	S4	1	4	24	2.4	205	Unpublished
5	2011-2012	HF-L	2	4	24	2.35-2.45	196	Tuohy et al. (2014)
5	2011-2012	HF-H	2	4	24	2.56-2.67	305	Tuohy et al. (2014)
5	2011-2012	JX-L	2	4	24	2.39-2.49	197	Tuohy et al. (2014)
5	2011-2012	JX-H	2	4	24	2.64-2.75	307	Tuohy et al. (2014)
6	2013-2015	FT70	3	4	24-25	2.25-2.67	280	Fenger et al. (2020)
6	2013-2015	RA60	3	4	24-25	2.25-2.67	280	Fenger et al. (2020)
6	2013-2015	RA50	3	4	24-25	2.25-2.67	280	Fenger et al. (2020)
7	2017-2018	LC	2	4	24	2.5	235	Unpublished
7/8	2017-2018	GP2.5	2	4	24	2.5	280	Fenger et al. (2021a)
8	2017-2018	GP3.0	2	4	24	3.0	280	Fenger et al. (2021a)
8	2017-2018	GP3.5	2	4	24	3.5	280	Fenger et al. (2021a)
8	2017-2018	GP4.0	2	4	24	4.0	280	Fenger et al. (2021a)

† artificial fertilizer and *in situ* biological nitrogen fixation; not including N deposition from animals and manure application

was 9.5 ha (range: 6 to 13.6 ha). At the beginning of each experiment the area was divided into six blocks according to soil type and drainage status and one paddock from each block was randomly assigned to a system and remained in that system until the end of the experiment. Mean paddock size was 1.67 ha (*SD* 0.4 ha).

5.2.4. Management of the grazing systems

The management of the grazing systems generally followed a standard set of rules. Each herd was under rotational strip-grazing management. Cows were turned out to graze approximately three days after calving and remained at pasture until they were dried off between mid-November and mid-December. During the main grazing season (from April to 1 August) in all of the systems in this study AHC was measured on a weekly basis and managed to consistently maintain a pre-grazing herbage mass (PGHM; >4 cm AGL) of 1400 kg ha^{-1}; i.e. an AHC of 700 kg ha^{-1}. This was mostly achieved by harvesting surplus herbage as silage. Under exceptional circumstances during the main grazing season when herbage growth rates fell below herd demand, cows were supplemented with concentrates once PGHM was less than 1000 kg ha^{-1}. The rate of supplementation depended on the extent of the herbage deficit. Silage was also fed if the cows had to be housed due to severe herbage deficit due to drought (e.g. 2006 and 2018) or due to excessively wet soil conditions i.e. a volumetric soil moisture content (VSMC m^3 m^{-3}) of between 0.6 and 0.7. The latter tended to be relatively short term (2 or 3 days) during the main grazing season. Supplementation with concentrates to each herd during the main grazing season and during AUTUMN was allocated at exactly the same rate within each year. Supplementation with silage was allowed to vary in line with the feed budget for each herd.

Supplementation with concentrates and silage varied for year to year depending on weather conditions and their impact on herbage growth and ground conditions.

As a general rule no herbage was harvested for silage after 1 August. AHC was allowed to increase from a target of 700 kg ha^{-1}, as outlined above, to a target peak of 1200 kg ha^{-1} in mid-September. Exceptions were made when it looked like herbage covers were going to greatly overshoot the target for mid-September and weather and ground conditions were suitable for harvesting surplus herbage as silage. It happened occasionally that weather and ground conditions were not suitable for harvesting silage, particularly later in the season, and AHCs were allowed to overshoot the target, which explains some of the higher peak AHCs in this study. Although some surplus herbage was harvested as silage in some systems after 1 August, the areas harvested and the quantities of herbage removed from each system were kept to a minimum and were very small relative to the quantities harvested during the main grazing season.

Similar to the main grazing season cows were housed temporarily during AUTUMN if ground conditions were deemed to be excessively wet. In studies 1 and 2 (Table 5.1) this decision was made by the farm manager based on experience. From 2007 onwards VSMC was measured using a soil probe (ML2x soil moisture measurement kit; Delta-T Devices Ltd, Burwell, Cambridge, UK) and this information was used for decision support. A VSMC of >0.6 (studies 3, 4 & 5), >0.7 (study 6) and between 0.6 and 0.7 (studies 7 & 8; Table 5.1) was used as a guide for housing the cows between 2007 and 2018.

CLOSING date marked the end of the grazing season and was defined as the final day in AUTUMN when all cows of each system were housed for the closed period and did not go out to pasture again until the following spring. The target in all studies was to maintain the cows at pasture until at least 1 December while hitting a target AHC of 500 kg ha^{-1} on 1 December. The latter condition was the reason that cows were rarely maintained at pasture until or after 1 December. When the AHC fell below the target of 500 kg ha^{-1} during November, cows were housed in order to allow the swards to grow up to the target. Hence, cows were housed prior to 1 December depending on the current AHC and the expected daily herbage growth rate (based on ten-year averages) between the CLOSING date and 1 December. The other criteria governing the decision to close pastures for the winter were ground conditions as described above and drying off the cows at the end of lactation. In all studies drying off of the younger and earlier-calving cows generally commenced in late November and was completed in the week before Christmas day (25 December). Hence, a range of CLOSING dates and CLOSING AHCs were recorded across systems.

5.2.5. Measurements

Meteorological data. Meteorological data was recorded at the climatological station located on the research farm. Soil temperature was measured daily at a soil depth of 10 cm. Soil moisture deficit (SMD) was calculated for each day of the experimental period of each year using the model developed by Schulte et al. (2005) assuming a poorly drained soil. The number of days when SMD was 0 mm or above was recorded. This has been defined as a threshold for trafficability with bovine livestock (Herbin et al., 2011, Piwowarczyk et al., 2011). In the present study a high number of days with SMD >0 mm were used to indicate better soil trafficability and a low number to indicate poorer soil trafficability.

Herbage production and nutritive value. Immediately before each grazing PGHM was determined on every paddock by harvesting a strip of herbage using (i) a lawnmower (HRH-536 rotary blade, Honda®, Alpharetta, GA, USA between 2001 and 2009 and (ii) an Etesia Hydro 124DS, (Etesia UK Ltd., Shenington, Oxon, UK) between 2010 and 2018. All mown herbage from each strip was collected and weighed. A 100 g (fresh weight) subsample was taken and dried for 16 h at 90°C for determination of dry matter content, which then was used for determination of PGHM (kg DM ha^{-1}). A second 100-g sub-sample was freeze-dried and milled through a 0.2 mm sieve before analyses for ash content (550 °C muffle furnace for 12 h), crude protein (CP; N content; Leco 528 auto-analyser, Leco Corp., St. Joseph, MI, USA) and *in vitro* organic matter digestibility (OMD) as described by Morgan et al. (1989). Post-grazing sward height was determined immediately after each grazing using a Filips rising plate meter (Grasstec, Mallow, Cork, Ireland). Herbage growth rate was determined as the mass of herbage grown between two harvests/grazings divided by the number of days in each interval; i.e. the rotation interval. Mean rotation interval per system was the mean rotation interval of all paddocks per system of each rotation during AUTUMN. Mean PGHM and herbage growth rate for each system during AUTUMN was determined likewise.

Milk production. Cows were milked at 0730 and 1530 h daily throughout lactation in all years of the study. Individual cow milk yield was recorded at each milking. The composition of milk from each cow was determined for a morning and for an evening milking once per week using a Milkoscan 203 (Foss Electric DK-3400, Hillerød, Denmark). Mean daily milk yield per cow was the mean yield of all cows per system each day during AUTUMN and likewise for other milk production variables including milk solids yield, which was the yield of milk fat plus protein per cow. The live-weight of each cow was recorded once every two weeks using a weighing scales and the Winweigh software package (Tru-Test Limited, Auckland, New Zealand). Body condition score (Edmonson, 1989; on a scale of 1 to 5) of each cow was recorded once every two weeks.

The amount of concentrate fed per cow was recorded at each milking (Dairymaster, Causeway, Co. Kerry, Ireland).

Grazing season length. The length of the grazing season was measured in terms of days at pasture per cow during AUTUMN. A whole grazing day was defined as when all cows per system were out day and night and not supplemented with silage. One-half day was defined as when all cows were out only by day and supplemented with silage by night. In November and December, when some of the cows were dried off and housed, the proportion of lactating cows out grazing per system was taken into account and the average number of grazing days per cow adjusted accordingly.

Accumulation of herbage during AUTUMN and the availability of herbage for grazing in spring. The compressed sward height of each paddock per system was measured using a Filips rising plate meter once per week during each grazing season and on average once per month during the closed period. Compressed sward height was converted into herbage cover, which was an estimate of mass of herbage >4 cm AGL per paddock using the following formula:

*Herbage Cover (kg DM ha^{-1}) = (Compressed Sward Height (cm) – Target post-grazing height (cm)) * Sward Density (kg DM cm^{-1} ha^{-1})*

A sward density of 240 kg DM cm^{-1} ha^{-1} was used throughout the AUTUMN of all years. Average herbage cover of each system on each measurement date was the sum of the herbage covers of all paddocks of the system divided by the total grazing area. Peak AHC was the highest AHC recorded per system during AUTUMN in each year. CLOSING AHC was the AHC measured during the week of the last grazing before the closed period. OPENING AHC was the AHC measured at the end of the closed period, i.e. when calved cows were turned back out to pasture, which typically took place in early February of the following year. The rate of herbage mass accumulation (growth rate) during the closed period was determined by the difference between CLOSING AHC and OPENING AHC divided by the number of days during the closed period. Some systems were missing data for either CLOSING AHC (five systems) or OPENING AHC (four systems) as defined above and were therefore removed from the dataset for the corresponding analysis.

5.2.6. Statistical analysis

The effect of accumulating herbage during AUTUMN on herbage production, nutritive value and milk production were subjected to an analysis of variance (ANOVA) using the GLM procedure in SAS (SAS 9.4). For the ANOVA, the dataset was grouped into high and low mean PGHM during AUTUMN. From within each of the 17 years the systems with the highest and lowest PGHMs were selected and assigned to each group resulting in n = 34 systems being compared. Year and PGHM system were fixed factors in the ANOVA to establish the effect of high vs. low PGHM within any year.

The full dataset (n = 60 systems) was analysed for associations between milk production variables and peak AHC during AUTUMN using the CORR procedure in SAS to evaluate associations across all grazing systems. The effect of accumulating herbage during AUTUMN on the length of the grazing season and the supply of herbage mass in the following spring was analysed in the full dataset (n = 60 systems) using multiple regression analysis to identify all factors associated with each dependent variable. Dependent variables were days at pasture during AUTUMN, CLOSING date, CLOSING AHC and OPENING AHC in the following spring. Independent variables tested were peak AHC, date of peak AHC, mean PGHM, mean post-grazing height, mean herbage growth rate, days at pasture per cow, stocking rate, amount of concentrate fed and soil trafficability (days with SMD >0 mm) during AUTUMN, date of the last harvest of silage, CLOSING AHC, CLOSING date, mean soil temperature, SMD and herbage growth rate during the closed period. Year was not included as an independent variable in this analysis in order to capture across year effects. Before analysis of each model a test for multicollinearity between independent variables was conducted using PROC CORR and PROC REG in SAS producing Pearson's correlation coefficients (*r*) and variance inflation factors, respectively. Variables with $r > |0.8|$ or a variance inflation factor greater than 10 were removed from the model. A best fit model was created for each dependent variable using the GLMSELECT procedure. Quadratic terms and interactions of second order between independent variables were considered in the model. A stepwise selection process was applied with a 5% significance level for inclusion and exclusion of variables into the model. Partial R^2 values shown refer to the part of the model R^2 explained by each additional variable in the model when all previous variables are controlled. Therefore, model variables are shown in the order of selection by the GLMSELECT procedure. Results are presented as mean ± *SE*

5.3. Results

5.3.1. Descriptive statistics

Minimum and maximum values as well as standard deviations for independent and dependent variables demonstrate that a wide range of AHCs during AUTUMN as well as at OPENING were encompassed by the dataset (Table 5.2). Mean AHC during AUTUMN was 859 ± 33.9 kg DM ha^{-1}. As peak AHC was highly correlated with both mean AHC (r = 0.96, P <0.001) and mean PGHM (r = 0.80, P <0.001) during AUTUMN, peak AHC was used as the main indicator of the mass of herbage accumulated during AUTUMN. The variation in weekly AHC and herbage growth rate during AUTUMN is shown in

Table 5.2: Mean, standard deviation (*SD*), minimum and maximum of the dependent and independent variables per system in the multi-year dataset (2001 to 2018) during AUTUMN (1 August to CLOSING date) and the closed period

Variable	Unit	n	Mean	*SD*	Min	Max
AUTUMN						
Days at pasture	days per cow	60	96	15.3	68	120
Herbage growth rate	kg DM ha^{-1} day^{-1}	60	46.6	10.25	25.4	72.9
Peak herbage cover†	kg DM ha^{-1}	60	1226	349.0	634	1800
Date of peak herbage cover	date	60	17 Sep	19.3‡‡	08 Aug	29 Oct
Pre-grazing herbage mass	kg DM ha^{-1}	60	1609	459.0	785	2953
Post-grazing sward height	cm	49	5.6	1.19	3.9	7.7
Rotation interval	days	53	35.7	6.87	23	54
Stocking rate	cows ha^{-1}	60	2.4	0.47	1.7	4.0
Soil moisture deficit >0 mm‡	days	60	56	23.8	13	96
The closed period						
CLOSING date	date	60	23 Nov	9.4‡‡	07 Nov	17 Dec
CLOSING herbage cover§	kg DM ha^{-1}	55	424	189.6	36	846
Herbage growth rate in closed period	kg DM ha^{-1} day^{-1}	51	2.75	2.59	-4.06	7.07
Soil moisture deficit in December	mm	60	-8.02	1.78	-9.98	-3.56
Soil temperature in closed period¶	°C	60	5.60	1.42	3.02	7.80
OPENING herbage cover††	kg DM ha^{-1}	56	581	265.1	118	1191

† Highest average herbage cover per system during AUTUMN; ‡ number of days where SMD was 0 mm or above; § Average herbage cover at the beginning of the closed period; ¶ Soil temperature measured at 10 cm soil depth; †† Average herbage cover at the end of the closed period (early February); ‡‡ *SD* in days

Figure 5.1a and 1b. The mean of the latest date per system on which silage was harvested to remove surplus herbage was 26 July ± 2.9 days. Figure 5.1c shows the mean development of AHCs during AUTUMN. Peak AHC occurred when herbage growth rate declined below demand.

5.3.2. Herbage production, nutritive value and milk production

The high PGHM systems had higher (*P* <0.001) PGHM (1783 vs. 1445 kg DM ha^{-1}, *SEM* 32.5), a longer (*P* = 0.002) rotation interval (37 vs. 34 days, *SEM* 0.7), a higher (*P* = 0.02) herbage growth rate (50 vs. 44 kg DM ha^{-1} day^{-1}, *SEM* 1.4) and a higher (*P* = 0.002) peak AHC (1345 vs. 1139 kg DM ha^{-1}, *SEM* 39.2) during AUTUMN. Post-grazing height was not significantly different between PGHM systems (5.6 ± 0.09 cm, *P* >0.05). Nutritive

Table 5.3: Mean, standard deviation (*SD*), minimum and maximum of milk production variables per system in the multi-year dataset (2001 to 2018) from 1 August to drying off

Variable	Unit	n	Mean	*SD*	Min	Max
Daily milk yield	kg cow^{-1} day^{-1}	60	16.3	2.07	12.0	19.5
Daily yield of fat and protein	kg cow^{-1} day^{-1}	60	1.39	0.167	0.98	1.67
Milk fat content	g kg^{-1}	60	45.6	4.89	32.4	54.4
Milk protein content	g kg^{-1}	60	39.8	1.94	36.7	44.1
Milk lactose content	g kg^{-1}	60	46.0	0.95	44.1	47.9
Body weight	kg cow^{-1}	60	576	37.84	469	625
Body condition score		60	2.96	0.09	2.81	3.20
Mean dry off date	date	60	4 Dec	5.8†	13 Nov	11 Dec
Concentrate feeding	kg fed cow^{-1}	60	193	151.4	0	566

† *SD* in days

value of herbage was not affected by PGHM (*P* >0.05) in terms of OMD (803 ± 2.8 g kg DM^{-1}), CP (210 ± 5.0 g kg DM^{-1}) and ash (112 ± 0.6 g kg DM^{-1}). Milk yield, milk solids yield, milk fat content, milk protein content and milk lactose content was not affected by PGHM (*P* >0.05; Table 5.3). Likewise, the correlation analysis showed no association between peak AHC and milk yield or milk solids yield.

5.3.3. Grazing season length, CLOSING and OPENING AHC

Days at pasture per cow during AUTUMN were positively associated with peak AHC per system, date of peak AHC, herbage growth rate per system during AUTUMN, and soil trafficability (*P* <0.01) as well as negatively associated with stocking rate per system (*P* <0.001), explaining 77% of the variation (Table 5.4). Within the associated variables only peak AHC and stocking rate were controlled by grassland management. The variation in peak AHC explained the largest part of the variation in days at pasture per system (partial R^2 = 0.46, Figure 5.2a). On average over the 17 years, each increase in peak AHC of 100 kg DM ha^{-1} increased the length of the grazing season by 2.2 ± 0.44 days, whereas each increase in stocking rate of one cow ha^{-1} decreased the number of days at pasture by 11.7

± 2.25. A later CLOSING date was associated with a higher peak AHC, higher SMD in December and better soil trafficability during AUTUMN (R^2 = 0.63; P <0.01; Table 5.4). CLOSING AHC was positively associated with peak AHC and date of peak AHC (P <0.01) and negatively associated with days at pasture (P <0.001), which explained 59% of the variation in CLOSING AHC (Table 5.4). The variation in peak AHC explained the largest part of the variation in CLOSING AHC (partial R^2 = 0.42, Figure 5.2b). On average, each increase in peak AHC of 100 kg DM ha^{-1} increased CLOSING AHC by 46 ± 6.5 kg DM ha^{-1}. Increasing CLOSING AHC by 100 kg DM ha^{-1} increased OPENING AHC by 82 ± 14.2 kg DM ha^{-1} (P <0.001, R^2 = 0.41, Table 5.4). There were moderate associations between mean soil temperature during the closed period and both OPENING AHC (r = 0.38, P = 0.003) and herbage growth rate during the closed period (r = 0.32, P = 0.02).

Table 5.4: Summary of the stepwise selection process from the multiple regression analysis of factors associated with days at pasture during autumn (1 August to CLOSING), CLOSING date, CLOSING AHC and OPENING AHC (February) in the multi-year dataset (2001 to 2018); *SE* = standard error, AHC = Average herbage cover (average herbage DM >4 cm above ground level; average of all paddocks per system); SMD = Soil moisture deficit

Dependent variable	Step	Independent variable	Estimate (*SE*)	Partial R^2	Model
Days at pasture†	0	Intercept	10.1 (17.22)		R^2 = 0.77
(days per cow)	1	Peak AHC¶, †† (kg DM ha^{-1})	2.20 (0.44)***	0.46	*RMSE* = 7.57
	2	Stocking rate† (cows ha^{-1})	-11.7 (2.25)***	0.16	n = 60
	3	Soil trafficability†, ‡‡ (days)	0.18 (0.04)***	0.08	
	4	Date of peak AHC (day in year)	0.23 (0.06)***	0.04	
	5	P. growth rate† (kg DM ha^{-1} day^{-1})	0.38 (0.13)**	0.04	
CLOSING date	0	Intercept	324.7 (4.92)***		R^2 = 0.63
(day in year)	1	Peak AHC¶, †† (kg DM ha^{-1})	1.48 (0.22)***	0.32	*RMSE* = 5.89
	2	SMD in December (mm)	2.57 (0.43)***	0.24	n = 60
	3	Soil trafficability†, ‡‡ (days)	0.11 (0.03)**	0.07	
CLOSING AHC‡	0	Intercept	-357.6 (232.37)		R^2 = 0.59
(kg DM ha^{-1})	1	Peak AHC¶, †† (kg DM ha^{-1})	45.5 (6.52)***	0.42	*RMSE* = 124.7
	2	Days at pasture† (days per cow)	-7.22 (1.66)***	0.09	n = 55
	3	Date of peak AHC (day in year)	3.54 (1.06)**	0.09	
OPENING AHC§	0	Intercept	278 (64.5)***		R^2 = 0.41
(kg DM ha^{-1})	1	CLOSING AHC‡, †† (kg DM ha^{-1})	82.2 (14.2)***	0.41	*RMSE* = 191.8 n = 51

† during AUTUMN; ‡ AHC at the beginning of the closed period; § AHC at the end of the closed period (early February); ¶ highest AHC per system recorded during AUTUMN; †† Increase of 100 kg DM ha^{-1}; ‡‡ number of days where SMD was above 0 mm; P <0.01 = **, P <0.001 = ***

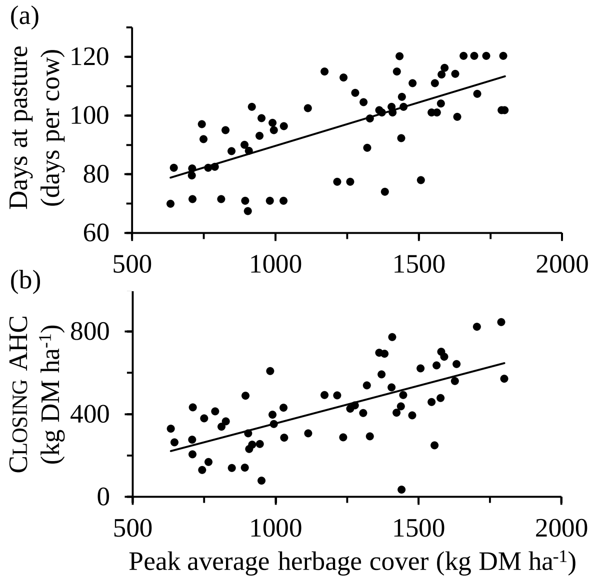

Figure 5.2: Relationship between amount of herbage accumulation (peak average herbage cover; AHC) during AUTUMN (1 August to CLOSING date) and (a) days at pasture (R^2 = 0.43, P <0.001) and (b) CLOSING average herbage cover (R^2 = 0.38, P <0.001) in the 60 grazing systems in the multi-year dataset (2001 to 2018). See Table 5.4 for regression estimates.

5.4. Discussion

5.4.1. The effect of pre-grazing herbage mass on herbage production, nutritive value and milk production during AUTUMN

During the autumn perennial ryegrass swards are in a vegetative state and accumulate herbage up to a ceiling mass at which new leaf growth and senescence are in balance (Parsons and Chapman, 2000). With decreasing light intensity and air temperature towards the end of the growing season senescence rate can exceed the rate of new leaf growth resulting in a net loss of herbage mass and associated negative effects on nutritive value of the herbage (Lawrence et al., 2017). In the present study there was no evidence that higher PGHM was associated with net loss of herbage mass during the AUTUMN. Indeed, in the comparison of high and low PGHM swards the high PGHM had a positive effect on herbage growth rate, which clearly indicates that ceiling mass had been not surpassed. In previous plot-based studies with perennial ryegrass swards net loss of herbage mass occurred when rotation intervals were longer than 84 days (from 9 August to 11 November; ceiling mass of 3185 kg DM ha^{-1}; Lawrence et al., 2017) or 61 days (from 20 September to 20 November; ceiling mass 2460 kg DM ha^{-1}; Hennessy et al., 2006). In a study with grass-clover swards between 2 July and 23 September highest herbage growth rates were reported with a rotation interval of 42 days compared to 56 or 84 days (daily growth rates of 59, 45 and 40 kg DM ha^{-1}, respectively; Phelan et al., 2013b). In the same study between 24 September and 16 December herbage growth rate was highest at 56 days rotation interval (daily growth rates of 17 versus 10 and 8 kg DM ha^{-1} for 42 and 84 days, respectively). The mean rotation interval of the high PGHM systems examined in the present study was 37 days. Hence, the rotation intervals in the present study were shorter than those likely to be subject to net senescence of herbage mass.

There was no indication that higher PGHM negatively affected utilisation of grazed swards during AUTUMN because there was no difference in post-grazing heights between the PGHM swards. Furthermore, PGHM had no effect on herbage nutritive value, milk and milk solids yield in the present study, similar to that recorded by Bryant and MacDonald (1983). In agreement with the present study, Dillon et al. (1998) found no difference in post-grazing height, nutritive value (OMD and CP) or milk yield from swards grazed at different average PGHMs (1930 vs. 2314 kg DM ha^{-1}) between 21 August and 6 December. Curran et al. (2010) also found no difference in post-grazing height and milk production of swards differing in PGHM (1600 vs. 2400 kg DM ha^{-1}, grazed at a daily herbage allowance of 15 kg DM per cow) between 21 July and 31 October. Although, in the latter study, Curran et al. (2010) reported higher OMD and higher CP in the lower PGHM swards. Nevertheless, the absence of a difference in milk yield in the present and previous studies clearly indicates that the nutritive value of both high and low PGHM swards were sufficient to meet the dietary requirements of spring calving dairy cows in mid and late lactation.

5.4.2. The effect of accumulating herbage during AUTUMN on the length of the grazing season and the supply of herbage mass in spring

The results of this study show that accumulating herbage during AUTUMN can effectively extend the grazing season and increase the proportion of grazed herbage in the diet of dairy cows. Peak AHC and stocking rate explained a greater part of the variation in days at pasture than soil trafficability during AUTUMN. Similarly, peak AHC explained a greater part of the variation in CLOSING date than SMD during December and soil trafficability during AUTUMN. Cows mostly had to be housed at CLOSING due to a deficit of herbage rather than poor soil trafficability.

The main period in AUTUMN when the grazing season can be extended (and the proportion of grazed herbage in the diet increased) was during the interval between peak AHC and CLOSING. At the mean stocking rate in this study of 2.4 cows ha^{-1}, and with the type of cow involved in this study the daily feed demand was approximately 50 kg DM ha^{-1}. Hence, each additional 100 kg DM ha^{-1} increased the length of the grazing season by approximately 2 days. This relationship also explains why a higher stocking rate decreases the number of days at pasture during AUTUMN because there is a higher daily feed demand by the grazing herd.

Higher peak AHC was associated with higher CLOSING AHC, which concomitantly resulted in higher OPENING AHC in the following spring. Hence, accumulating herbage mass during AUTUMN facilitated extending the grazing season in AUTUMN and in the following spring. This is likely to improve profitability due to lower feed costs and a lower requirement for housing and management of slurry etc. (Läpple et al., 2012, Hanrahan et al., 2018). Previous studies focused on increasing the mass of herbage at turnout in early spring by closing swards earlier before the winter, which consequently meant fewer days at pasture and a shorter grazing season during AUTUMN. It has been shown that later closing resulted in lower herbage mass for grazing in spring and vice versa (Ryan et al., 2010, Lawrence et al., 2017, Claffey et al., 2020). The results of the present study demonstrate that accumulating herbage during AUTUMN can provide a double dividend of more days at pasture during the AUTUMN and a higher OPENING AHC. Nevertheless, the low predictability of OPENING AHC from CLOSING AHC and the association with soil temperature during the closed period in the present study demonstrates that the grazing management during the preceding autumn does not always directly impact on the mass of herbage in the following spring, which is somewhat similar to that found by Bryant and MacDonald (1983). Low temperatures and inclement weather during the closed period can cause loss of the accumulated herbage mass. Hennessy et al. (2006) and Claffey et al. (2020) reported that following the imposition of closing treatments (early vs. late closing dates) the mass of herbage in the subsequent spring did not follow a consistent pattern in successive years. This was attributed to variations in meteorological conditions and herbage growth rates during the closed period.

5.4.3. Implications for grassland management

Peak AHC is an indicator of the mass of herbage accumulated during AUTUMN. It has been used in guidelines for autumn grassland management in pasture-based systems; at a stocking rate of 2.5 cows ha^{-1} a peak AHC of 1130 kg DM ha^{-1} on 15 September has been recommended by Kennedy et al. (2016). This is similar to the mean peak (1139 kg DM ha^{-1}) of the low PGHM systems in the present study. While it is not possible to clearly identify an optimum peak AHC based on the results of this study it is clear that there were only benefits from increasing peak AHC from 1139 to 1345 kg DM ha^{-1}, which was the mean peak AHC in the high PGHM systems in the present study.

Herbage growth rate during AUTUMN was variable as it was mainly dependent on weather conditions (Figure 5.1b). In years with high herbage growth rate during the herbage accumulation interval a moderate peak AHC can be achieved by harvesting surplus herbage for silage. Ensilage is associated with losses of dry matter and nutritive value of the herbage (Borreani et al., 2018) and an increase in production costs (Finneran et al., 2012a). There may be an upper limit for peak AHC where the difference in production cost between storing herbage mass *in situ* and ensiling excess herbage mass does not compensate for losses due to net senescence. Identifying such upper limits for peak AHC at different stocking rates would be useful for developing practical guidelines for optimally extending the grazing season while avoiding excessive net senescence of accumulated herbage.

5.5. Conclusion

Higher mean PGHM (1783 vs. 1445 kg DM ha^{-1}) and a higher than commonly recommended mean peak AHC (1345 vs. 1139 kg DM ha^{-1}) did not negatively impact on herbage growth rate, herbage utilization, the nutritive value of herbage or milk production of spring-calving dairy cows during AUTUMN in the present study. Higher peak AHC increased herbage growth rate and days at pasture per cow during AUTUMN, and CLOSING AHC. A higher CLOSING AHC was associated with a higher OPENING AHC in February.

Therefore, the results of the present study show that the length of the grazing season and the proportion of grazed herbage in the diet of dairy cows can be increased by accumulating herbage during AUTUMN. This has potential to lower costs of production in pasture-based dairy systems.

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Chapter 6 Discussion and conclusions

This study set out to investigate aspects of grassland management on farms where a long grazing season and maximum intake of grazed herbage are more difficult to achieve. Chapter 3 has shown that it was possible to achieve a long grazing season under wet soil conditions. The system with the longest grazing season was the most productive and profitable option despite also incurring higher treading damage. Chapter 4 demonstrated that a higher stocking rate on the grazing platform (GPSR) shortened the grazing season but did not lower the productivity of fragmented dairy farms. In Chapter 4 grazed herbage intake per cow and net profitability per ha decreased with higher GPSR and higher fragmentation. Nevertheless, Chapter 4 demonstrated that on a fragmented farm with a fixed grazing platform (GP) size net profitability per farm can increase with higher GPSR even though grazed herbage intake per cow and net profitability per ha decreased. Chapter 5 showed that the length of the grazing season can be extended by specific grassland management. Together these results provide important and new insights into grassland management for farms where the length of the grazing season is restricted. This Chapter will combine and discuss all findings of the present study together, list the implications for practical farming and offer recommendations for future work in this area of research.

6.1. Overall discussion

6.1.1. Effect of grazing season length on profitability

This study has reiterated the positive impact of intake of grazed herbage on profitability of pasture-based dairy farming as demonstrated in previous studies (Läpple et al., 2012, Ramsbottom et al., 2015, Hanrahan et al., 2017). When the data of Chapter 3 and Chapter 4 (scenario 1, all years except 2018) is combined net profitability per ha increased (P <0.001) by €345 for each 1 t increase in annual intake of grazed herbage per cow (Figure 6.1). This equals an increase of €138 per ha net profitability for every increase of 1 t grazed herbage intake per ha overall farm area. In 2018 severe drought conditions significantly increased concentrate input compared to all other years, which is why it is analysed separately here. The relationship between days at pasture per cow and net profitability per ha was not as strong (R^2 = 0.74, P <0.001). Net profitability per ha increased by €4.74 for each day per cow more at pasture (all years except 2018).

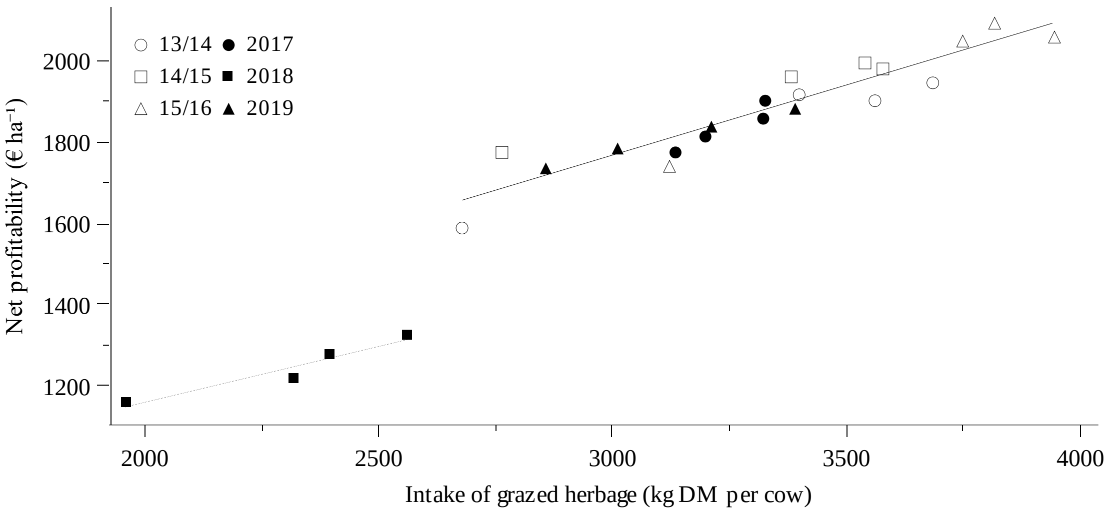

Figure 6.1: Relationship between intake of grazed herbage (kg DM per cow) and net profitability (€ ha^{-1}) in the grazing systems in Chapter 3 and Chapter 4 (scenario 1) in all years except 2018 (solid line, y = 345 x + 729, R^2 = 0.88, P <0.001) and in 2018 (dotted line, y = 276 x + 605, R^2 = 0.94, P = 0.03)

In a similar analysis of on-farm data Hanrahan et al. (2018) found an average increase in net profitability per ha of €173 per t of DM increase in herbage mass used per ha and €1.85 per day increase in grazing season length. One explanation for the difference in results between the present study and Hanrahan et al. (2018) is that in the latter study there was no association between grazing season length and production cost identified. In the present study labour costs increased with less days at pasture due to higher management requirements. This also highlights the multiple components affecting the relationship between grazed herbage intake and net profitability. A higher intake of grazed herbage per cow not only decreased feed costs and increased labour costs in both Chapter 3 and Chapter 4. In Chapter 4 there were additional variable costs caused by fragmentation and in Chapter 3 a higher grazed herbage intake was associated with higher milk solids production.

6.1.2. Effect of grazing season length on milk production

A shorter grazing season and less grazed herbage in the diet had negative effects on milk solids production per cow in Chapter 3 but no effect in Chapter 4. Milk protein content and the amount of silage fed during lactation were negatively associated in Chapter 3 but not in Chapter 4 (Figure 6.2).

On average milk protein content was generally higher in Chapter 3 (mean 38.4 g kg^{-1}) compared to Chapter 4 (mean 36.3 g kg^{-1}), while the amount of silage intake during lactation was generally lower in Chapter 3 (mean 442 kg per cow) compared to Chapter 4 (mean 919 kg per cow). Days at pasture were on average 245 days in Chapter 3 and 224 days in Chapter 4, while days in milk (lactation length) were 282 days in Chapter 3 and

292 days in Chapter 4. Furthermore, the difference between low and high silage intake during lactation between grazing systems was larger in Chapter 3 with 278 (S<7) vs. 899

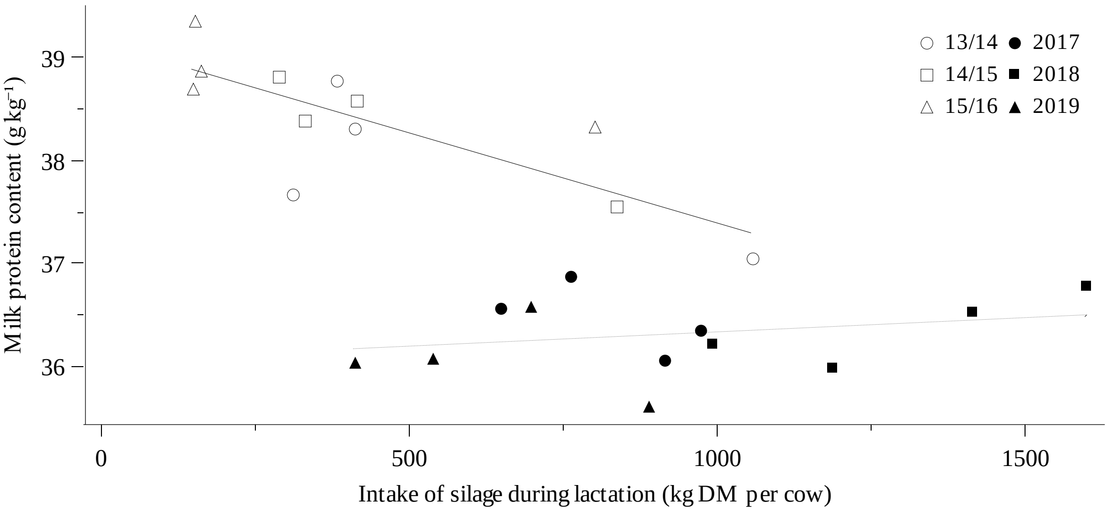

Figure 6.2: Relationship between the proportion of silage fed during lactation and milk protein content (g kg^{-1}) in all grazing systems in Chapter 3 (solid line, y = -1.74*10^3 x + 39.1, R^2 = 0.63, P = 0.002) and Chapter 4 (dotted line, R^2 = 0.06, P = 0.42)

(CONTROL) kg DM per cow (difference of 621 kg DM per cow) compared to Chapter 4 with 684 (GP2.5) vs. 1154 (GP4.0) kg DM per cow (difference of 470 kg DM per cow). It is possible that the general higher level of silage feeding and the smaller difference between systems in Chapter 4 alleviated a negative effect of silage inclusion on milk protein content. Furthermore, in Chapter 3 the silage was mainly fed during the first half of lactation while in Chapter 4 silage was mainly fed during the second half of lactation. The lower energy requirements of dairy cows in the second half of lactation might have further lessened a potential effect of silage inclusion on milk protein content during that time. This is supported by the results of Chapter 5 where a longer grazing season and therefore a lower requirement for silage supplementation during autumn had no effect on milk protein content during autumn. Previous studies have found similar results where a higher inclusion of silage into the diet decreased milk protein content in early lactation

(Dillon et al., 2002, Kennedy et al., 2005). However, in contrast to the present study some earlier studies reported a negative effect of silage inclusion in the diet on milk protein content during autumn and therefore the second half of lactation (Dillon et al., 1998, Reid et al., 2015, Claffey et al., 2020). Nevertheless, the variation in milk protein content in the latter studies did not affect milk solids production during autumn, which is again in agreement with the results of the present study.

6.1.3. Extending the length of the grazing season

Extending the length of the grazing season by grassland management is especially valuable for farms with limitations in access to land available for grazing. Chapter 5 has demonstrated that a surplus of herbage growth can be accumulated and stored *in situ* for grazing later in the season. The results found in Chapter 5 have recently been confirmed by a farm systems study (Evers et al., 2021). Similar to Chapter 5, Evers et al. (2021) concluded that accumulating herbage during autumn (achieved by extending autumn grazing rotation interval) can extend the grazing season into late autumn while increasing the amount of herbage available at the beginning of the following grazing season. Herbage production, nutritive value of the sward, post-grazing sward height and animal performance were relatively insensitive to changes in pre-grazing herbage mass, which is in agreement to the results of Chapter 5. Nonetheless, in the study of Evers et al. (2021) the grazing season was not actually extended in late autumn in the experiment. All systems finished the grazing season at the same time (20 November). Systems with higher herbage availability (peak average herbage cover (AHC) of 1250 kg DM ha^{-1}) finished the grazing season with a higher closing AHC (870 kg DM ha^{-1} on 1 December) while systems with lower herbage availability (peak AHC of 750 kg DM ha^{-1}) finished the grazing season with lower closing AHC (420 kg DM ha^{-1} on 1 December). Hence, the present study in Chapter 5 is currently the only study actually showing the link between herbage accumulation (peak AHC) and days at pasture during autumn.

With higher GPSR feed demand from the GP increases (Chapter 4). In relation to management to extent the grazing season this means that on the one hand systems with high GPSR will reach peak AHC earlier. Herbage growth rate will fall below daily feed demand earlier than in systems with low GPSR and a lower daily feed demand. This means that on the other hand systems with higher GPSR can build higher peak AHC as the interval when accumulated herbage is fed to cows is longer. Similarly, Evers et al. (2021) highlighted that grassland management has to be adapted for more intensive systems with higher stocking rates to support the higher feed demand. Furthermore, it was concluded that accumulating more herbage mass during autumn can be an effective strategy to increase herbage supply in higher stocked systems.

An extension of the grazing season involves turning cows out to pasture in conditions that entail a high risk of treading damage. The results of Chapter 3 have shown that grazing under wet soil conditions may not be as detrimental to herbage production as commonly believed. Unlike the majority of previous studies, the experiment in Chapter 3 has evaluated the effect of treading damage in an actual farm systems study over three whole and consecutive grazing seasons on a heavy soil. Hence, there is strong evidence that these results are easily transferrable and highly applicable to commercial Irish dairy farms. The results of Chapter 5 indicated that cows mostly had to be housed due to deficits of herbage for grazing rather than poor soil trafficability. This highlights that on wet farms there is scope to implement management to increase herbage available for grazing in late autumn and early winter. Overall, the results of Chapter 3 and Chapter 5 together indicate that even under difficult conditions on farms with wet soils extending the grazing season by grassland management is possible and profitable.

6.2. Overall conclusions

One of the major contributions of the present study was to confirm the importance of a long grazing season for pasture-based systems even under difficult circumstances. A lower proportion of grazed herbage in the diet decreased net profitability per ha in all cases. With a shorter grazing season variable costs increased due to higher silage making and slurry handling costs. Where milk solids production per cow was affected, gross output decreased with a lower proportion of grazed herbage in the diet due to lower milk solids output.

The effect of a higher inclusion of silage into the diet during lactation on milk solids production differed between experiments. When silage was mainly fed during the first half of lactation milk protein content and milk solids production decreased linearly with more silage fed. In experiments where silage was mainly fed during the second half of lactation, milk protein content and milk solids production were not affected.

Higher GPSR did not affect system productivity albeit with fewer days at pasture per cow and a lower proportion of grazed herbage in the diet. With higher GPSR there was a higher feed demand on the GP and hence a higher requirement for silage supplementation per cow. Days at pasture per cow decreased with higher GPSR by between 26 days across the whole year and 12 days during autumn for each increase in 1 cow per ha GPSR.

At a fixed herd and overall farm size a higher degree of farm area fragmentation and longer distances between GP and non-GP parcels decreased net profitability per farm and per ha due to an increase in variable costs. At a fixed GP size, increasing GPSR linearly increased gross output per farm. The increase in total production costs with higher GPSR was almost linear however, with an increasing effect of a quadratic term the longer the distances between GP and non-GP parcels. As a result, the relationship between GPSR and net profitability was quadratic and marginal benefit per cow decreased with higher GPSR. The profitability of increasing GPSR from the baseline of 2.5 cows ha^{-1} was mainly determined by external factors. There was no specific point within the range of GPSR tested where the benefits of higher milk output from the GP were counterbalanced by negative impacts and increased costs associated with farm fragmentation. Higher milk prices, shorter distances and lower land rental price increased the optimum GPSR to maximise profitability of fragmented systems and vice versa.

Overall, total annual herbage production was not affected by grazing system in any of the experiments indicating that grazed swards are relatively insensitive to variations in grazing season length and the aspects of grassland management tested in the present study.

This study has clearly emphasised the importance of grassland management to extend the length of the grazing season on pasture-based dairy farms. Accumulating herbage during autumn was shown to facilitate extending the grazing season into late autumn while also increasing the amount of herbage available at the beginning of the following grazing season. The resulting increase in pre-grazing herbage mass during autumn did not affect milk or herbage production or nutritive value of the herbage.

The present study further highlighted that extending the grazing season requires allowing dairy cows access to pastures during wet soil conditions which increases the risk of treading damage. The results showed that the severity of treading damage did not affect herbage production. Lowering the risk of treading damage by restricting access to pasture in wet soil conditions (completely or temporarily) decreased system profitability. VSMC provided an objective indicator of the risk of treading damage but there were no benefits of keeping cows indoors during periods with VSMC between 0.5 and 0.7. Therefore, the findings of this study highlighted the importance and contributed to the understanding of grazing season length for pasture-based dairy farms in general and specifically for farm with wet soils.

6.3. Overall implications

The findings of the present study suggest the following:

- Dairy cows can be kept on pastures for most of the day up to a VSMC of 0.7. Measurements of VSMC can be used to ascertain treading risk but the usefulness of those measurements for decision support needs further investigation. The degree of plastic deformation incurred within a whole farm system is not necessarily aligned with herbage production or profitability.
- Inclusion of silage into the diet can have negative effects on milk solids production when fed during the first half of lactation. This implies that prioritising the availability of herbage for grazing in spring can minimize the negative effect of a shorter grazing season on milk output.
- On farms with fragmented farm area a GPSR of up to 4 cows per ha can be profitable depending on degree of fragmentation, the distance between GP and non-GP parcels, milk price and land rental price. An evaluation of the individual circumstances is necessary to offer appropriate recommendations about increasing GPSR for fragmented dairy farms. The lower the milk price the more important it was to consider distance between GP and non-GP parcels and land rental price. It also needs to be considered that systems with higher GPSR are more sensitive to changes in herbage growth and less resilient to changes in input and output prices.

- Accumulating herbage during autumn can provide herbage for grazing in late autumn and early winter as well as the following spring, which negates the need to close pastures earlier in order to facilitate early turnout. This is especially important for systems with high GPSR. With higher GPSR more herbage can be accumulated during autumn meaning that the herbage accumulation interval can commence earlier.
- Overall, this study strengthens the importance of a long grazing season and a maximised proportion of grazed herbage in the diet of dairy cows in pasture-based systems. This suggests that management to extent the grazing season should be priority on most farms.

6.4. Recommendations for future work

This study has raised important questions about grassland management for pasture-based dairy systems. Common to all experiments conducted in the present study was that more extreme circumstances than what was tested could bring more insight into upper limits or tipping points of the management strategies.

(i) Grazing with dairy cows on soils at VSMC >0.7 could determine a ‘tipping point’ at which the severity of treading damage is detrimental to herbage production.

(ii) Testing a GPSR of >4 cows ha^{-1} could ascertain a tipping point at which the amount of silage fed during lactation affects milk solids production. This would also provide more insight into the potential optimum GPSR of fragmented dairy farms.

(iii) Investigating grazing systems with high peak AHC (>1345 kg DM ha^{-1}) could determine if an upper limit for peak AHC exists where the difference in production cost between storing herbage mass *in situ* and ensiling excess herbage mass does not compensate for potential losses due to net senescence. This would again help to identify an optimum peak AHC for pasture-based systems. This needs to be established in relation to the level of GPSR.

In all years of the experiment in Chapter 4 herbage growth rate during autumn was higher than average, which facilitated an accumulation of herbage even in the high GPSR systems. A further investigation is required at average or low herbage growth during autumn in high GPSR systems. The appropriate timing for the beginning of the herbage accumulation interval in high GPSR systems also needs further investigation. Different supplementation strategies, for example (i) small amounts of silage supplementation every day and late closing vs. (ii) no silage supplementation until all available herbage is grazed in conjunction with earlier closing. This also requires an economic evaluation.

This study investigated the effects of treading damage during wet soil conditions over three consecutive grazing seasons. However, the effect of treading damage on soil structural properties was not investigated. Long-term effects of severe treading damage on soil structure are possible (Greenwood et al., 1997, Greenwood and McKenzie, 2001, Drewry et al., 2008). Hence, further investigations over a longer period could assess potential long-term effects of treading damage in wet soil conditions on soils and herbage production.

The management thresholds of VSMC used in the present study may not have been sensitive enough. There was still treading damage at VSMC <0.5. The upper limit of 0.7 VMSC may have avoided excessive damage. Soil moisture limits for animal traffic that are guided by the consistency behaviour of a specific soil could provide a more sensitive measurement that would also be applicable across differences in soil characteristics between dairy farms. A limit for access to pasture at the plastic limit of the soil could eliminate plastic soil surface deformation in grazing systems. An assessment of a whole-farm system without plastic deformation of the soil surface could evaluate if this will produce higher quantities of herbage and if that balances out negative effects of a shorter grazing season on profitability. This will likely depend on the soil type and the likelihood of wet soil conditions during the grazing season. Since the liquid limit is not frequently surpassed during the grazing season, studies on the topic are rare. Such a limit for grazing would be most beneficial in a wetter than usual year. Nonetheless, the assessment of consistency limits requires more complex soil testing which makes the system less applicable as simple on-farm decision support.

Concerning fragmented farms, this study looked at a whole fragmented farm scenario with non-GP parcels rented out in low GPSR systems as required. There are several more scenarios that could be investigated and compared to the results of the present study; (i) a scenario where only the grazing platform is owned and the non-GP parcels are rented in as required, (ii) more extensive use of zero-grazing during the grazing season to fill feed deficits from the GP in high GPSR systems, (iii) rearing of young stock on non-GP parcels.

The practice of zero-grazing has become more popular on fragmented farms as it offers a way of maintaining grazed herbage in the diet of dairy cows when herbage growth on the GP is low (Holohan et al., 2021). In the present study, an extended use of zero-grazing was limited by the availability of machinery. Holohan et al. (2021) identified knowledge gaps in cost analysis, productivity and profitability of zero grazing on Irish dairy farms. A further investigation within potential application systems is, hence, required to evaluate if zero-grazing could offer a less expensive and practicable alternative to fill feed deficits during the grazing season in fragmented systems with high GPSR.

The costs of housing cows for longer in both economic evaluations included in the present study, especially the increase in labour costs, were based on assumptions. A further investigation of such costs on a day-to-day basis could improve the accuracy of economic comparisons of grazing systems with variations in grazing season length.

This study has highlighted the importance of high quality silage for systems with restrictions in grazing season length, as a higher proportion of the silage is fed during lactation. Further research is required to establish optimal management guidelines for the production of high quality silage within pasture-based systems that were traditionally designed to supply lower quality silage mainly to dry cows.

Environmental regulations have become increasingly strict over the last decade (e.g. recent EU Green Deal). Hence, an assessment of differences in environmental footprints between systems varying in GPSR is required to evaluate the sustainability and longevity of farms that increase GPSR now. Furthermore, the recent increase in cow numbers and intensity of dairy production coincided with a decline in water quality in Ireland (EPA, 2021). Further investigations are required to establish the nitrogen loads and nitrogen losses on the grazing platform of high GPSR systems.

More broadly, this study provided deeper insight into the vulnerability of pasture-based systems in general and especially systems with high GPSR to changes in herbage growth rate due to drought conditions. Extreme weather events and periods of low rainfall are projected to occur more frequently. This is likely to severely affect pasture-based systems but studies on the topic are rare (Lee et al., 2013, Chang-Fung-Martel et al., 2017). Hence, further investigations are required that focus on impacts of and adaptations to extreme climate events in pasture-based systems.

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